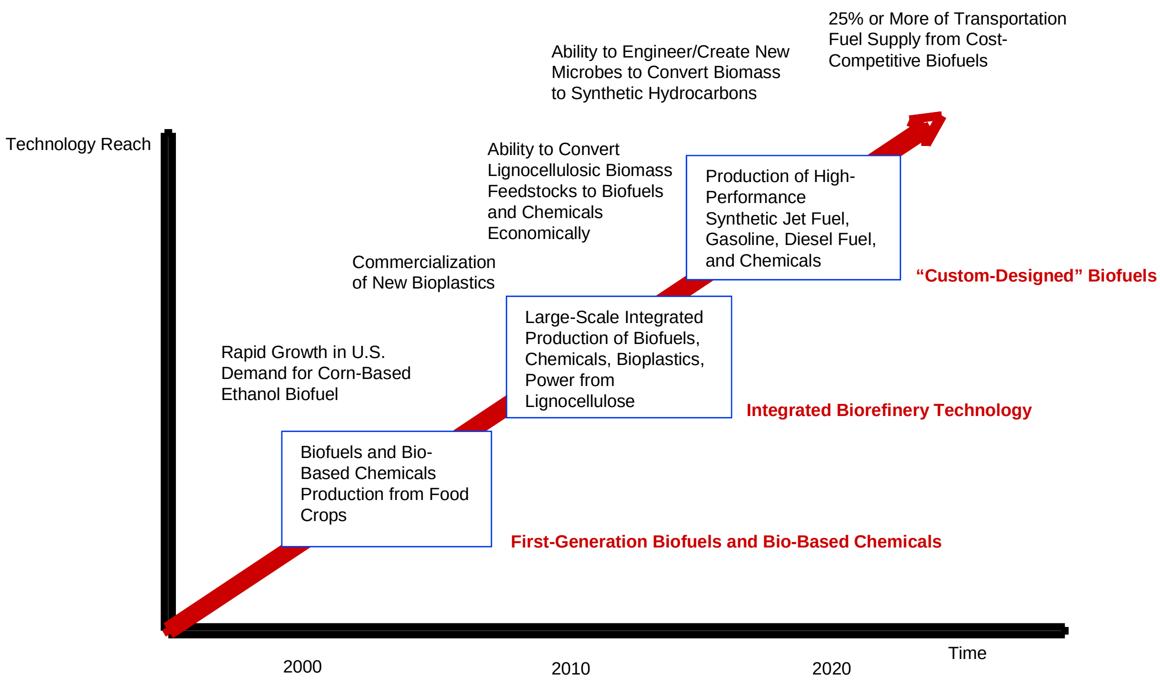
APPENDIX C: BIOFUELS AND BIO-BASED CHEMICALS (BACKGROUND)

The Technology

Figure 6[1]
TECHNOLOGY ROADMAP: BIOFUELS AND BIO-BASED CHEMICALS



Source: SRI Consulting Business Intelligence

Biofuels and Bio-Based Chemicals Technologies

Biofuels markets are booming in areas such as the United States, Europe, and Brazil based on current first-generation biofuels technologies—fuel ethanol from crops such as corn and sugarcane and biodiesel from crops such as rapeseed and soy. For future sustainability, the main biofuels R&D focus is on emerging second-generation processes that produce energy-efficient biofuels and do not compete with the food chain for feedstocks. Second-generation processes convert lignocellulosic materials, including agricultural and forest residues such as corn stover, rice straw, wheat straw, and bagasse and possible nonfood bioenergy crops such as switchgrass, poplar, and Miscanthus grass (elephant grass). (Note on terminology: Lignocellulose, the most abundant biomass,

[1] The Technology Roadmap highlights the timing, features, and applications of significant technology milestones that would be necessary for developers of this technology to achieve if successful (equivalent to commercial) application—and possible disruption—is to occur by 2025.

consists of three main polymers: cellulose, hemicellulose, and lignin. In common usage, *cellulosic ethanol* refers to ethanol made from lignocellulose.)

Cellulosic ethanol technology is still a few years away from economic viability. The DOE, a major and long-term supporter of lignocellulose conversion R&D, is helping to make cellulosic ethanol cost competitive with gasoline by 2012 by supporting two alternative types of technology platforms:

- A biochemical or sugar platform depending on acid or enzymatic hydrolysis of lignocellulose to sugars with subsequent fermentation to ethanol
- A thermochemical platform using gasification of biomass to syngas with subsequent fermentation or catalytic conversion to alcohols.

A significant effort is also under way to enable future integrated biorefineries in the United States that make a range of biofuels, chemicals, power, and other high-value products from lignocellulosic feedstock rather than using petroleum. A range of established energy companies and new technology start-ups are working to develop new technologies, often with cofunding from the DOE. In 2007, the DOE awarded grants for the construction of six full-scale pioneer biorefineries in the United States that expect to reach economic viability by 2012. DOE also plans to provide an additional $200 million in funding over five years for the development of small-scale cellulosic-ethanol biorefineries that will experiment with new feedstocks and processing technologies and $375 million for three new U.S. Bioenergy Research Centers that will focus on developing new, more efficient methods for producing cellulosic ethanol and other biofuels.

Biodiesel is another biofuel seeing rapid growth worldwide. Feedstocks include plant-derived oils such as rapeseed, soy, and palm oil, as well as waste oils. Jatropha, a weed that grows in arid climates, is also gaining support in India and some other locations. Conventional biodiesel processing often converts less than 10% of the mass of dried plants, so a clear need exists for more efficient biodiesel technologies. Choren Industries GmbH (Freiberg, Germany) is developing a new biomass-to-liquids (BTL) technology that involves high-temperature gasification of biomass followed by a catalytic Fischer Tropsch process to make a high-cetane synthetic biodiesel. Algae are a potentially rich source of biofuels and an area of intense interest today. Significant potential exists for cultivating high-oil-content, high-growth microalgae containing more than 50% oil for conversion to biodiesel. Algae can grow on marginal land or in water so as not to compete with food crops. Costs are still much too high, but many start-up companies—along with DOE national laboratories—are now developing new algae-to-biodiesel approaches.

New biofuels are also under development. Biobutanol is attracting the attention of a number of companies because it has some key advantages over ethanol—the predominant U.S. biofuel—including higher energy content and better transport characteristics. BP Biofuels is progressing a near-term effort with DuPont to develop and commercialize biobutanol. The biobutanol-fermentation process initially will use DuPont's biocatalyst and bioprocess technology using locally grown sugar beets. BP and DuPont are working on the development of a second-generation process using a more-targeted biocatalyst and the ability to process lignocellulosic feedstocks.

Future breakthroughs in cellulosic-ethanol production and entirely new biofuels may come from the field of synthetic biology. Several start-up companies are using synthetic-biology techniques to make renewable hydrocarbon fuels that are very similar to today's petroleum fuels and are thus completely compatible with existing fuel infrastructures. Researchers are engineering microbes by incorporating genetic pathways from other microbes, plants, and animals. Synthetic Genomics (Rockville, Maryland), founded by biotechnology pioneer Craig Venter, is trying to produce a highly engineered "synthetic organism" that can perform multiple tasks well: efficiently break down cellulose like a bacterium, ferment sugar like a yeast, and tolerate high levels of ethanol. Hoping to improve on the attributes of ethanol fuel, start-up companies Amyris Biotechnologies, Inc. (Emeryville, California), and LS9, Inc. (San Carlos, California), are both targeting the custom-designed fuels arena. Amyris is focusing on advanced diesel and jet-fuel formulations; LS9's focus is on jet fuel, low-sulfur gasoline biofuels, and specialty biochemicals. Although still early stage, the companies hope to bring these products to market within four or five years. Technology challenges include the massive scale-up necessary to produce the new biofuels in large volumes.

A growing number of bio-based chemicals, such as the biodegradable bioplastic PLA (polylactic acid) that derives from corn, are already in commercial production, and several additional products will reach commercialization in the next few years. The longer-term plan is to use lower-cost lignocellulosic feedstocks in stand-alone plants or future integrated biorefineries. Production of high-value chemical building blocks and biopolymers is key to the success of biorefineries.

The Enabling Building Blocks

For biochemical-conversion technologies, a major R&D focus is on improving pretreatment technology for breaking hemicellulose down to component sugars and developing more cost-effective cellulase enzymes (biocatalysts) for breaking cellulose down to its component sugar. Another key enabling technology is the engineering of microorganisms and enzymes that can efficiently convert the complex cellulosic wastes to simple sugars and then to ethanol or chemical building blocks. Lignocellulosic feedstocks contain both five-carbon pentose sugars (D-xylose and L-arabinose) and six-carbon sugars (glucose, mannose, and galactose). Cost-effective processes need to ferment all five sugars rapidly, but the pentoses in particular are not easily metabolized by common yeasts in use for ethanol production today. For thermochemical-conversion technologies, much of the current R&D is on syngas production and use to make fuels and other valuable products. Technology developers are also working to demonstrate their integrated conversion processes in real-world applications in rural areas.

Implications of Advancement in Various Technological Capabilities

Rising prices for crops such as corn, sugar, wheat, and oilseeds and inadequate infrastructure are serious impediments to the wholesale adoption of first-generation biofuels—in spite of ambitious biofuels targets by the United States and other governments that aim to reduce oil imports significantly and reduce GHG emissions. The development and implementation of new lignocellulose conversion and biorefinery technologies could enable a range of new biofuel and bio-based chemical products that are fully cost competitive (without government subsidies) with conventional petroleum-based fuels and products—especially if crude oil prices remain above about $50 per barrel—beginning in the 2010 to 2015 timeframe. Future biofuels and bioproducts may also offer improved performance and environmental attributes, including biodegradability.

Synergistic Technologies

A large-scale bioenergy economy will rely on technologies such as genetic engineering and agricultural practices to help increase biomass yields and lower cultivation costs. Harvesting crops, collecting biomass residues, and storing and transporting biomass resources are critical aspects of the biomass-resource supply chain. Biomass-handling systems are also important—they can represent a significant portion of the capital and operating costs of a biomass conversion facility. For example, rice straw is very fibrous and can be difficult to process.

New integrated biorefinery technology requires new bioprocessing techniques and lower-cost separation methods in addition to improved biocatalysts. The design of bioreactors is another important area of research to allow maximum process efficiency.

Applications

Key Uses and Instantiations of Biofuels and Bio-Based Chemicals

Future U.S. biofuels and bio-based chemical-production facilities will likely be much more diverse geographically than today's biofuels and emerging bioplastics plants, which are mainly in Midwestern agricultural states. Integrated biorefineries based on waste agricultural and other lignocellulosic biomass feedstocks will use locally available resources to produce biofuels and other bio-based products. The six biorefinery demonstration plants that the DOE is cofunding illustrate a range of locations and approaches:

- Abengoa Bioenergy (Chesterfield, Missouri) will operate a facility in Kansas to process 700 tons per day (tpd) of corn stover, wheat straw, switchgrass, and other feedstocks to produce 11.4 million gallons per year of cellulosic ethanol and syngas for energy.
- Alico Inc. (LaBelle, Florida) will turn 770 tpd of yard, wood, and vegetative wastes such as citrus peel into 13.9 million gallons per year of cellulosic ethanol, 6255 kW power, 50 tpd ammonia, and 8.8 tpd hydrogen.
- BlueFire Ethanol, Inc. (Irvine, California), will convert 700 tpd of sorted green waste and wood waste from an urban landfill in Southern California to produce 24 million gallons per year of cellulosic ethanol.

- Poet Design & Construction (Sioux Falls, South Dakota) will convert an existing ethanol facility in Iowa to a biorefinery processing 842 tpd of corn fiber and stover to produce 26.4 million gallons per year of cellulosic ethanol.
- Iogen Biorefinery Partners, LLC (Arlington, Virginia), will operate a biorefinery in Idaho to convert 700 tpd of wheat straw, barley straw, corn stover, switchgrass, and rice straw to produce 18 million gallons per year of cellulosic ethanol.
- Range Fuels Inc. (Broomfield, Colorado) will operate a plant in Georgia to convert 1200 tpd of woody residues and energy crops to produce some 40 million gallons per year of ethanol and 9 million gallons per year of methanol.

Current Affected Products and Services

Today's biofuels—ethanol and biodiesel—most commonly see use in blends with conventional gasoline and diesel fuels today. Typical ethanol blends in the United States are E-10 and E-85, which contain 10% and 85% ethanol, respectively. The market for E-85 is growing, driven by high gasoline prices and various state policies to promote biofuels. Ethanol biofuel has some drawbacks regarding distribution—it is not pipeline transportable because it mixes with water and is moved by rail and truck to blending terminals, thus complicating the supply chain. A small but growing percentage of U.S. vehicles run on E-85, but the United States needs many more flex-fuel vehicles and also more fueling stations that offer E-85. E-85 is currently available at only about 1100 fueling stations out of some 170 000 fueling stations in the United States. Brazil is the only country thus far that has both an extensive biofuels infrastructure in place and widespread availability of FFVs. Many Brazilian drivers use E-80 to E-85 and all gasoline sold in Brazil must contain 20% to 25% ethanol.

Biodiesel is most popular in European countries and is also growing rapidly in the United States and Brazil. Biodiesel is typically used in blends with petroleum-derived diesel in concentrations varying from 2% to 10% (B2 to B10). Biodiesel has the significant advantage that it can often be used in pure form (B100) in diesel engines without modification, and it can also make use of the existing diesel-fuel infrastructure.

Many chemical companies today are positioning themselves to make bioplastics and other emerging bio-products where they see significant new market opportunities. NatureWorks makes 90% of the world's supply of biodegradable plastic PLA from corn at its Blair, Nebraska, facility, and the longer-term plan is to use lower-cost lignocellulosic feedstocks. PLA is in wide use for biodegradable packaging and other applications, although it still has high costs relative to those of petroleum-based plastics.

New Capabilities Created by Biofuels and Bio-Based Chemicals

The target markets and end users for current and future biofuels are consumers, businesses, and government agencies that currently rely on conventional fossil fuels for vehicles. Most of these customers are primarily driven by economics—biofuels must be cost competitive with conventional gasoline and diesel fuels. Ethanol is by far the major biofuel in the United States but has some distribution limitations and lower energy content than petroleum-derived gasoline. Cellulosic ethanol will also have these limitations but should be much lower cost in the future. Biofuels such as biodiesel (and eventually biobutanol and synthetic hydrocarbons) more easily integrate with the existing fuel infrastructure. Properties of future biofuels, —such as extremely low-sulfur synthetic gasoline—may be optimized for performance and quality.

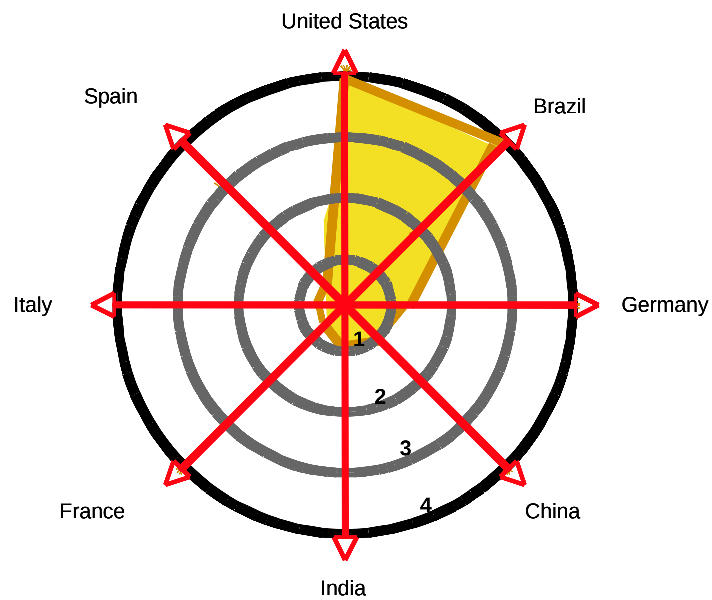
Bio-based chemicals and bioplastics from renewable resources will offer many benefits, including environmentally friendlier, more efficient products and processes and less dependence on high-cost crude oil and natural-gas liquids for feedstocks and energy. NatureWorks reports that its PLA biopolymer process provides substantial reduction in CO_2 emissions and fossil fuel use in comparison with fossil-fuel–based polymer processes. DuPont and Tate & Lyle (London, England) recently began manufacturing corn-based PDO (1,3-propanediol) from fermentation of sugars from corn in Loudon, Tennessee. DuPont Tate & Lyle reports that production of Bio-PDO consumes about 40% less energy and reduces greenhouse gas emissions by about 20% versus petrochemical-based feedstock. Bio-PDO has a higher purity level and causes less irritation than ingredients it can replace in personal-care and cosmetic products. Bio-PDO is also replacing DuPont's PDO process based on petrochemicals and is a key element in DuPont's Sorona polymer (polytrimethylene terephthalate) platform, which has wide application in automotive, engineering polymers, fibers, and coatings.

Timeline

New technologies for cellulosic-ethanol and biodiesel may become economically viable in the next several years. Integrated biorefinery technology is under development, and initial demonstration plants should be in operation by 2012, producing a range of biofuels, chemical building blocks and biopolymers, and other products.

Issues Determining the Development of Biofuels and Bio-Based Chemicals Technologies

Figure 7
BIOFUELS USE IN KEY COUNTRIES



Legend: Annual Production and Use of Biofuels (Ethanol and Biodiesel) in 2005

1 = Low (< 1 billion liters)
2 = Mid-Low (1-5 billion liters)
3 = Mid-High (5-10 billion liters)
4 = High (>15 billion liters)

Source: SRIC-BI

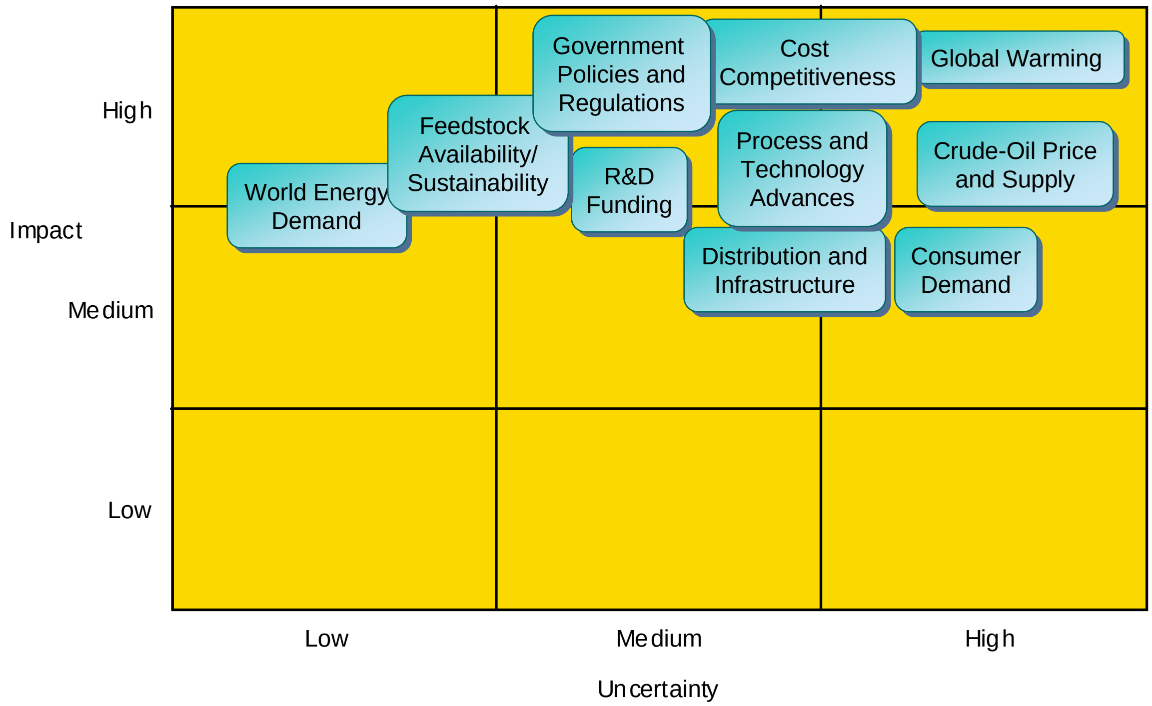
- Biofuels markets are beginning to expand in many countries worldwide, driven by issues of energy security, record-high crude-oil prices ($50 to $75 per barrel), environmental concerns—especially global warming, rising energy demand, and national desires to support local economics and achieve clean technology leadership. Ethanol fuel for vehicles is in wide use in Brazil and the United States, and demand is now growing in the Europe, China, India, Canada, Colombia, and other areas. Biodiesel is popular in Europe and is also growing rapidly in countries including the United States and Brazil. Government policies in favor of biofuels are helping to stimulate private investment in a broad range of ambitious biofuels projects.
- The use of biofuels has grown rapidly in recent years because many countries have introduced or increased biofuels targets, mandates, and generous subsidies in recent years. The United States has long provided a tax credit of 51¢ per gallon of fuel ethanol, and the Bush administration's latest biofuels initiative, the Twenty-in-Ten initiative, aims to reduce U.S. gasoline use by 20% by 2017 by increasing the use of

renewable transportation fuels. For the past 25 years, Brazil's ProAlcool program has included blending mandates, retail-distribution requirements, production subsidies, and other measures. The new European Council Energy Action Plan calls for biofuels to account for 10% of all transport fuel sold by 2010 (with binding commitments for member states). China and India require ethanol-blended gasoline in several provinces and states (China recently limited biofuels feedstocks to nonfood crops in response to rising food prices attributable to high biofuels demand). Other countries with current or planned biofuels requirements include Colombia, Malaysia, Thailand, Japan, the Dominican Republic, and the Philippines.

- Many established energy companies as well as a host of new technology start-ups are rushing to make strategic investments to capitalize on today's huge market momentum in biofuels and emerging opportunities. For example, BP recently announced a huge grant of $500 million for the next ten years to establish an Energy Biosciences Institute at the University of California, Berkeley. The Energy Biosciences Institute should open by late 2007, with the overall goal of making the large-scale use of technology to convert lignocellulosic biomass viable. However, some competing oil companies strongly oppose biofuels targets and subsidies.
- Agricultural interests are strong proponents of the use of biofuels today to provide rural economic-development opportunities. Public support for biofuels also appears to be very positive. But careful planning will be necessary to prevent competition for land between cultivation of crops for energy and cultivation of food—especially until lignocellulosic conversion technologies become viable. The large-scale use of biomass resources to replace fossil fuels offers many benefits but will also have long-term environmental and social impacts that many people (and scientists) do not yet understand. Complex issues and interactions exist surrounding feedstock cultivation and collection, water supply, and ecological impacts such as deforestation, erosion, and loss of biodiversity. (For example, some studies on Brazil suggest that reducing the rate of deforestation would be a more effective way to achieve carbon sequestration—a major goal associated with biofuels—than planting sugarcane for ethanol production.)
- In the United States, the use of new biomass resources, such as diverting municipal wastes from landfills to energy production, could provide visible and positive impacts.
- Many developing countries are interested in economic-development opportunities that could result from producing biofuels for export and domestic use. Brazil has the largest biofuels economy in the world converting sugarcane to low-cost ethanol and hopes to become a major biofuels supplier to the rest of the world. Malaysia, a major producer of palm oil, is targeting biodiesel production for markets worldwide. Several other countries in the Caribbean, Southeast Asia, the Middle East, and Africa are also considering opportunities in biofuels.

Items to Watch

Figure 8[2]
BIOFUELS AND BIO-BASED CHEMICALS: ISSUES AND UNCERTAINTIES



Source: SRI Consulting Business Intelligence

From Figure 8, the key areas of uncertainty to monitor and better understand are:

- *Global warming.* The main uncertainty is the speed and the extent to which government policies in the transportation sector will push the development of low-carbon fuel technologies. For example, global warming is a key driver behind California's Low-Carbon Fuel Standard that requires fuel providers to reduce GHG emissions of transportation fuels by at least 10% by 2020.
- *Cost competitiveness*. The cost competitiveness of biofuels is a major determinant of their success in the marketplace. Consumers will be drawn to choose biofuels when biofuels cost close to—or below—petroleum-based gasoline and diesel prices. The cost competitiveness of new biofuels will depend on lower-cost process technologies as well as competing crude-oil prices. Biofuels may continue to require government subsidies for cost competitiveness for at least several years to come.

[2] Figure 8 illustrates major issues and events that will have an impact on the rate or direction of a technology's development and thereby application. The impact of these issues and events is plotted against a measure of uncertainty, where uncertainty implies insufficient knowledge of how (and usually just when) the issue or event will be resolved or be sufficient to drive or hold back development of the technologies. An organization that is able to accurately predict or (better) influence or dictate the outcome (thereby moving the issue/event to the left of the figure), will have a distinct advantage over organizations that are still in the dark or just passively following developments.

- *Crude-oil price and supply*. The uncertainty mainly relates to future crude-oil prices and supply. The availability of future conventional-oil supplies is uncertain. In particular, the timing to reach peak-oil production is very uncertain and could have a huge impact on oil prices and potential supply disruptions in the time frame to 2025. Higher crude-oil prices improve the competitiveness of biofuels. Conversely, a significant drop in future oil prices (for example, as a result of big increases in nonconventional-oil production) would decrease the competitiveness of biofuels and perhaps jeopardize government support for biofuels programs.
- *Government policies and regulations*. Government support can take a wide variety of forms. The extent to which governments use policy targets, economic subsidies, and incentives at the national and local level to promote new biofuels will be a major factor in their market success.
- *Process and technology advances*. Biofuels process technologies require significant improvements in their efficiency, cost, and ability to convert a wide range of lignocellulosic materials if they are to achieve widespread use. Advances in biotechnology will be a key enabler.
- *Feedstock availability/sustainability*. In the longer term, the use of agricultural wastes and energy crops to make biofuels and bio-based chemicals will be necessary for sustainability. To prevent a potential backlash against biofuels (from opposing industries, private citizens, and environmentalists) and to ensure sufficient future feedstock availability, key stakeholders need to develop realistic assessments of all the complex issues surrounding a large bio-based economy, including impacts around feedstock cultivation and collection, impacts on water quality and supply, and ecological impacts such as deforestation, erosion and loss of biodiversity.
- *R&D funding*. Government funding—often in partnership with private companies and universities—has provided the majority of R&D funding for many advanced biofuels technologies. Government R&D support is a useful (and perhaps necessary) complement to today’s fast-growing private-sector investments that tend to focus on near-term commercial projects. Increases in R&D funding can help achieve faster biofuels deployment in the short term and improve the performance and viability of biofuels technologies in the longer term.
- *World energy demand*. A key uncertainty is how the world—particularly developing nations such as China and India—will meet its growing energy needs for transportation, while reducing carbon emissions. This issue will have a major impact on conventional energy prices and supply.
- *Consumer demand and distribution and infrastructure*. Infrastructure systems can create significant barriers for new biofuels by limiting their availability and increasing costs. The extent to which an expanded distribution and infrastructure system for fuels such as E-85 is put into place in the United States is uncertain. Also uncertain is the degree to which consumers will choose to purchase environmentally friendly fuels and flex-fuel vehicles, even if they are more expensive.

Directional Signposts

Identifying the major issues that will determine how biofuels and biobased chemicals technologies will develop and understanding the uncertainty of items important to watch help us to understand better the potential dynamics of development and application that we might see in the future. That heightened sense of awareness is necessary because the United States will want to formulate a policy and act before unambiguous evidence on the drivers and barriers to, and direction of advancement of these technologies is available. Preparation for a watch-and-respond system is essential to identify signposts that would indicate whether the advancement of the technologies is proceeding rapidly or not. The following developments are likely to occur near the suggested years, and their outcomes will strongly influence the status of the biofuels and biobased chemicals area. Their occurrence would indicate that the above issues and uncertainties were being resolved in the direction of positive development and application of biofuels and biobased chemicals technologies.

- 2007—The Bush administration announces its Twenty-in-Ten initiative, which aims to reduce U.S. gasoline use by 20% by increasing the use of renewable transportation fuels to 35 billion gallons of ethanol equivalent a year by 2017 (from some 5 billion gallons of biofuel use today).
- 2008—California implements a Low-Carbon Fuel Standard (LCFS) that requires fuel providers to reduce carbon and other GHG emissions of transportation fuels by at least 10% by 2020. Fuel providers will likely offer biofuels to meet the standard at least initially and work to develop more efficient biofuels to meet future standards.
- 2010—Cellulosic-ethanol–production technology could become economically viable on a commercial scale, enabling the spread of energy-efficient biofuels production facilities based on abundant lignocellulosic biomass feedstocks that do not compete with food or feed needs.
- 2010 to 2015—Algae-derived biofuels technology could become cost competitive, allowing high-volume biofuels production on marginal land or water or, for example, in closed photo-bioreactors that capture CO_2 emitted from power plants during the day.
- 2012—Successful commercial-scale demonstrations of integrated biorefinery technology could enable the large-scale and economical coproduction of biofuels, chemicals, bioplastics, power, and other high-value products from lignocellulosic feedstock.
- 2012 to 2020—”Custom-designed” biofuels emerge, enabled by highly engineered microbes that can convert biomass to synthetic hydrocarbons products, such as high-performance jet fuel, low-sulfur gasoline, advanced diesel, and specialty biochemicals. Such hydrocarbon products will be wholly consistent with existing fuel infrastructures and vehicle engines.
- 2025—U.S. biofuels consumption could displace 25% or more of petroleum-based fuels, with similar reductions in CO_2 emissions. Petrochemical products may also see a major transition to bio-based feedstocks.

Within the timeline in which these developments are likely to occur, some specific signposts will be important to watch for and monitor to understand the direction in which and the pace with which the field is advancing and to assess the potential threats to and opportunities for U.S. interests. Key signposts, which, if positive, would indicate progress toward biofuels and bio-based chemicals include:

- The timing and nature of biofuels promotion policies in the United States and other regions (e.g. quotas, subsidies, specific support for domestic or low-emission fuels)
- The timing and nature of global warming policies in the United States and internationally (e.g. carbon taxes, post-Kyoto Protocol carbon reduction agreements)
- The level of continuing R&D support from the Department of Energy and Department of Agriculture for the development and commercialization of advanced biofuels technologies
- Crude oil prices and supply
- Cost and efficiency improvements in biofuels conversion processes
- The influence of food-versus fuel debates and public opinion on the availability of feedstocks such as corn and the spread of biofuels (especially in the near term)
- Improvements in feedstock yield and supply resulting from breeding and genetic modification of plants for very high growth or high biofuels yields
- Fuel efficiency gains in vehicles and the spread of alternative vehicle technologies such as hybrid electric, electric, and fuel cell vehicles
- Development of an E85 ethanol fuel infrastructure (fueling stations and flex-fuel vehicles) to enable widespread use of high-ethanol-concentration fuels
- International trade in biofuels from low-cost suppliers in Brazil, the Caribbean, Southeast Asia, and other locations.

Abbreviations

The following abbreviations are used in this Biofuels and Bio-Based Chemicals disruptive technology profile:

BTL biomass-to-liquids
DOE Department of Energy (U.S.)
FFV flex-fuel vehicles
GHG greenhouse-gas
PDO 1,3-propanediol
PLA polylactic acid
R&D research and development
tpd tons per day