Cellulosic Ethanol

Quick Facts

- Cellulosic materials, such as agricultural or forestry residues, short rotation woody crops, and a variety of grasses, can be used to produce biofuels like ethanol. The process of converting cellulosic materials to ethanol is more complex than current ethanol production from corn or sugarcane, and the technology is not yet used at commercial scale.

- Cellulosic ethanol is currently an emerging technology and will require continued technological advancements and reduced costs to become commercially viable.

- The Energy Independence and Security Act (EISA) of 2007 includes requirements for cellulosic ethanol use, beginning with 100 million gallons of cellulosic ethanol in 2010 and increasing yearly to 16 billion gallons by 2022. EISA also requires that cellulosic ethanol achieve at least a 60 percent reduction in life-cycle greenhouse gas emissions per gallon relative to gasoline.

Background

Ethanol, an alcohol that can be produced from a wide variety of plant materials as feedstocks, is used as a liquid fuel in motor vehicles. At present corn starch and sugarcane are the two main feedstocks used, respectively producing starch- and sugar-based ethanol. Another type of plant material, cellulose, can also be used to produce ethanol, but doing so requires additional processing to break down the cellulosic materials into sugars. Ethanol produced from cellulose is referred to as cellulosic ethanol.

Cellulosic materials, which provide structure to plants, are found in the stems, stalks, and leaves of plants and in the trunks of trees. The abundance of cellulosic materials – roughly 60 to 90 percent of terrestrial biomass by weight – along with the fact that they are not used for food and feed (unlike corn and sugarcane), are key reasons why cellulosic ethanol and other cellulose-based biofuels have attracted scientific and political interest. Cellulose and hemicellulose, which are referred to collectively as cellulosic materials, can be broken down into sugars, which can then be fermented into ethanol. Cellulosic materials being examined for the production of biofuels include those derived from switchgrass, prairie grasses, short rotation woody crops, agricultural residues, and forestry materials and residues.

Ethanol is chemically the same whether it is produced from corn, sugarcane, or cellulose, but the production processes are different and the necessary production technologies are in different stages of development. Corn- and sugar-based ethanol production technologies have been used at commercial scale for decades (see *CLIMATE TECHBOOK: Ethanol*). In contrast, some of the technologies needed to produce cellulosic ethanol, an "advanced biofuel" (broadly defined as a biofuel derived from organic materials other than simple sugars, starches, or oils[1]) are quite new. As of mid-2009, no large, commercial-size cellulosic ethanol facilities were in operation in the United States.

Description

The production of ethanol from cellulosic materials is more complicated than the processes employed for starch- or sugar-based ethanol, because the complex cellulose-hemicellulose-lignin structure in which cellulosic materials are found needs to be broken up before fermentation can begin. The cellulosic ethanol conversion process consists of two basic steps: pretreatment and fermentation. This two-step process increases the complexity of, and processing time required for, converting the cellulosic biomass into ethanol, relative to the processes used to convert corn or sugarcane to ethanol.

- **Pretreatment**
  Pretreatment is necessary to prepare cellulosic materials for a subsequent hydrolysis step which converts the hemicellulose and cellulose into sugars. Typical pretreatment involves a chemical pretreatment step (e.g., acid) and a physical pretreatment step (e.g., grinding). These steps make the cellulose more accessible to enzymes that catalyze its conversion to sugars in a subsequent step and begin the breakdown of hemicellulose into sugar. Following pretreatment, the conversion of cellulose to sugar is completed using a chemical reaction called hydrolysis, normally employing enzymes secreted by certain organisms (typically fungi or bacteria) to catalyze the reaction. The pretreatment and hydrolysis process usually results in one co-product, lignin, which can be burned to generate heat or electricity. Using lignin instead of a fossil-based energy source to power the conversion process reduces cellulosic ethanol's life-cycle greenhouse gas (GHG) emissions, compared to corn-based ethanol. (This is also an example of biomass substitution for fossil fuels; for more information, see *CLIMATE TECHBOOK: Agriculture Overview*.)

- **Fermentation**
  Once the sugars have been obtained from the cellulosic materials, they are fermented using yeast or bacteria in processes similar to those used for the corn-based ethanol production. The liquid resulting from the fermentation process contains ethanol and water; the water is removed through distillation, again similar to the corn-based ethanol process. Finding the most effective and low-cost enzymes for the pretreatment process and organisms for the fermentation process has been one of the main areas of research in the development of cellulosic ethanol.[2]

The type of feedstock and method of pretreatment both influence the amount of ethanol produced. Currently, one dry short ton[3] of cellulosic feedstock yields about 60 gallons of ethanol.[4] Projected yields with anticipated technological advances are as high as 100 gallons of ethanol per dry short ton of feedstock.[5]

Environmental Benefit / Emission Reduction Potential

Cellulosic ethanol has the potential to provide significant lifecycle GHG reductions compared to petroleum-based gasoline. In addition, the use of cellulosic materials to produce ethanol may yield a variety of other environmental benefits relative to corn-based ethanol.

- **GHG emission reduction potential**
  Researchers at the University of California at Berkeley estimated that on a life-cycle basis, cellulosic ethanol could lower GHG emissions by 90 percent relative to petroleum-based gasoline.[6] Other analyses have shown that cellulosic ethanol produced using certain feedstocks could be carbon-negative, which means that more carbon dioxide (CO_2) is removed from the atmosphere than is emitted into the atmosphere over the entire life-cycle of the product (see *CLIMATE TECHBOOK: Agriculture Overview* for a discussion of carbon storage in plants and soils).[7] However, these studies do not include estimates of emissions due to indirect land use change (discussed under "Obstacles to Further Development"), which can affect GHG emission profiles significantly.

  An analysis undertaken by the California Air Resources Board as it developed the California Low Carbon Fuel Standard found significant life-cycle GHG emission reductions from cellulosic ethanol relative to gasoline (see preliminary estimates in Table 1).[8]

Table 1. Life-cycle GHG Intensity for Cellulosic Ethanol, based on the California GREET Model[9]

Fuel	Feedstock	CA GREET GHG (g CO_2e/MJ)	GHG Reduction Compared to Gasoline
Cellulosic Ethanol	Farmed Trees	1.60	98.3%
Cellulosic Ethanol	Forest Residues	21.40	77.7%
California Gasoline (incl. 10% ethanol)		95.9	

Note: These estimates do not include the impact of indirect land use change on GHG emissions.

- **Other environmental considerations**
  Using biomass for transportation fuels raises questions regarding land use and land use change, fertilizer and pesticide use, water consumption, and energy used for production and cultivation of feedstocks. Grasses and trees generally require lower inputs than other row crops such as corn. For example, grasses (e.g., switchgrass) are perennial crops that do not need to be re-planted for up to 20 years. Both grasses and trees require fewer passes of field equipment compared to annual crops such as corn,[10] and they generally have lower fertilizer and pesticide needs.[11] In addition, cellulosic feedstocks can be grown on marginal lands not suitable for other crops, although in this case per acre yields can be lower than feedstocks grown on other lands. Feedstocks can also include a variety of residues (e.g., agricultural and forestry residues). Where agricultural and forestry residues are used, care must be taken to ensure long-term soil health.

Cost

The increased complexity and longer processing time associated with producing ethanol from cellulosic materials also makes cellulosic ethanol more expensive to produce than corn- or sugarcane-based ethanol. As of early 2009, no commercial-scale facilities in the United States were producing cellulosic ethanol and costs will remain largely uncertain until the technology is demonstrated at a commercial scale. In 2006, U.S. Department of Energy (DOE) researchers reported achieving a cellulosic ethanol production cost of $2.25 per gallon.[12] At this cost, cellulosic ethanol is competitive with petroleum-based gasoline when oil prices are near $120 per barrel.[13]

Two key factors that shape the cost of producing cellulosic ethanol are the high capital costs and uncertain feedstock costs.

- **High capital costs**
  A first-of-its-kind cellulosic ethanol plant with a capacity of 50 million gallons per year is estimated to cost $375 million, roughly 6 times the capital cost of a similarly sized corn ethanol plant.[14] These high initial investment costs can present a considerable hurdle to deployment, especially given the greater risk associated with investments in new technologies. As the technology matures, future plants are expected to have reduced capital costs.[15]

- **Uncertain feedstock costs**
  Like all biofuels, costs of cellulosic ethanol are highly sensitive to feedstock costs. Therefore, estimating biomass supply costs is critical to estimating future cellulosic ethanol prices. Future feedstock production costs are uncertain and predictions depend on the assumptions made by analysts. Some predict that as the cellulosic ethanol industry matures, establishing a larger market for cellulosic crops and allowing feedstock producers to gain experience, costs could decline. On the other hand, as demand increases for cellulosic materials and the supply of low-cost waste products

is used up, costs could increase. If technological advances and experience bring down capital costs, uncertain feedstock costs will continue to be an important factor in determining the cost competitiveness of cellulosic ethanol with other liquid motor fuels.

The overall cost of cellulosic ethanol is expected to decline in the future as technological advances are made, particularly in pretreatment steps. Table 2 provides a summary of cost estimates from several recent studies.

Table 2. Estimated future costs of cellulosic ethanol and price of oil where ethanol becomes cost-competitive

Study	Cellulosic Ethanol Production Cost (per gallon)	Cost of Oil (per barrel)	Projected Year	Other Assumptions
Wyman, 2007	$0.75	$40		Feedstock accounts for 2/3 of production cost; $50/ton feedstock
Goldemberg, 2007	$1.07	$60	2012	
Hamelinck et al., 2005	$1.50 $0.90 $0.60	$80 $45 $30	2010 2015-2020 2025	
Aden, 2002	$1.00-$1.35	$55-$70	2015-2020	Biomass feedstock cost ~$25-$50/dry short ton

Sources: Goldemberg, J. (2007). "Ethanol for a Sustainable Energy Future." *Science* 315(5813): 808-810. Aden, A., M. Ruth, et al. (2002). "Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover." *Other Information: PBD*: 1 Jun 2002. Hamelinck, C. N., van Hooijdonk, G., and Faaij, A. P. C. (2005) "Ethanol from Lignocellulosic Biomass: Techno-economic Performance in Short-, Middle-, and Long-term." *Biomass and Bioenergy* 28(4): 384-410. Wyman, C. E. (2007). "What is (and is not) Vital to Advancing Cellulosic Ethanol." *TRENDS in Biotechnology* 25(4): 153-157.

Current Status

Cellulosic ethanol is not yet produced at a commercial scale in the United States. Public and private efforts continue to support research on cellulosic ethanol, and technological advances are expected to reduce costs and improve production methods. As of early 2009, no commercial-size cellulosic ethanol facilities were in operation in the United States. However a number of demonstration plants are in operation and a number of commercial-size facilities are expected to begin production by 2011.[16] In 2007, the DOE funded six facilities with annual plant production goals ranging from 11.4 million to 40 million gallons of cellulosic ethanol.[17] Although two of the funded companies canceled their plans to move forward due to economic difficulties, the remaining four companies intend to begin production by 2010-2011 and, together, produce a minimum of 70 million gallons of cellulosic ethanol per year. In 2007, the National Academy of Sciences found that the United States, using currently available crop residues as a feedstock, could produce about 10 billion gallons of cellulosic ethanol per year. This value assumes a production yield of 60 gallons of cellulosic ethanol per dry short ton, requiring the use of 160 million dry short tons of crop residues. If technological improvements increase production yields to 90 gallons per dry short ton, as some studies expect, annual production volumes could be about 14 billion gallons of cellulosic ethanol per year.[18]

In addition to production of ethanol, cellulosic materials are also being examined as a way to produce other biomass-based substitutes for existing fossil fuels (e.g., gasoline, diesel, and jet fuel) and biobutanol. Like the cellulosic ethanol production process, the thermochemical process that produces biomass-based replacements for existing fossil fuels is not yet at commercial scale, and research in this area is ongoing with the support of the DOE. Biobutanol, like ethanol, is an alcohol-based fuel that can be produced from biomass feedstocks. Biobutanol can be added to gasoline at higher blending quantities than ethanol (in unmodified engines), has a higher energy content per volume than ethanol, and is less corrosive, enabling transport in existing petroleum pipelines.[19] Biobutanol is currently in research stages and no commercial production facilities currently exist.

Overall, as of January 2009, there were 26 projects using one of these three pathways (cellulose to ethanol, biomass-based substitutes for existing fossil fuels, or biobutanol) to produce fuel from cellulosic materials.[20]

Obstacles to Further Development or Deployment

Technological immaturity and high cost are two key barriers to cellulosic ethanol at present. Making this fuel competitive in the marketplace will require more experience and significantly reduced production costs, including capital costs. If the costs of cellulosic ethanol production come down as the technology matures, this fuel will still face some, although not all, of the obstacles that corn-based ethanol currently faces.

- **Flex-fuel vehicle deployment**
  Recent research indicates that current passenger vehicles may be capable of running on fuel blends containing up to 20 percent ethanol by volume (E20).[21] Higher-level blends (up to E85) can be used by flex-fuel vehicles. Flex-fuel modifications are relatively inexpensive when made during vehicle production (estimated to be $50 - $100 per vehicle[22]), but retrofitting existing vehicles could be costly. As of 2008, an estimated 7.3 million light-duty E85 vehicles,[23] or roughly 3 percent of the roughly 250 million passenger vehicles currently registered in the United States,[24] were flex-fuel vehicles. Higher-level blends also require dedicated pumps to dispense the fuel. Currently most of the 1,600 stations with E85 dispensing capability are concentrated in the Midwest, where most ethanol production occurs.[25]

- **Infrastructure requirements**
  Ethanol cannot be shipped in existing crude oil or petroleum fuel pipelines, because ethanol can absorb water and other impurities that accumulate in these pipes, affecting fuel quality, and because ethanol's corrosiveness can shorten pipeline lifetime. Instead, ethanol is currently transported via rail (60 percent of domestic ethanol shipped), truck (30 percent), and barge (10 percent).[26] Currently in the United States, cellulosic feedstocks can be most easily grown in the Midwest and Southeast, but much of the demand for transportation fuels is along the coasts. Thus, large volumes of ethanol may need to be shipped long distances to reach areas of high demand in the future. Without substantial infrastructure investment, increased ethanol shipping could result in significant bottlenecks on both rail and highway networks. These problems could be reduced by encouraging the use of high-level ethanol blends (i.e., E85) regionally instead of low-level blends (E10) on a national basis. Distributing and using ethanol close to where it is produced – i.e., in the Midwest and Southeast – would also minimize the GHG emissions associated with transporting ethanol.[27,28]

- **Food versus fuel**
  Unlike corn ethanol (or ethanol produced from sugarcane), cellulosic ethanol does not necessarily compete with food markets for feedstock directly. However, the production of cellulosic crops is constrained by land availability, which is a limited resource. To decrease competition with other agricultural crops, cellulosic feedstocks could be grown on degraded or marginal farmland unsuitable for production of food crops. However, doing so can decrease yields or increase input energy and fertilizer requirements, which could result in higher feedstock prices and increased GHG emissions.

- **Land use change**
  The production of fuels from biomass feedstocks has direct and indirect impacts on land use. For example, clearing grasslands or forests to plant biofuel crops are direct land use changes that result in releases of carbon stored in soils and vegetation. Indirect land use change refers to the land use changes that result from the impacts on land and biomass prices due to increased demand for biomass for biofuel production and the interactions with ongoing demand for food, feed, and fiber products.

  Accounting for indirect land use changes is particularly challenging and relies upon a number of estimates and assumptions. Recent studies have shown that the GHG impacts of indirect land use changes could significantly affect the overall life-cycle GHG emissions of biofuels. Both direct and indirect land-use change remain important areas of concern and a topic of continued scientific research.

Policy Options to Help Promote Cellulosic Ethanol

Federal, state, county, and local governments currently support biofuels in a variety of ways. For a discussion of policies that support biofuel production and consumption generally, see *CLIMATE TECHBOOK: Biofuels Overview*. The following discussion summarizes policies that specifically target cellulosic ethanol and other advanced biofuels.

- **Mandates requiring biofuel use**
  The Energy Independence and Security Act (EISA) of 2007 establishes a renewable fuel standard that steadily increases U.S. biofuel use to 36 billion gallons by 2022. Advanced biofuels comprise 21 billion gallons of the total requirement, with cellulosic ethanol making up 16 billion gallons.

- **Subsidies and tax credits**
  In addition to subsidies and tax benefits already in place promoting corn ethanol (discussed in *CLIMATE TECHBOOK: Ethanol*), producers of cellulosic biofuels benefit from an income tax credit of $1.01 per gallon, more than double the $0.45 tax credit available for corn ethanol.[29]

- **Funding for pre-commercial scale plants**
  Federal funding for pilot-scale advanced biofuel plants will help accelerate advanced biofuels toward profitability. See the 'Current Status of Technology' section for more detail on current federal funding.

Related Business Environmental Leadership Council (BELC) Company Activities

- BP
- Dupont
- Royal Dutch/Shell
- Weyerhaeuser

Related Pew Center Resources

Biofuels for Transportation: A Climate Perspective, 2008.

Agriculture's Role in Greenhouse Gas Mitigation, 2006.

CLIMATE TECHBOOK: Biofuels Overview, 2009.

CLIMATE TECHBOOK: Ethanol, 2009

Further Reading/Additional Resources

National Renewable Energy Laboratory, "Biomass Research"

Renewable Fuels Association, "Cellulosic Ethanol"

U.S. Department of Energy (DOE)

- *Biomass Energy Data Book*, 2009
- Biomass Program: Information Resources
- Cellulosic Ethanol Production
- *Transportation Energy Data Book*, 2008

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[1] Other examples of advanced biofuels include bio-based hydrocarbon fuels (e.g., diesel fuel) from cellulosic materials, biogas from landfills and sewage waste treatment, and butanol or other alcohols produced from organic matter.

[2] The U.S. Department of Energy (DOE) is working with biotechnology and biofuel companies to reduce enzyme costs, which are currently one of the key barriers to cost-competitive production of cellulosic ethanol. See U.S. DOE. "Testimony of Alexander Karsner, Assistant Secretary, Office of EERE, Before the Subcommittee on Conservation, Credit, Energy & Research; Committee on Agriculture; U.S. House of Representatives." March 7, 2007. http://www1.eere.energy.gov/office_eere/congressional_test_030707a.html.

[3] A dry short ton of material has been dried to a relatively low, consistent moisture level (dry weight).

[4] This is based on a mix of feedstocks, mainly waste products and some energy crops. For more information, see Tables 4.3 and 4.5, Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. *Transitions to Alternative Transportation Technologies: A Focus on Hydrogen*. Washington, DC: National Academies Press, 2007.

[5] Granda, Cesar B., L. Zhu, and M.T. Holtzapple. (2007). "Sustainable Liquid Biofuels and Their Environmental Impact." Environmental Progress 26(3): 233-250.

[6] Farrell, A. E., R. J. Plevin, et al. (2006). "Ethanol Can Contribute to Energy and Environmental Goals." *Science* **311**(5760): 506-508.

[7] High-diversity prairie grasses and agricultural residues, such as corn stover, have both been studied as potentially carbon negative feedstocks when indirect land use change impacts are not included. For more, see Tilman, D., J. Hill, et al. (2006). "Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass." *Science* 314(5805): 1598-1600.

[7] Sheehan, J., A. Aden, et al. (2003).

[8] For more information, see California Air Resources Board, Low Carbon Fuel Standard Program, http://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

[9] These life-cycle GHG intensities were calculated for the purposes of the California Low-Carbon Fuel Standard program. For more information on the analysis, see California Air Resources Board, Stationary Source Division. *Detailed* California-*Modified GREET Pathway for Cellulosic Ethanol from Farmed Trees by Fermentation.* Release Date: February 27, 2009. http://www.arb.ca.gov/fuels/lcfs/022709lcfs_trees.pdf; California Air Resources Board, Stationary Source Division. *Detailed California-Modified GREET Pathway for Cellulosic Ethanol from Forest Waste*, Release Date: February 27, 2009. http://www.arb.ca.gov/fuels/lcfs/022709lcfs_forestw.pdf; and California Air Resources Board. Fuel GHG Pathways Update, Presentation: January 30, 2009. http://www.arb.ca.gov/fuels/lcfs/013009lcfs_pthwy.pdf.

[10] Parrish, D.J. and J.H. Fike. (2005). "The Biology and Agronomy of Switchgrass for Biofuels." *Critical Reviews in Plant Sciences*. 24(5): 423-459.

[11] Fertilizer impacts can include eutrophication (increased chemical nutrients in an ecosystem) that leads to hypoxia (oxygen depletion) in aquatic environments.

[12] Goldemberg, J. (2007). "Ethanol for a Sustainable Energy Future." *Science* 315(5813): 808-810.

[13] All oil prices used for comparison in this section are calculated assuming refinery costs and profits are 30% of crude oil costs, and that distribution and marketing costs and taxes are equivalent for ethanol and fossil fuels.

[14] Energy Information Administration. (2007). "Biofuels in the U.S. Transportation Sector." Available: http://www.eia.doe.gov/oiaf/analysispaper/biomass.html. Accessed April 25, 2009.

[15] McAloon, A., F. Taylor, et al. (2000). Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks. *Other Information: PBD*: 25 Oct 2000: Size: 30 p.

[16] Fehrenbacher, K. (2008). "11 Companies Racing to Build U.S. Cellulosic Ethanol Plants." Available at: http://earth2tech.com/2008/06/03/12-companies-racing-to-build-cellulosic-ethanol-plants-in-the-us/. Accessed: March 12, 2009.

[17] U.S. Department of Energy. (2007). "DOE Selects Six Cellulosic Ethanol Plants for Up to $385 Million in Federal Funding." Press Release. Available at: http://www.energy.gov/news/4827.htm. Accessed: March 12, 2009.

[18] Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. Transitions to Alternative Transportation Technologies: A Focus on Hydrogen. Washington, DC: National Academies Press, 2007.

[19] Suszkiw, Jan. (2008). "Banking on biobutanol: new method revisits fermenting this fuel from crops instead of petroleum." *Agricultural Research*. 56(9):8-9.

[20] For more information, see Renewable Fuels Association, "Celluosic Ethanol," http://www.ethanolrfa.org/resource/cellulosic/.

[21] State of Minnesota. (2008). "E20: The Feasibility of 20 Percent Ethanol Blends by Volume as a Motor Fuel." Minnesota Department of Agriculture and the Minnesota Pollution Control Agency.

[22] Yost, N. and D. Friedman. (2006). *The Essential Hybrid Car Handbook: A Buyer's Guide*. The Lyons Press: 160 pages.

[23] U.S. Department of Energy. (2009). "Light Duty E85 FFVs in Use." Excel file. Available: http://www.afdc.energy.gov/afdc/data/docs/ffvs_in_use.xls. Accessed April 27, 2009.

[24] Bureau of Transportation Statistics (2009). "National Transportation Statistics, 2009." Available: http://www.bts.gov/publications/national_transportation_statistics/. Accessed April 27, 2009.

[25] For more information on the distribution of E85 stations, see U.S. DOE, "E85 Fueling Station Locations," http://www.afdc.energy.gov/afdc/ethanol/ethanol_locations.html.

[26] U.S. Department of Agriculture. (2007). "Ethanol Transportation Backgrounder." Available: www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5063605. Accessed April 27, 2009.

[27] Morrow, W.R., W.M. Griffin, H.S. Matthews. (2006). "Modeling switchgrass derived cellulosic ethanol distribution in the United States." *Environmental Science & Technology*. 40, 2877-2886.

[28] Ibid (Wakeley).

[29] Renewable Fuels Association. (2008). "Cellulosic Biofuel Producer Tax Credit." Available: www.ethanolrfa.org/resource/cellulosic/documents/CellulosicBiofuelProducerCreditBrief.pdf. Accessed April 27, 2009.