SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

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Chapter 1: The Biofuels Pathway

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Biofuels have been seen as the nearest-term answer to the need for alternatives to petroleum fuels in the transportation sector. Despite recent debate over life-cycle environmental impacts and potential food-sector impacts, much interest remains in the expansion of biofuel production capacity to displace petroleum and provide low-carbon fuels—especially for heavy transport and aviation, where few other sustainable alternatives to liquid fuels exist. Besides, biofuels (and bioenergy production more generally, including heat and power applications) offer opportunities for economic development, diversification of the farm sector, integration of forest management, and diversion of urban wastes from landfills.

But these opportunities come with substantial challenges. With the current state of technology, the lowest-cost biofuels do not provide major environmental benefits, while the biofuels that are expected to provide significant benefits are not yet commercially viable. Resources for the United States have been estimated to be sufficient to produce enough biofuel to meet roughly a third of the nation's transportation fuel demand, but large uncertainties are associated with these estimates and sustainability of production and manufacturing processes is not yet fully understood. Additionally, best uses for biomass—whether to produce the liquid biofuels discussed in this chapter, to generate electricity for electric vehicles, to produce hydrogen for fuel cell vehicles, or to be used in other sectors—are still to be sorted out through technology innovation and market action.

This chapter discusses some of the major questions regarding future use of biofuels in the transportation sector and highlights STEPS research on these issues.

What is the technical outlook for advanced biofuel production technologies?

- To what extent can biofuels contribute to future transportation fuel supply? What are the constraints on feedstock for those biofuels? Where is advanced biofuels production likely to take place in the United States?
- How compatible are biofuels with existing vehicles and infrastructure?
- What are the environmental impacts of biofuels compared to alternatives? How do we measure sustainability for biofuels?
- What policies and business strategies are needed to support biofuels in both the near and long term?

CHALLENGES ON THE BIOFUELS PATHWAY

These complex technical and environmental challenges must be overcome before biofuels can make a major contribution to transportation energy needs:

- **Technical challenges.** The portfolio of advanced technologies that can convert biomass to fuels on a large scale is mostly in the demonstration phase, and the challenges associated with scaling up those technologies lie ahead.
- **Logistical challenges.** Biofuels can be produced from a variety of feedstocks and transported by rail, ship, pipeline, or truck, similar to gasoline. Depending on the biofuel, it may be possible to utilize the existing petroleum infrastructure, either by blending biofuels with conventional fuels or by producing designer biofuels that can drop in to existing supply systems. Other biofuels, such as ethanol (or E85—85 percent ethanol and 15 percent gasoline), would require dedicated storage and transport systems.
- **Resource availability.** The amount of biomass feedstock available, regionally and nationally, for conversion to fuels is uncertain and limited compared to transportation fuel demand. The supply depends in part on yields of energy crops and on market participation of waste and residue biomass suppliers.
- **Environmental and sustainability issues.** Large-scale biofuels production places significant demands on arable land, water, and agricultural inputs. The environmental impact of using these resources must be weighed against the benefits from producing biofuels. The range of impacts is large as a result of the variety of biomass feedstock, regional differences in native ecosystems and crop yields, and the efficiency of biofuel production.
- **Macroeconomic impacts.** Use of biomass for energy can impact markets for other biomass products, especially food and feed. Indirect land-use effects resulting from this market force lead to potentially larger greenhouse gas emissions than the reductions realized by fossil fuel replacement.
- **Transition issues / coordination of stakeholders.** Transitional barriers for biofuels are lower than for other alternative fuels. In the case of E85, greater deployment of flexible-fuel vehicles is needed to stimulate demand. Coordination is needed between suppliers of biomass feedstocks and investors in biorefineries.
- **Policy challenges.** Biofuel policies must be crafted to maximize benefits. This is a dynamic challenge as the impacts are uncertain and highly variable, and they depend on a number of outside forces. This challenge is highlighted by the discussion of indirect land-use change presented in Chapter 12.

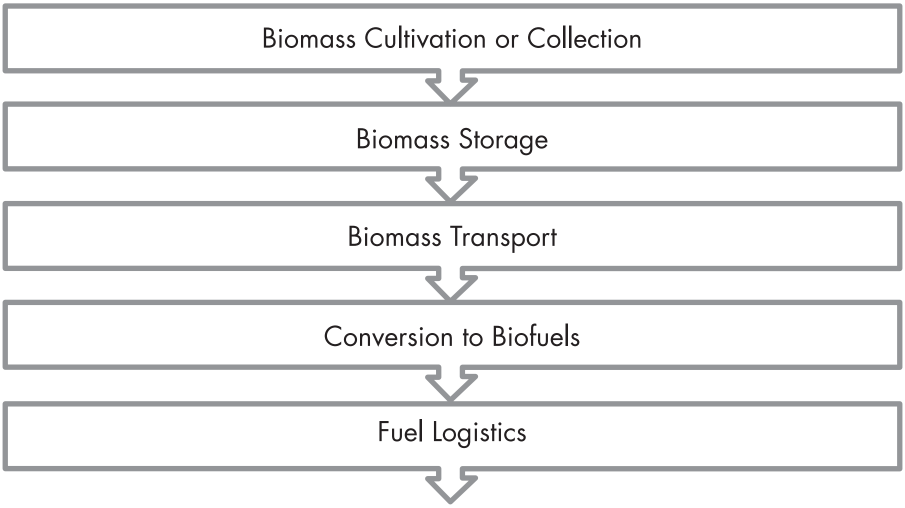
Technology Status and Outlook

Biofuels are a diverse set of fuels derived from biomass (material of recent organic origin—for example, plant material, animal products, and organic wastes). These fuels can be alcohols (ethanol, butanol, or methanol), hydrocarbons (similar to gasoline, diesel, and jet fuel), hydrogen, or synthetic natural gas. This chapter focuses only on the liquid fuels.

Biomass can be converted to liquid fuels using many different routes. There is great diversity among these routes in both technological readiness and long-term outlook for meeting transportation energy needs. In large part, the commercial readiness rests with the conversion technology, and the long-term potential depends on the feedstock. First-generation processes are commercially available today, and advanced processes aiming to convert cellulosic materials (such as agricultural, forest, or municipal solid wastes and energy crops) and algae are under development.

The generic pathway for production of a biofuel has five components. First, the biomass is grown and harvested or separated from a waste stream. Then the biomass is stored, either at the site of production, the biorefinery, and/or an intermediate depot. If it’s stored at the biorefinery or an intermediate depot, transportation to the conversion facility (biorefinery), which is the third component, precedes this. Fourth, at the biorefinery the biomass is converted to biofuels and coproducts. Fifth, the biofuels are distributed to refueling stations, with possible blending with petroleum fuels at an intermediate fuel terminal. The cost of biorefineries is the largest single capital investment in the supply chain (about 85 percent of the investment), with feedstock production equipment and fuel delivery equipment playing a much smaller role.

COMPONENTS OF A BIOFUEL PRODUCTION PATHWAY



Production of a biofuel has five components. The biomass is (1) grown and harvested, (2) stored, (3) transported to the conversion facility (biorefinery), and (4) converted to biofuels. Then, (5) the fuel is distributed to refueling stations.

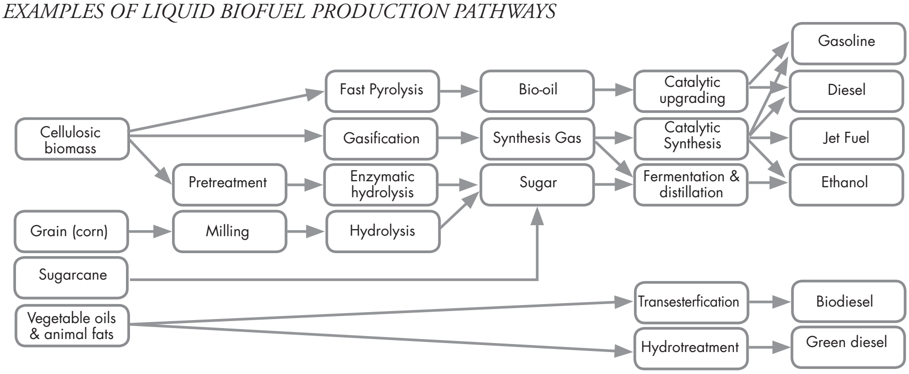
Conversion technology is the current roadblock to realizing significant production of advanced biofuels. The development of practical and cost-effective conversion technologies for cellulosic biomass feedstocks is key. Even with significant research investment, no large-scale commercial capacity yet exists for biofuels other than direct sugar and starch fermentation biorefineries to make ethanol based on beverage alcohol production practices, and the transesterification of lipids to make biodiesel. These two types of biofuel—ethanol from yeast fermentation of sugar and starch, and biodiesel from fats, oils, and greases—comprise the class of so-called first-generation biofuels and are made using moderately mature technologies.

Research into exploiting the chemical diversity and energy content of other biomass feedstocks has continued to promise new technologies to expand the scale of biofuel production. So-called second- and later-generation conversion technologies are in development to utilize cellulosic resources either through thermochemical processes that utilize heat, pressure, and catlysts to produce fuels or through biological processes utilitizing organsims and enzymes to reduce the plant material to sugars and then ferment these to the desired products.

Technologies to gather biomass resources and transport them to biorefineries exist in well-established industries of agriculture, forestry, and waste management. However, large-scale development of biorefineries with consistent, dependable feedstock supplies will depend on improvements in storage and transportation technologies. Stability of sugars in storage is a major concern for maintaining year-round feedstock quality for biological conversion processes. More efficient long-distance transport will improve the flexibility of the biorefineries in their feedstock sourcing.

The biofuels that are commercially available use food crops as feedstocks. These feedstocks—sugar, starch, and oils—are relatively easy to convert to ethanol or biodiesel but represent only a small fraction of the biomass of the plant, limiting the yield of fuels per unit of land area. The advantage to using these feedstocks is that established commodity markets provide a reliable supply of the feedstock, and extensive research has been done on improving the yields of these crops. On the other hand, the utilization of feedstocks that are not currently used on any large scale for food or feed such as wood, herbaceous energy crops, and algae avoids direct market impacts on food commodities, although indirect effects may remain.

EXAMPLES OF LIQUID BIOFUEL PRODUCTION PATHWAYS



Liquid biofuels are already being produced from sugar/starch crops and oil plants / animal fats with first-generation technologies. Second-generation technologies will produce ethanol and diesel from cellulosic biomass.

Ethanol from sugar/starch crops

Ethanol from sugar is the simplest route for producing biofuels. The sugar source is predominantly sugarcane, but sugar beets or high sugar content food-processing wastes can also be used. Sugarcane ethanol is a mature technology developed in large part in Brazil. The cane is milled to extract the sugars, which are then fermented to ethanol using yeast. Ethanol is distilled from the beer, leaving a liquid by-product (vinasse, which is used as a fertilizer) and the cane fiber (bagasse, which is used to produce heat and power). In 2009, 6.6 billion gallons of ethanol were produced from sugarcane in Brazil.

Ethanol produced from corn is the dominant biofuel pathway in the United States. The corn ethanol industry is well established, with 204 corn ethanol facilities producing 13.2 billion gallons of ethanol in 2010.[1] There are two types of technologies: wet mill and dry mill. Wet mill technologies separate the germ, fiber, gluten, and starch components of the corn kernel through steeping, screens, cyclones, and presses. The starch fraction can then be converted to ethanol. It is the more capital- and energy-intensive process with lower ethanol yields but higher-value coproducts. Dry mill processes first grind the corn, sending the full kernel through the saccharification and fermentation process before separating ethanol from the coproduct, distillers grains (typically dried, in which case it becomes dried distillers grains or DDG). Dry mill ethanol facilities were responsible for more than 86 percent of ethanol production in 2010.[2]

Biodiesel from oils and fats

Biodiesel (which here refers only to fatty acid methyl ester or FAME) is a mature technology for creating diesel-like fuels from oils and animal fats. In 2009, 4.7 billion gallons of biodiesel were produced worldwide, with 540 million gallons produced in the United States (predominantly from soybean oil) and 2.65 billion gallons produced in Europe (predominantly from rapeseed oil). Biodiesel is also produced from waste greases and animal fats at small volume. It is made by transesterfication, a catalyzed chemical conversion of oils or fats and an alcohol (typically methanol) to biodiesel and significant quantities of glycerol coproduct. FAME can be produced from virgin seed oils, waste greases, or animal fats, though the process design is optimized differently for the different resources. The dominant production process in the United States, accounting for approximately 78 percent of biodiesel production in 2008,[3] uses alkali catalyst with virgin soy oil feedstock;[4] an acid catalyzed process is most economic for waste cooking oil.[5] The dominant cost in producing biodiesel is that of the feedstock, especially true for virgin seed oils.

An alternative technology to produce diesel fuels from oils is the hydrotreatment process.[6] In this process, the lipids and hydrogen pass through a hydroprocessing unit where the oxygen is stripped from the lipids through decarboxylation and hydrodeoxygenation reactions. The resulting products are a combination of "green diesel" and lighter hydrocarbons (naphtha and/or propane) with by-products of water and carbon oxides (CO and CO_2). The green diesel fuel is reported to have a number of desirable properties: high cetane number (70–90), energy density equivalent to ultra-low sulfur diesel, sulfur content of less than 1 ppm (USLD < 10 ppm sulfur), and good stability. Green diesel could potentially be used as a premium blendstock allowing for the use of lower-valued light-cycle oil as part of a diesel blend. This technology has recently been commercialized.

Biofuels from cellulosic biomass

Advanced routes of biofuel production take advantage of more of the plant and of cellulosic biomass materials such as wood, grasses, straws and stovers from agriculture, and the organic fraction of municipal wastes (paper, cardboard, wood, textiles, and such). In simple terms, cellulosic biomass is made up of three major components: cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are carbohydrate polymers that can be broken down into component sugars for fermentation. Lignin is inert for biological conversion processes but can be utilized in thermal conversion processes.

There are a host of conceptual designs for creating liquid fuels from cellulosic biomass, but the commercially viable conversion technologies have yet to be determined. Most have not been proven beyond the laboratory scale. A number of pilot, demonstration, and early commercial-scale biorefineries are under development using a broad suite of technologies; these will provide a greater understanding of the commercial viability of the schemes in the near future. The technologies can be classified as utilizing biological conversion processes, thermochemical processes, or a combination of the two.

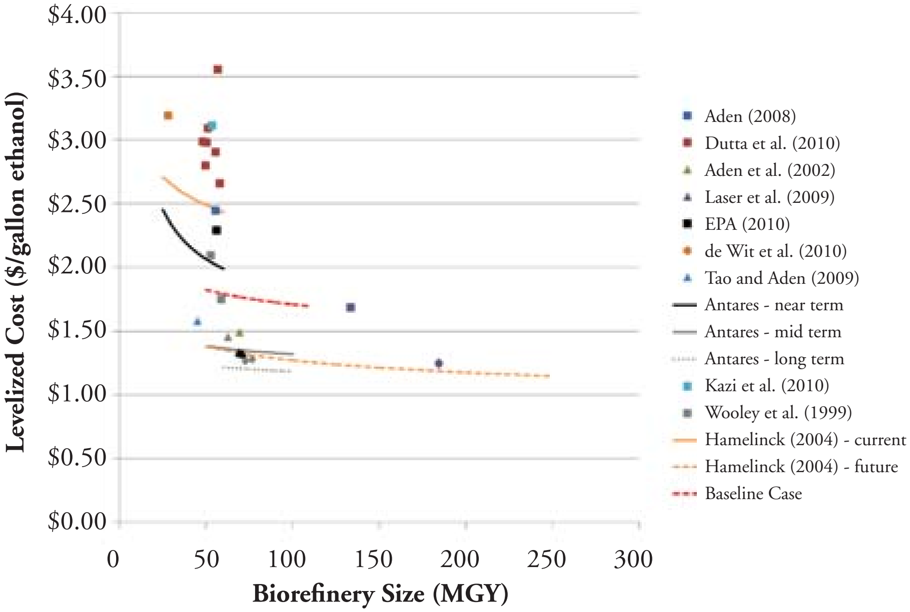
Estimates of the cost of production rely on a number of engineering studies with process-level modeling of the biorefinery. The majority of studies of cellulosic ethanol consider the biochemical pathway where the cellulose and hemicellulose are converted to sugars through enzymatic hydrolysis and saccharification, then fermented to make ethanol. The thermochemical pathway via gasification and synthesis has been found to be similar in cost and performance to the biochemical pathway at the scale of 45 million gallons of ethanol per year.[7] The biochemical route is taken to be the model cellulosic ethanol technology due to the larger base of supporting literature. The thermochemical pathway may prove to be the technology better suited in certain cases, but the performance is likely to fall in the range studied.

Biological conversion of cellulosic biomass to ethanol (cellulosic ethanol) has been the focus of significant research and is well described in literature. It is the basic technology of 7 of the 14 demonstration and commercial biorefineries receiving funding from the U.S. Department of Energy. Four demonstration biorefineries are currently operational worldwide and are expected to produce more than 3 million gallons in 2011.

The biochemical pathway begins with feedstock pretreatment to make the cellulose available to the enzymes. There are a number of techniques under research and development for this pretreatment, including dilute acid hydrolysis, ammonia fiber explosion, liquid hot water, and steam explosion. In the process of exposing the cellulose, the hemicellulose is broken into its component sugars (xylose, arabinose, and so on). The exposed cellulose is then converted to glucose with cellulase enzymes. Glucose is fermented to ethanol and the five-carbon (C5) sugars are fermented to ethanol either in a combined reactor using recombinant Zymomonas mobilis or in separate reactors using yeast for the C6 sugars and Z. mobilis for the C5 sugars. In some advanced designs, a consolidated bioprocessing (CBP) approach is taken where all biological conversions (enzyme production, enzymatic hydrolysis, and fermentation) occur in the same reactor.[8] This design is attractive, but the enzyme to make it possible has yet to be identified. In most designs, the lignin is separated from the beer, dried, and combusted to produce steam and electricity for the biorefinery with some net export of electricity.

The projected costs for cellulosic ethanol production using current technology cover a large range, with three main sources of variation. First is the expected yield of ethanol from cellulosic material. Estimates range from 52.4 gallons to 76.4 gallons per dry ton of switchgrass or corn stover. This variation is due to difference in the performance of the pretreatment, cellulase enzymes, and fermentation organisms each study assumes.[9] Second is the capital investment required, where a variety of configurations have been studied and different yields assumed. Within the same study, capital costs varied by 42 percent due to different configurations of pretreatment, hydrolysis, fermentation, and distillation.[10] The third factor is the variable operating cost—mainly the cost of cellulase enzymes. For example, one study[11] projects cellulase enzymes available at $0.32/gal of ethanol where another puts the cost at $1.05/gal. Also of interest is that the estimate for year 2000 technology in an earlier study falls below the more recent estimates of current costs, demonstrating that as more is learned about these technologies, limitations are identified that lead to additional costs.

COMPARISON OF PRODUCTION COST ESTIMATES FOR CELLULOSIC ETHANOL

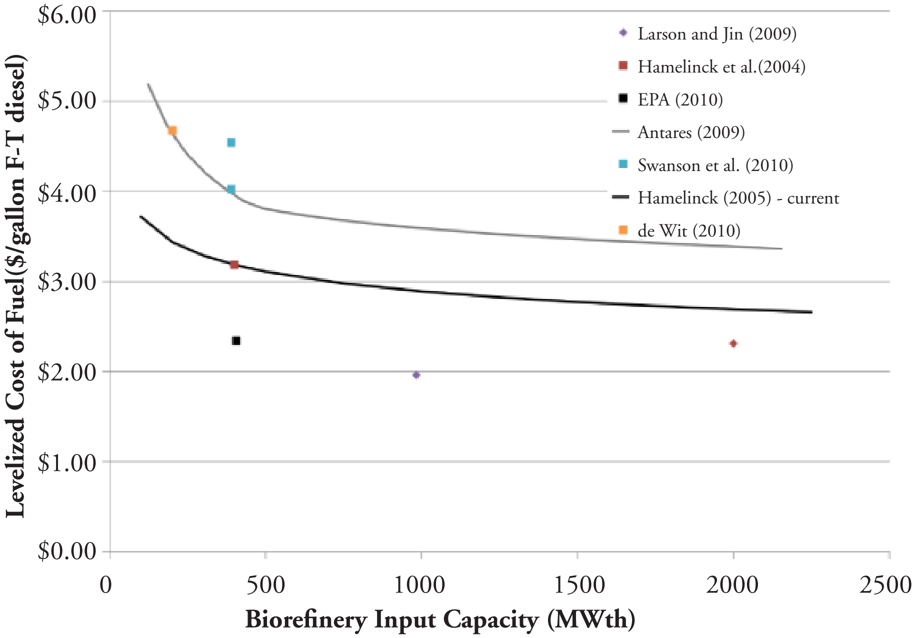


This chart compares estimates of the levelized cost of production of cellulosic ethanol via the biochemical pathway arrived at by a number of different studies.[14] Near-term technology assessments are represented by squares, midterm technology (7–15 years ahead) by triangles, and long-term projections by diamonds.

Thermochemical conversion of cellulosic biomass to fuels can take many routes, borrowing from fossil energy technologies in many cases. The Fischer-Tropsch (F-T) synthesis process is among the most studied and furthest developed. Commercial facilities exist or have existed in the past for production of F-T fuels from both coal and natural gas. In order to commercialize biomass F-T fuels, a number of modifications are needed compared with coal or natural gas-based F-T fuels. An economically viable biomass gasification technology must be developed along with optimization of gas cleanup and the F-T synthesis processes for the resulting biomass-based synthesis gas. A number of biomass gasifier configurations have been studied, each with benefits depending on the context of the project.[15]

Projected costs for current technology F-T diesel production cover a large range, representing some disagreement on which technologies are current and which are unproven, as well as differences in design. One study[16] states that hot gas cleanup (tar cracking) is not yet commercial while all other studies use it. One study[17] uses an indirectly fired atmospheric gasifier while most others use pressurized, oxygen-blown, directly fired gasifiers. In projecting future technology versus current technology, one study[18] foresees no changes in the design but projects reductions in capital and operating costs due to incremental improvements and increases in scale. Another study[19] presents a case with mature technology where a once-through configuration is designed for greater electricity production than the other studies. The EPA projection[20] is significantly lower compared to other studies at similar scale and timeframe, but the study provides little information to support this estimate.

COMPARISON OF PRODUCTION COST ESTIMATES FOR F-T DIESEL



This chart compares estimates of the levelized cost of production of F-T diesel arrived at by a number of different studies.[21] Near-term technology assessments are represented by squares, midterm technology (7–15 years ahead) by triangles, and long-term projections by diamonds.

F-T diesel is just one example of the gasification/synthesis thermochemical production route to produce hydrocarbon biofuels. Other conversion technologies are based on the route with a difference in the catalytic synthesis that takes place after the synthesis gas is produced. Another example is methanol-to-gasoline (MTG) technology, which combines methanol synthesis of the synthesis gas and a catalytic conversion of methanol to gasoline.

An alternative thermochemical route to producing hydrocarbon fuels from cellulosic biomass is fast pyrolysis with upgrading. Fast pyrolysis uses high temperatures in the absence of oxygen to degrade the solid biomass into a bio-oil similar to petroleum but with high oxygen and water contents. The bio-oil can be upgraded to fuels (gasoline, diesel, and/or jet fuel) through a combination of hydrotreating, hydrocracking, and dehydration.

Biofuels from algae

Biofuels could be produced from algae with many advantages over both first-generation biofuels and cellulosic biofuels. Algae produce significantly higher biomass in the same area compared to other energy crops. Some strains also produce high fractions of oils. Also, algae do not require soils to grow, which reduces the pressure biomass production would put on lands with agricultural production. And algae can use degraded water resources.

Algae cultivation can take place in an open pond, a closed photobioreactor (PBR), or a combination of the two. Open ponds are less capital-intensive but lack the environmental control of PBRs. Species control is one of the principal challenges for open-pond technology since native algae strains tend to outcompete the desired strain selected for optimal fuel production.[22] Hence, only three algae species have been successfully cultivated in open ponds for an extended time period.[23] All three species are “extremophiles” in that they can survive under extreme conditions such as high pH or salinity that prohibit the growth of other organisms. PBRs can also suffer from contamination issues, but the controlled environment and closed system makes it easier to prevent contamination.

The harvesting and dewatering step can be capital- and energy-intensive. Open pond biomass concentrations are typically 0.5 g/L[24] while PBR concentrations are on the order of 1 to 12 g/L.[25] Bulk harvesting techniques such as flocculation and settling can be used to increase the biomass concentration to approximately 1 percent,[26] which may be acceptable for some fuel production processes such as anaerobic digestion or alcoholic fermentation, but the water content must be decreased further in order to use other biofuel production pathways. Filtration and centrifugation—both energy-intensive processes—can reduce the water content down to approximately 80 percent, resulting in algae paste. This paste can be dried or used in its wet form, depending on the production process. Filtration can be cost-effective for filamentous or large algae cells, but centrifugation is more cost-effective for small, spherical strains such as those of the genus Chlorella.

Possible thermochemical methods for converting algae biomass into fuel include thermochemical liquefaction, gasification with Fischer-Tropsch processing, and pyrolysis.[27] Alternatively, lipid extraction and transesterification can be used to produce biodiesel. Hydrotreating the lipids could be used to produce renewable diesel.[28] All of these techniques, with the exception of thermochemical liquefaction, require dry or nearly dry biomass, which requires substantial energy inputs. Techniques for lipid extraction from microalgae are not well established.

Biomass Resources for Biofuel Production

Biomass resources are often characterized by their mass, but this can be misleading as the energy content of biomass materials varies significantly, and energy is what is interesting. The solar energy annually captured as biomass by all terrestrial plants is approximately 2,500 exajoules (EJ), or more than fifteen times global petroleum use. Obviously, the vast majority of this will not and should not be made available for energy production. Most of global biomass production either provides greater value to society in its natural state or cannot be economically accessed for bioenergy production. Hence, the fraction of biomass that can advantageously be employed to produce transportation fuels is very small. Global estimates suggest that 10 to 25 percent of transportation fuel needs could be met with biofuels,[29] with biofuels playing a larger role if vehicles are made more efficient and biomass productivity is increased. In 2009, only 2 percent of transportation fuel demands were met using biofuels, predominantly in the form of ethanol from sugarcane and corn, and biodiesel from rapeseed, palm, and soy oils. There is room for growth in biofuels, but they cannot be expected to provide more than 25 percent of transportation energy globally.

In the United States, estimates of biomass that could be developed in the near term range from 208 to 801 million dry tons,[30] of which we estimate that between 156 and 443 million tons could be from waste and residue sources. Growth in waste and residue sources will be limited. Producing more biomass will require the growth of energy crops. By 2030, more than a billion tons of biomass could be sustainably produced from agriculture, forestry, and municipal waste,[31] sufficient to meet roughly a third of transportation fuel demand, and possibly more with advancements in the efficiency of future vehicles.[32]

Underlying the projections for biofuel potential are assumptions regarding technology development (making currently unattractive cellulosic feedstocks economic), land use, food demand, and overall agricultural productivity (including energy crop yields). One main concern is the ability of the land base to support energy production as well as food production. In these arguments food production is always given the priority, but the market does not prioritize food, as a consequence of disparities in purchasing power across the global population. Some small fraction of the biomass resource consists of organic wastes that do not interfere with land markets. These resources are limited relative to transportation fuel demand and will grow minimally in response to demand for biomass, but they avoid some sustainability concerns of crops grown for energy production. Residues from conventional agricultural crops and forestry operations provide significant potential although there is some debate over the sustainable use of these resources.[33] Residue resources may increase over time and in response to market demands for biomass as farmers maximize the total value of their crops. This resource has the potential to lead to adverse impacts on food production. The rest of the resource depends on lands that are currently idle or lands being freed through increases in agricultural productivity. Researchers who developed a global estimate of biofuel potential using abandoned agricultural land that is not currently forested or urbanized found an upper limit on biofuels grown on these marginal lands to be 12 times current production or approximately 17 percent of current global petroleum consumption.[34]

Biofuel production will need to be improved in several ways to meet this potential. First, the development of biofuel technologies that can utilize cellulosic biomass would enable access to the significant waste or residue streams from agriculture and forestry sectors as well as urban wastes.

Additional biomass could come from purpose-grown crops such as switchgrass, Miscanthus, oil seeds, algae, and many others, but the extent to which these can contribute to overall supply is not fully understood and can potentially expand beyond the limits suggested here. Industrial algae production could also significantly expand biomass resources due to high growth rates and yields and could potentially use marginal water, but future production levels and costs also remain highly speculative.[35]

Additionally, best uses for biomass are still to be sorted out through technology innovation and market action.The liquid biofuels discussed in this chapter would mostly be used in internal combustion engine vehicles. Electrification of the light-duty vehicle fleet might provide higher-efficiency use of biomass in this sector compared with liquid fuel production, although heavy transport and aviation will still likely depend on or prefer liquid fuels for economic reasons. Biomass can also be used to produce hydrogen, and if large-scale reliance on hydrogen for transport and other power sectors emerges, liquid biofuel production may serve mostly as an interim market solution. Multiple markets for biomass in the energy and bio-based product sectors are likely to continue to develop, extending the portfolio of conversion options and driving innovation toward more integrated production chains.

CASE STUDY: HOW THE U.S. BIOFUEL SUPPLY MIGHT MEET RFS2

The United States adopted a volumetric mandate for biofuels (the Renewable Fuel Standard or RFS) in 2005 and strengthened it in December 2007 as part of the Energy Independence and Security Act (EISA). The RFS2 mandates annual consumption of biofuels increasing to a quantity equivalent to 36 billion gallons of ethanol on an energy basis (2.9 EJ or 23.7 billion gallons of gasoline equivalent or gge) in 2022. While the law was written as a volumetric mandate, the EPA has interpreted the law as a mandate of energy quantities in order to provide a level playing field for all biofuels.[36] Specific mandates are defined each year for several subcategories of renewable fuels differentiated by feedstock and life-cycle carbon intensity (CI). In 2022, for example, of 21 billion ethanol equivalent gallons of advanced biofuels (not corn ethanol; 50-percent reduction in CI from gasoline required), 16 billion gallons must be cellulosic biofuels (from cellulosic feedstocks; 60-percent reduction in CI from gasoline required); the remaining 15 billion gallons to reach the 36 billion gallon total can be any renewable fuel with a 20-percent reduction in CI, including corn ethanol (existing corn ethanol facilities were given a grandfathered exemption to the CI requirement).

The UC Davis Geospatial Bioenergy Systems Modeling (GBSM) project has developed a spatially explicit model of how future biofuel supply chains in the United States might be constructed, and has applied the model to analyzing the domestic potential to meet RFS2. The GBSM aims to assess the potential U.S. biofuel supply by simulating it and its environmental impacts under scenarios of resource constraints, technology limitations, and policy limitations. The modeling framework incorporates a spatially explicit assessment of biomass resources, engineering-economic models of biorefineries, a GIS-based transportation cost model, and a supply chain optimization model. At the heart of the research is the integrated supply chain model, which maximizes the profit of the biofuel industry over the full supply chain using real-world data on potential biomass supply and including distribution of biofuel to the consumer. The model describes the optimal behavior of an industry to supply biofuels given a fuel demand, a biofuel selling price, and constraints on feedstock supply. Simply put, if biofuel can be delivered to the refueling stations for less than the given selling price, it is profitable for the industry to supply that biofuel, and the infrastructure would be built to reap that profit. If biofuels cannot be delivered for less than the selling price, the fuel demand is met with conventional fuels at the given selling price. In addition, when demand for fuel exceeds the supply of feedstock, the difference is made up with conventional fuels. Results of the model show that the potential for biofuel production in the United States is significant relative to current production.

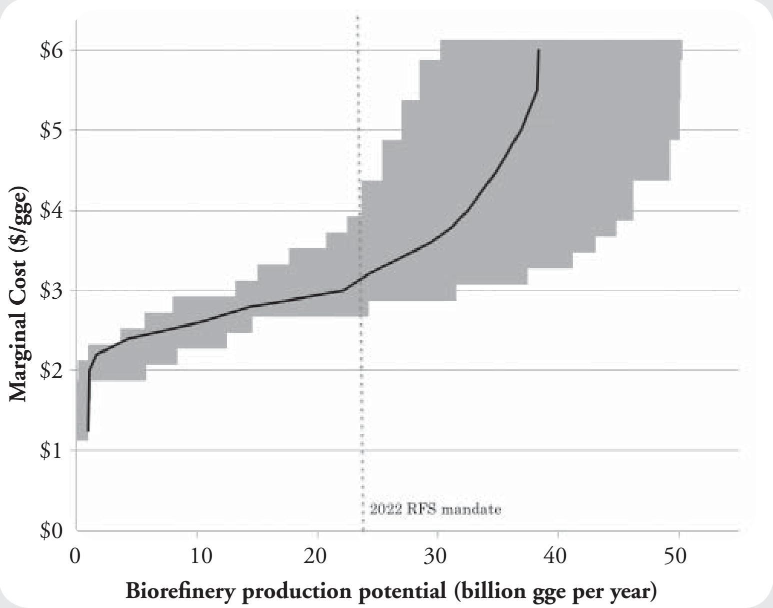
Biofuel supply is dependent on a number of highly uncertain parameters. First is the resource base—what will be made available to the biofuel industry and at what cost. Second is the conversion technologies—what will be the conversion efficiency and cost of the conversion for unproven technologies. Finally, the demand for biofuels is unknown in two important aspects despite the mandated volume: (1) the amount of each fuel type (ethanol, biodiesel, biomass-based F-T diesel) that will be acceptable to use in the future vehicle fleet, and (2) the price the market will be willing to pay for each. Because of the uncertainty of these three sets of parameters, the study considers a range of outcomes through sensitivity analysis.

The biomass resources considered for this study include agricultural residues, switchgrass, forest residues (including unused mill residues), pulpwood, municipal waste, yellow grease, and animal fats. The model also uses the 2009 USDA long-term projections to describe conventional agriculture including corn, seed oils, and crop acreage for estimating residues,[37] which limits the analysis to 2018. Still, given the uncertainty in all parameters and the stability of the projection in 2015–2018, the analysis can be used to comment on the 2022 supply.

The supply of agricultural residues is constrained in order to maintain soil organic matter and for erosion control. These sustainability parameters will be different for each field and are not fully understood. Switchgrass is only considered to be grown on marginal land to avoid competition with food crops. This assumption is convenient for modeling energy crops with minimal impact on the food sector but may not be the way the market allocates land use. The yields and costs of production for both agricultural residues and switchgrass are not well known. To capture this, we developed three scenarios of each. We also developed three scenarios of availability of municipal wastes to capture the uncertainty in the participation rates of municipalities in making their wastes available for energy conversion. The biofuel conversion technologies considered range from biodiesel from seed oils, yellow grease, and animal fats to cellulosic ethanol or Fischer-Tropsch diesel and naphtha from wastes, residues, and energy crops. Scenarios were run at three levels of optimism for the cellulosic ethanol technology and two levels of optimism for Fischer-Tropsch technology. On the demand side, three scenarios were also developed, with ethanol consumption limited to blends with gasoline of (1) 10 percent or 20 percent for all vehicles, (2) 10 percent for conventional vehicles, and (3) 85 percent for all flexible-fuel vehicles. Aggregate scenarios were developed from all logical combinations of the resource, technology, and demand scenarios.

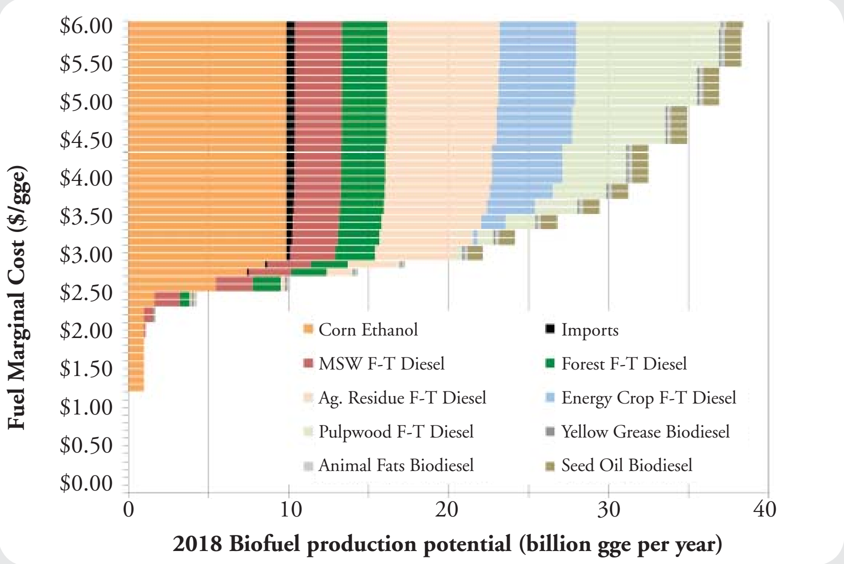
For each scenario, the research found the optimal design of the biofuel system over a range of prices to produce supply curves. These supply curves show the quantity of biofuels that would be made available at a given market price. The curves indicate biofuel potentials in 2018 ranging from 21 to 46 billion gallons of gasoline equivalent (gge) at prices below $4/gge depending on the resource and technology scenario. These volumes would meet 9 to 21 percent of the projected total transportation gasoline and diesel demand and would represent an increase of 300 percent over 2009 production levels. Below $3/gge, between 12 and 32 billion gge are projected to be feasible. The baseline scenario resulted in 32.5 billion gge at $4/gge and 22 billion gge at $3/gge. Constraints on the sustainable supply of biomass restrict growth of biofuels to not much more than the quantities available at $4/gge. The maximum supply identified under the assumptions used was 50 billion gge at $6/gge in the high feedstock scenario. This maximum supply would increase if cost-competitive production of algae-based biofuels is developed or if yields for energy crops on marginal land are higher than projected.

Biomass from waste and residue resources (municipal solid waste, agricultural residues, and forest residues) can provide quantities of biofuels that assist with policy goals. This resource is especially important as it avoids many sustainability concerns of biofuels produced from crops. Nationally, waste and residue resources are projected by the model to provide 7 to 16 billion gge of biofuel per year, accounting for between 35 and 64 percent of the RFS2 mandate in both 2018 and 2022. The remaining biofuels are predominantly corn ethanol (up to 10 billion gge) and soy biodiesel (up to 1 billion gge) in the 2018 case and expanding to include switchgrass and pulpwood-based biofuels at the higher volumes of the 2022 mandate.



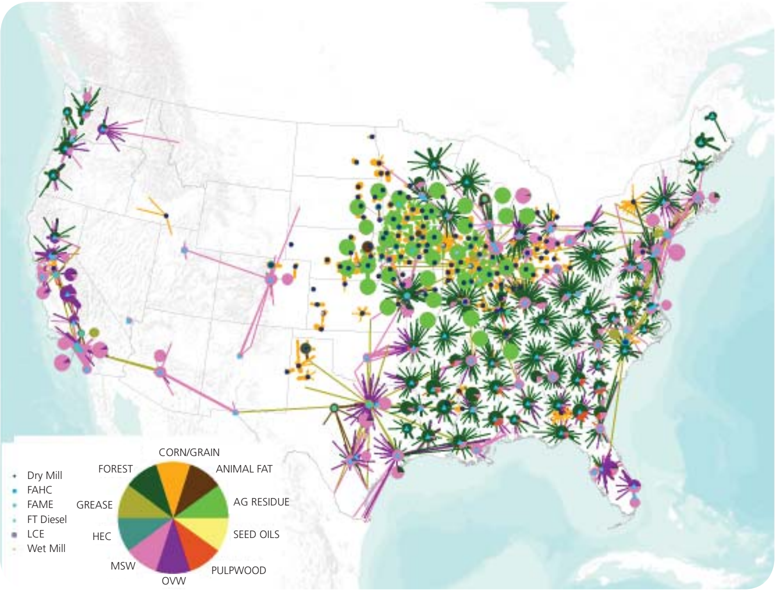
The GBSM arrived at this baseline supply curve for biofuels in 2018. The curve indicates the quantity of biofuels that would be made available at a given market price (gge = gallons of gasoline equivalent). RFS2 requires that 36 billion gallons of ethanol equivalent be sold annually by 2022, which converts to 24 billion gge. The shaded area shows the range of outcomes for the different scenarios evaluated by the model.

Investments in biorefineries required to meet mandated volumes of biofuels are large and depend on the specific pathways chosen. Greater reliance on cellulosic technologies requires higher capital investment than systems that rely on conventional biofuel technologies such as corn ethanol or fatty acid methy ester (FAME) biodiesel; however, these technologies have significant sustainability and energy-balance benefits over corn-based technologies. In addition, systems where the Fischer-Tropsch technology is chosen to convert cellulosic biomass have higher capital costs than systems where cellulosic ethanol is the technology of choice for cellulosic biomass. The total investment in biorefineries required to meet the 2022 RFS2 mandate is between $100 and $360 billion, with a baseline estimate of $160 billion. This would entail an annual investment of $9 to $30 billion ($13 billion baseline) during the years from 2010 to 2022.



The GBSM arrived at this baseline supply curve for biofuels in 2018 by production pathway (gge = gallons of gasoline equivalent). The biofuel conversion technologies considered range from biodiesel from seed oils, yellow grease, and animal fats to cellulosic ethanol from wastes, residues, and energy crops, and Fischer-Tropsch diesel and naphtha from wastes, residues, and energy crops.

GBSM modeling gives a picture of how the biofuel industry is likely to organize spatially in the United States. Feedstock availability is the dominant force in determining the spatial distribution of biorefineries. Biomass is more expensive to transport than finished fuel products, which leads to the conversion industry locating largely to minimize feedstock transport cost. Cellulosic biofuel production will be predominantly located in the Midwest where the industry can utilize agricultural residues and the Southeast to access forestry residues. Additional biorefineries are sited near population centers to take advantage of both municipal waste resources and local fuel markets. The GBSM predicts large cellulosic biorefineries that draw feedstock from as far as 100 miles away.



This map shows the spatial distribution of biorefineries in 2018 projected by the GBSM to meet the RFS2-mandated volumes of biofuels. The pie chart shows the relative size of individual refineries and their feedstock portfolio. Lines indicate the source of these feedstocks. Corn ethanol facilities are shown as small blue dots and are not to scale with the other refineries.

The ability of the U.S. transportation fuel sector to utilize ethanol is a significant factor shaping biofuel development. Either an increased ethanol blend maximum (currently at 10 percent but approved by the EPA to increase to 15 percent) or significantly increased flexible-fuel vehicle penetration will be required to utilize future ethanol production, which is likely to exceed 10 percent of the U.S. transportation fuel supply. Conversion of cellulosic biomass to drop-in hydrocarbons through the Fischer-Tropsch or other processes may provide an alternative fuel pathway. A review of the literature on cellulosic conversion technologies did not show a distinct cost advantage for either production method given the current state of technology development. The majority of scenarios result in Fischer-Tropsch diesel as the product biofuel.

In summary, domestically produced biofuels have the potential to achieve the goals set out by RFS2 at costs that are within the range of historical gasoline prices. A significant fraction of these fuels will come from waste and residue resources. Whether this potential will turn into real fuel depends on advancements in conversion technologies and the development of reliable feedstock supply chains in a short time period.

Vehicle and Infrastructure Compatibility

Biofuels are generally compatible with internal combustion engine vehicle (ICEV) technologies and can also be used in hybrid electric drive trains. Many ICEVs already use liquid biofuels, whereas only a small fraction have been adapted to run on gaseous fuels or hydrogen. However, most of the existing fleet of gasoline and diesel ICEVs can only operate on a relatively low biofuel blend—up to 10 percent by volume of ethanol or 5 percent of biodiesel—to avoid adverse effects on vehicle operation and durability. The percentage of ethanol that can be blended into gasoline for conventional vehicles is currently under debate. All vehicles in Brazil must be capable of accepting blends of up to 25 percent ethanol. In the United States, the EPA has recently approved the use of E15 (15 percent ethanol and 85 percent gasoline) for vehicles made after 2001. This decision may not lead to E15 being offered, though, as safeguards must be in place to prevent older vehicles and small off-road engines from mistakenly using E15.

An increasing number of flexible-fuel vehicles (FFVs) in the United States, Brazil, and Sweden can use higher blends of ethanol (up to 85 percent) or 100 percent gasoline. FFVs vary the engine operation depending on the ethanol content of the fuel, measured by the oxygen sensor in the exhaust. In addition, they use larger fuel injectors and different materials in the fuel system to guard against the corrosive nature of ethanol. In Brazil 17 percent of vehicles are FFVs. In the United States, 3.3 percent of vehicles are currently FFVs, but that is expected to grow to 15 percent by 2020. Estimates of the cost of making vehicles flexible-fuel capable range from $50 to $100 per vehicle,[38] which is the cheapest modification for alternative fuels. The issue is getting enough on the road to make E85 a viable fuel option for refueling stations.

Biodiesel can legally be blended at any percentage with petroleum diesel. However, some engine manufacturers do not honor warranties if biodiesel blends are used. The most common blend is B20 (20 percent biodiesel by volume) to avoid issues with cold weather.

“Drop-in” biofuels are hydrocarbon fuels produced from biomass that can be blended freely with petroleum gasoline or diesel and used in conventional vehicles without modification. These fuels provide a seamless transition to alternative fuels as the vehicles and infrastructure require no modification. One drop-in biomass-based diesel fuel produced by the hydrotreatment process is in early commercialization. Other drop-in biofuels are still precommerical, though a few demonstration facilities exist. The cost of these fuels has yet to be determined, and it is unclear whether it will be more costly to develop drop-in fuels or to overcome the infrastucture and vehicle compatibility issues of ethanol. Additionally, these fuels will not be an exact match for petroleum fuels and will require refining to get the fuel properties in line with specifications for gasoline and diesel.

Since liquid biofuels blended in limited amounts are similar to neat gasoline or diesel in terms of vehicle performance and refueling time, and do not require new vehicle types, they can be relatively transparent to the consumer. Fuel costs may therefore be the main factor determining consumer acceptance. In Brazil, for example, FFV users select their fuel based on price. Reduced range and reduced fuel economy with ethanol and, to a lesser extent, biodiesel, can also be a factor in consumer acceptance.

An extensive infrastructure is required to supply liquid biofuels to a refueling station, as explored in greater detail in Chapter 5. Some forms of biofuel might be transported in the existing gasoline and diesel distribution infrastructure, but some forms cannot. If drop-in biofuels were produced, they could be co-transported with existing fuels. Ethanol cannot be transported in gasoline pipelines because of its tendency to absorb water and its corrosiveness. It requires its own distribution and storage systems through the fuel distribution terminal. Gasoline-ethanol blends of 15 percent ethanol or less can be blended at the distribution terminal and used in existing refueling station infrastructure. New and separate storage tanks and dispensing pumps at the refueling station will be needed for blends beyond E15.

Sustainability Aspects of Biofuels

Vigorous debate is going on within the academic community and among government, environmental, and industry groups regarding the sustainability of biofuel production, considering both its environmental impacts and its competition with food production.The sustainability of any biofuel is dependent on the specific pathway used to produce it. However, information that relates sustainability to the supply potential is scarce. The definition of “sustainable biofuels” is neither clear nor agreed upon. Generally, the definition of a sustainable practice is one that meets current needs without compromising the ability of future generations to meet their needs.[39] But the generality of this definition leaves lots of room for interpreting how it applies to the questions surrounding biofuel production.[40]

Biofuel production can be environmentally unsustainable in a number of ways: by causing habitat loss/deforestation, soil degradation, greenhouse gas emissions, pollution of water and air, aquifer depletion, and so on. (See Chapter 7 for more on the direct land-use and water impacts of biofuels production; see Chapter 12 for more on the GHG emissions and indirect land-use impacts.) A significant amount of water is required to grow energy crops and to convert any feedstock into biofuels, and many biofuel pathways can lead to reduction in water quality through intensification of agriculture.[41] Whether a particular biofuel reduces life-cycle air pollutant emissions compared to a baseline petroleum fuel depends on the production pathway, with some pathways yielding a net benefit and others a net detriment.[42] Removing agricultural residue for use in biofuel production also raises concerns about soil quality impacts and carbon emissions.[43] And production of biofuels can pose a threat to biodiversity when it results in habitat loss as well as impacts on water and soil quality.[44]

Competition for land between food and energy crops is also cause for caution. The boom in production of corn-based ethanol in response to both federal mandates and rising gasoline prices played a significant role in the doubling of the price of corn from 2006 to 2008.[45] Most options to produce biofuels on a significant scale will require the use of large quantities of agricultural land. But productive agricultural land is a limited and valuable resource that provides basic nourishment to a growing global population. The question of whether it is a good idea to incentivize the development of another major use for this scarce resource is becoming important, especially since many agricultural practices have negative environmental impacts.

Furthermore, introducing biofuel production that is competitive with petroleum fuels links the global agricultural and land markets to energy markets. It is not likely to be possible to limit production of biofuels to marginal land; biomass, like traditional crops, will grow better and be more profitable on good agricultural land. A potential danger in linking these markets is that it amplifies the impact of petroleum prices on food prices.

Although expanding the quantity of lands in agricultural production can ease the problem of direct food-fuel competition, this expansion often leads to major environmental impacts, including deforestation, habitat loss, and resulting loss in biodiversity,[46] as well as greenhouse gas emissions caused by releasing the carbon stocks of the converted land.[47] These impacts can more than cancel the gains achieved by the production of biofuels.

Despite these serious issues, it is important to note that there is a great deal of variability in the potential impact of biofuel production pathways—on both food production and the environment. Within this variability, the opportunity exists for a limited sustainable biofuels industry. But the viability and extent of such a sustainable biofuels industry depends on the costs of production, primary and coproduct market values, and any subsidies for such production influencing overall profits. The policy basis for subsidies, as well as for mandates and other expressions of government influence, therefore requires extensive information relating to net economic, environmental, and social benefits, if any. The present debate over biofuels in part reflects high levels of uncertainty about these outcomes and the need for more comprehensive information.

Policies and Business Strategies Needed to Support Biofuels

The ease of manufacture for first-generation biofuels has led to various national incentives for large-scale development. Brazil, for example, has built a large biofuel industry under government policy and financial support around ethanol from sugarcane, a historically important crop for the country. The United States has similarly encouraged ethanol production from corn (maize), making it the largest source of biofuel in the nation for both petroleum displacement and motor fuel oxygenates. But both sugarcane and corn ethanol production have been criticized as being less sustainable and environmentally beneficial than government policy might suggest. This is particularly the case for corn ethanol in light of more recent analyses suggesting that increasing crop production in response to rising fuel prices and ethanol market value or to fulfill biofuel mandates can lead to indirect land-use changes that in turn cause excess emissions of greenhouse gases relative to the fossil fuels the ethanol is intended to replace. The subject remains open to debate as neither global modeling nor direct monitoring capabilities are sufficiently well developed to provide definitive understanding around the issue.

Policies intended to promote the development of a sustainable biofuels industry must account for the multitude of factors highlighted in the previous section or accept that unintended consequences will occur. Such policies must allow for a high degree of uncertainty in the impacts and be flexible to respond to new information as it is generated. In addition, some degree of certainty within the policy must be imposed in order to promote a business environment that is friendly to investment.

Past and current biofuel policies have not taken this holistic approach but have instead focused on four policy goals: energy security, rural economic development, criteria air pollutant reduction, and greenhouse gas emission reduction. Policy is in the early phases of incorporating some sustainability aspects in addition to greenhouse gas reduction. At the national level, policies have focused on developing a domestic alternative to petroleum fuels using mandates and subsidies for biofuels as the main policy instruments.

As mentioned earlier, the federal RFS2 program establishes specific annual volume standards for cellulosic biofuels, biomass-based diesel, advanced biofuels, and total renewable fuels that must be used in transportation. To meet RFS2 by 2022, 16 billion gallons of biofuel must come from cellulosic feedstocks, such as agricultural and forest biomass, in addition to the 15 billion gallons of conventional biofuels produced largely from grain. The requirements include definitions and criteria for both fuels and the biomass feedstock used to produce them, including a ceiling for direct emissions and emissions from land-use change during all stages of fuel and feedstock production, distribution, and use by the consumer.

California's Low-Carbon Fuel Standard (LCFS), which mandates a 10-percent decrease in the carbon intensity of transportation fuels sold by 2020 relative to a 2010 baseline, accounts for the indirect effects of land-use change coupled with biomass production.[48] You can read more about this in Chapter 11.

The policy challenge is to promote sustainable biofuels while not promoting biofuels that could cause more harm than good. Government policies aimed at increasing biofuel production and use must accurately assess the associated social, environmental, and economic impacts. Several micro- and macro-level considerations need to be assessed. On a micro scale, the local impacts of the individual biorefinery and its supply chain need to be considered. On the macro scale, the impacts of the biofuels industry as a whole on agricultural markets and scarce global resources of arable land and high-quality water must be considered. Assessing the micro-scale impacts requires meticulous accounting and auditing, leading to additional cost for producing certified sustainable fuels. The macro-scale impacts are more difficult to determine and cannot be directly controlled by the individual producers of biofuels.

Summary and Conclusions

- There are a large number of pathways for biofuels production. The costs and benefits of biofuels vary greatly, depending on the specific pathway taken.

- With the biofuels production technology that is mature now, so-called first-generation technology, the lowest-cost biofuels do not provide major environmental benefits. Some represent marginal improvements over petroleum while others are actually worse than petroleum fuels in terms of environmental impacts.

- The biofuels that are expected to provide significant environmental benefits (advanced biofuels) are not yet commercially viable. Significant quantities of advanced biofuels are expected to be produced before 2015 by the first commercial-scale biorefineries. If the technologies prove to be viable, rapid expansion will take place in response to the existing strong government mandates. These biofuels are expected to have small greenhouse gas footprints but face some of the same indirect land-use change challenges as conventional biofuels if cultivating their feedstocks displaces food crops.

- Biofuels can make limited but significant contributions to a sustainable transportation energy supply. Liquid biofuels have an advantage over other petroleum alternatives (hydrogen and electricity) in serving sectors such as aviation and freight that require easily transportable, energy-dense fuels.

- STEPS research on the supply potential of biofuels shows that advanced biofuels from waste, residues, and energy crops grown on marginal land could provide between 2 percent and 16 percent of transportation energy in the United States in the next decade, with an additional 5 percent from conventional corn and soy-based biofuels. This result depends significantly on advancements in conversion technologies, the development of reliable feedstock supply chains, and the participation of potential biomass suppliers. This includes the participation of farmers in providing residues, waste management companies in providing the organic fraction of municipal solid waste, and forestry operations in collecting more of the timber that's not suitable for sale.

- Balancing sustainability with increasing production is delicate and will require policy intervention. Sustainable exploitation of biomass resources requires the consideration of many factors, some of which are not directly controlled by the biofuels industry. Capturing all factors within a regulatory framework will be difficult. Additionally, such complex regulations will be difficult to translate into a well-defined space in which industry can confidently operate. Chapter 12 explores this topic in more depth.

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