Transportation Fuels for the 21st Century

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As we enter the 21st century, policy-makers face complex decisions regarding options for meeting the demand for transportation fuels. There is now a broad scientific consensus that the burning of fossil fuels has been contributing to climate change,[1] and the transportation sector is a major contributor (see Figure 1). Yet global demand for energy and transport fuel is rapidly rising.

The U.S. Department of Energy's Energy Information Agency (EIA) projects that, from 2006 to 2030, the most rapid growth in energy demand will be in nations outside the Organization for Economic Cooperation and Development (OECD), especially in the emerging economies of China, India, Brazil, and Russia.[2,3] In the United States, imported petroleum currently accounts for approximately 40% of the national trade deficit.[4] There have been significant disruptions in the regional oil and gas supply from the Gulf of Mexico during recent hurricane seasons, and the 2010 Gulf of Mexico oil spill has raised new questions about the safety and the future of offshore drilling.

Concerns surrounding the sustainability of petroleum-based fuels have caused attention to shift toward biofuels. EIA's global projections show ethanol, biodiesel, and other biofuels reaching 5.9 million barrels per day in 2030. Particularly strong growth in biofuels consumption is projected in the United States, where, as mandated by the Energy Independence and Security Act of 2007 (EISA), biofuel production is expected to increase from 0.3 million barrels in 2006 to 1.9 million barrels per day in 2030 (see Figures 2 and 3), or 13% of projected U.S. transportation fuel demand. Other regions with large projected increases in biofuel production include the OECD nations in Europe and non-OECD economies in Asia and Central and South America.

The Transportation Fuels Challenge

A brief review of the U.S. history of ethanol use further illustrates the complexity of fuel use decisions. During the 1973 Arab oil embargo, ethanol was

used to extend fuel supplies, but its use waned once foreign supplies were restored. When the U.S. Clean Air Act was amended in 1990 to require the addition of oxygenates to fuel, efforts to promote ethanol as an additive met with little success because the petroleum-based additive methyl tertiary-butyl ether (MTBE) was less expensive, and consumer acceptance of ethanol blends was lukewarm. However, after MTBE was found in the late 1990s to contaminate subsurface drinking water supplies, domestically produced ethanol gained traction with U.S. policy-makers and the public. Tax incentives, import tariffs, and research funding encouraging ethanol use were instituted, and in 2007 new volumetric requirements for renewable fuels were put in place.

Following the late-2007 passage of EISA, the U.S. Environmental Protection Agency (EPA) revised the National Renewable Fuel Standard (RFS2) program to mandate usage amounts for various types of renewable fuels, including cellulosic ethanol, biomass-based diesel, and total advanced renewable fuels, from 2010 through 2022.[5] EISA required the use of life-cycle assessment to ensure that reductions in greenhouse gas (GHG) emissions were achieved. Fuels meeting these GHG reductions include corn-based ethanol fuels that use new fuel-efficient technologies; sugarcane-based ethanol; and biodiesel from soy, waste oils and algae. Many U.S. states have also established biofuel mandates.

Nonetheless, because of the complexity of production and supply of transportation fuels, significant questions remain regarding the long-term economic, social, and environmental outlook for the production and use of various fuel types. For example, the U.S. National Research Council is currently studying the potential economic and environmental impacts of the renewable fuel standards, as well as barriers to achieving them (see www8.nationalacademies.org/cp/projectview.aspx?key=49174).

This article argues for an integrated, transdisciplinary approach to the development of policy alternatives for meeting transportation needs. This approach should entail scientifically sound, life-cycle comparisons of entire supply chains, and should include assessments of land, ecological, air and water resources, processing technologies, storage and distribution infrastructure, health, consumer behavior, and economics. While all solutions (including fuel efficiency, electric vehicles, mass transit and reduced sprawl) should be examined on an equal footing, this article's focus is on liquid and gas fuels. Without making predictions or recommendations of what the future transportation fuel mix should be, it identifies key steps needed to reach those decisions.

Alternative Fuel Options

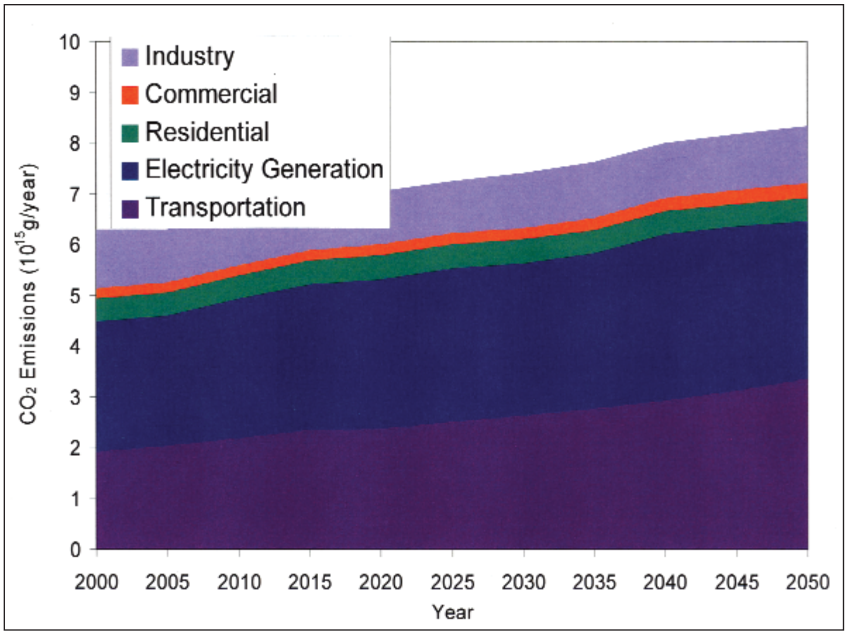
Currently, approximately 95% of transportation fuels (i.e., gasoline, diesel, jet fuel) are "conventional fuels," derived from petroleum.[6] However, current research is being targeted toward a number of different feedstocks, production technologies, and propulsion systems.

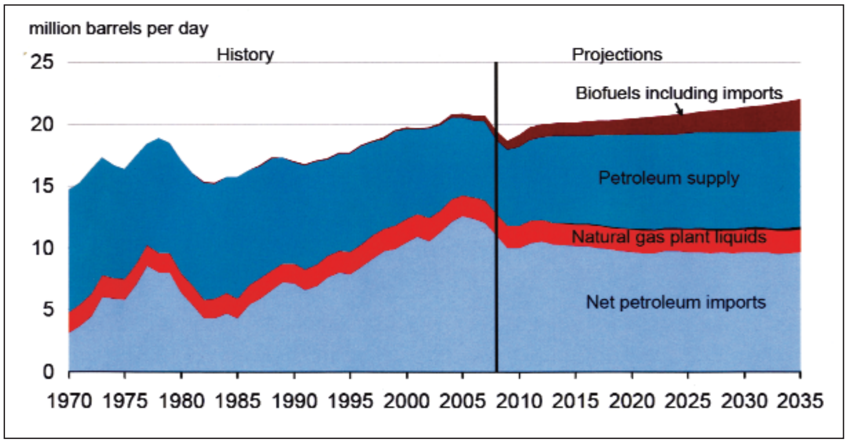
Feedstocks

Many feedstocks used for transportation fuel have multiple uses in different sectors, including power generation and chemicals production. Fossil feedstocks include petroleum, tar sands, oil shale, natural gas, and coal. Tar sands are alternatives to petroleum that are currently being mined and refined, particularly in Canada. Natural gas and liquefied petroleum gas (LPG) can be used in special vehicles designed to run on gaseous fuels. Coal is not presently used to produce transportation fuels in the United States, but serves as a feedstock for "coal-to-liquids" (CTL) processes in other countries.

Figure 1. *A projection of sectoral CO_2 emissions growth from the U.S. energy system, assuming no new national-scale actions to reduce CO_2 emissions.*

Source: Loughlin, D. Modeling the Air Pollution Impacts of Alternative Energy Scenarios Using U.S. EPA MARKAL; National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC. Presented at the U.S.-Korea Conference on Energy, Technology & Entrepreneurship, Raleigh, NC, July, 2009.





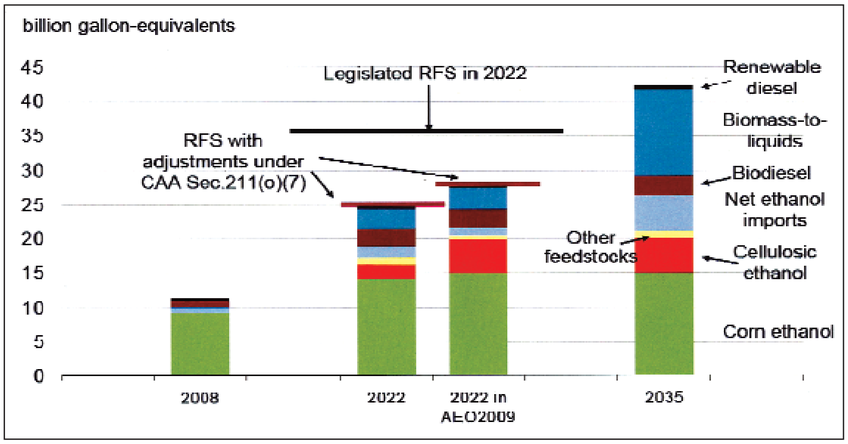


Figure 2 (top). U.S. liquid fuels supply: biofuels are linked to most of future growth (Annual Energy Outlook 2010, Newell).

Figure 3 (bottom). Biofuels are projected to grow, falling short of the 36 billion gallon renewable fuel standard target in 2022, exceeding it in 2035 (Annual Energy Outlook 2010, Newell).

Notes: RFS= Renewable Fuel Standard; CAA= U.S. Clean Air Act

Non-fossil feedstocks are predominantly biomass-based. Biomass refers to organic plant matter and includes a number of potential feedstock types. Natural sugar-producing crops include sugar beets and sugar cane, and this sugar is fermented to ethanol in countries such as Brazil. More common in the United States are starch crops, including corn, wheat, and other grains; the starch is enzymatically converted to sugar, which is then fermented to ethanol.

Natural plant oils (soybean oil) and cooking greases are also used as alternative fuel feedstocks, primarily for diesel fuels. While not currently used for producing biofuels, cellulosic materials, such as woods, agricultural residues (corn stover, wheat straw), and prairie grasses (switchgrass) will be used for fuels production in the near future. Even algae are being developed as feedstocks for renewable fuels.

Internationally, Brazil is using its vast sugarcane resources to produce billions of gallons of fuel ethanol and has been doing so for many years. In fact, Brazil's fuel distribution and vehicle infrastructure are well adapted to ethanol use. In the European Union, grains and oilseed crops are the primary feedstocks for biofuels production. Wheat is used to produce ethanol while rapeseed (closely related to canola) is used to produce biodiesel.

Production Technologies

Petroleum feedstocks are refined into liquid transportation fuels in complex, integrated refineries. Petroleum is distilled into various fractions, which are then converted to blend stocks for gasoline, diesel, and jet fuels using a variety of catalysts and chemical reactions. Because refineries are designed and optimized to handle a particular slate of crude oils, the introduction of a new feedstock, such as tar sand oils, can require significant refinery modifications.

Natural gas generally requires extensive cleanup by removal of impurities before it can be compressed (CNG) or liquefied (LNG) for vehicular use. It can also be converted to liquid hydrocarbon fuels through "gas-to-liquids" (GTL) processes. CTL processes can also be employed, in which coal is gasified and the resulting syngas is converted to liquid fuels through chemical processes.

Biomass can be converted to liquid fuels through a variety of processes, collectively known as biorefining (see Figure 4). Biochemical processes use microorganisms such as yeast or bacteria to convert sugars to fuels. Ethanol, used primarily today as a gasoline oxygenate, is produced in this fashion. However, microorganisms are also capable of producing advanced biofuels such as higher alcohols (e.g., butanol) or hydrocarbons that are very similar to gasoline and diesel. The plant or algal oils mentioned above can be converted to biodiesel through a chemical process known as transesterification. This is being practiced at commercial scale in several countries, including the United States. Alternatively, these oils can be utilized in an existing petroleum refinery to produce a hydrocarbon fuel known as renewable diesel, or "green diesel."

Other biomass conversion processes, including gasification and pyrolysis, are collectively known as thermochemical. These processes are somewhat analogous to petroleum refining in that they involve catalytic reactions and elevated temperatures.

Most of the "biomass-to-liquid" category illustrated in Figure 3 is expected to come from these thermochemical processes.

In gasification, the resulting syngas (composed mostly of carbon monoxide and hydrogen) is converted into liquid alcohols or hydrocarbons. Biomass pyrolysis occurs at a lower temperature than gasification, in the absence of oxygen, and produces a liquid product commonly referred to as "bio-oil," or pyrolysis oil. These oils generally have poor quality and are unstable, but they can be upgraded to acceptable fuels using hydroprocessing techniques.

A recent study by the U.S. National Academies comparing CTL with other alternative fuel technologies (including corn-based ethanol, cellulosic ethanol, and biomass-to-liquids) concluded that several of these technologies are promising and that co-processing of fossil and non-fossil feedstocks might be desirable.[7]

Fuels and End Uses

Internal combustion engines propel an overwhelming majority of vehicles today, whether light-duty vehicles using gasoline or heavy-duty vehicles using diesel fuel. Alternative liquid fuels, such as alcohols, biodiesel, and renewable hydrocarbon fuels, typically are blended with their petroleum counterparts, but can also be used in higher concentrations by flexible fuel vehicles. While internal combustion engines provide good performance, they are energy inefficient compared to electric vehicle propulsion systems. Electricity, produced from any number of renewable and nonrenewable feedstocks, serves as the basis for battery-equipped electric vehicles, hybrid electric vehicles, or plug-in hybrids. Hydrogen or methanol fuel cells are not currently used in the commercial transport sector, but could be in the future.

Interdisciplinary Evaluation of Alternative Fuel Options

Determining the suitability of any fuel choice requires evaluating its entire supply chain in comparison with that of other alternatives. Each link in that chain poses questions of efficacy, feasibility, and impact, all requiring specialized analysis. For example, Figure 5 illustrates a biofuel supply chain along with the related analyses that may be useful to decision-makers. Most of the component analyses identified in the lower part of the figure, and several of the full supply chain analyses identified above, were conducted as part of the regulatory impact analysis[8] for EPA's RFS2 program. We will consider the supply-chain components in sequence.

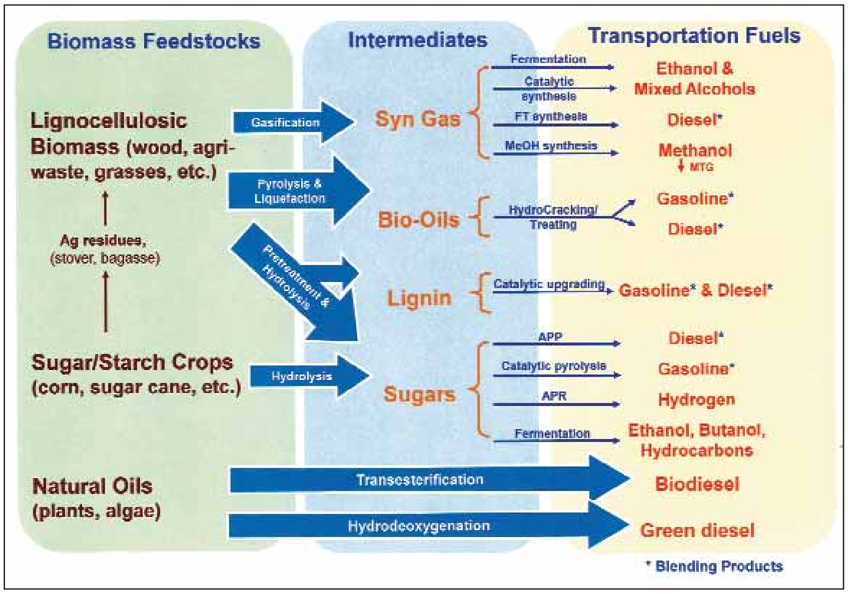


Figure 4. *The biorefining process: biomass may be converted to fuels by numerous pathways.*

Feedstock Production

Obtaining the large biomass volumes required to help meet U.S. demand appears to be feasible, although it will entail substantial changes in land use or land management.[9] Economic models exist for projecting future shifts among crops, as is needed to assess benefits and impacts. The expected expansion of U.S. corn acreage has raised concerns about potential impacts on grassland birds, fertilizer runoff to the Gulf of Mexico, and global food security. The use of cellulosic feedstocks, by contrast, would ameliorate many of these concerns, but could raise others. For example, some nonnative plants could become invasive, and invasiveness has proven difficult to predict or control. Concerns have been raised about potential GHG emissions associated with shifting land from nonagricultural use to feedstock production,[10] but methods for projecting the extent or location of these shifts are poorly developed.[11]

Feedstock Logistics

Feedstock logistics include harvesting, collection, storage, preprocessing, and transportation. Many available biomass sources, such as grasses,

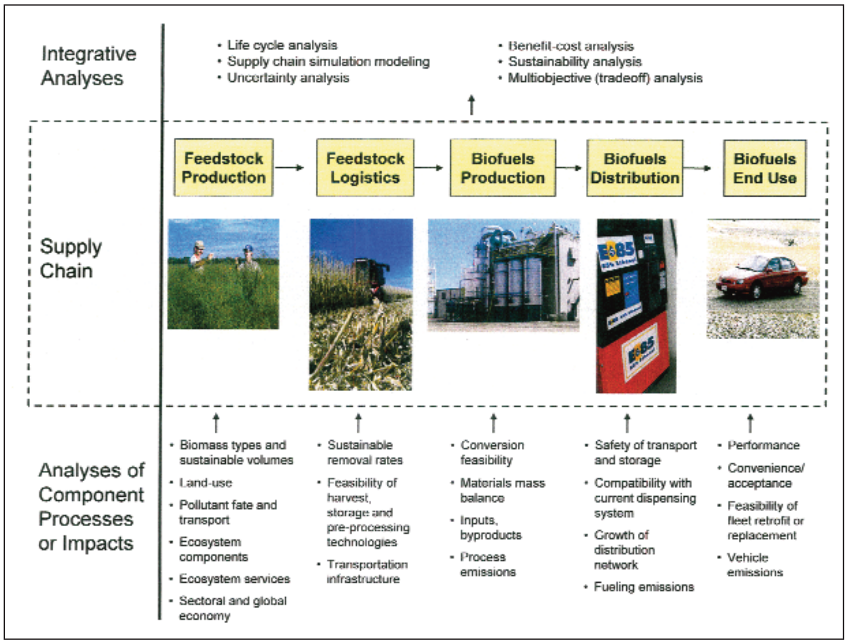


Figure 5. *Interdisciplinary analysis requirements for evaluation of transportation alternatives: biofuel example.*

Source: Modified from "Strategic Framework for Biofuels Efforts"; National Advisory Council for Environmental Policy and Technology, letter to U.S. EPA Administrator Stephen L. Johnson; U.S. Environmental Protection Agency, Washington, DC, dated July 13, 2007. Photographs are from the National Renewable Energy Laboratory PIX Library.

agricultural residues, or forest thinning, are costly to transport because they are bulky and widely dispersed. Some are produced in very large quantities during a brief season and require costly storage while demand catches up with supply. Modeling and optimization of feedstock logistics is a critical challenge for the success of any new fuel.

Fuel Production

Process design for a new fuel requires the ability to analyze specific compounds in the raw biomass, as well as in process intermediates. New chemical, spectroscopic, and electron-microscopic methods are providing researchers with powerful new tools to experiment with the deconstruction of biomass. By these methods, all aspects of the cellulosic ethanol production process have been demonstrated to be technically feasible at the laboratory and pilot-plant scales.

Commercialization of any fuel requires production processes that can be conducted year-round at a massive scale. Feasible outlets for all by-products and waste streams must also be identified. Modeling tools have been developed that allow simulation of the entire biorefinery, facilitating process design and economic analysis, although not all of the data required to fully validate these models are yet available. These tools can be applied to emerging biofuels for which technological feasibility is more uncertain. For algal biofuels, operations such as harvesting, oil extraction, lipid storage, and co-product development may determine cost-effectiveness.[12]

Fuel Distribution

Evaluation of a fuel's transportability needs to account for its unique properties. For example, ethanol's corrosivity makes it more difficult to safely store or transport by pipeline than gasoline, and its higher electrical conductivity complicates the performance of existing leak detection systems. When blended fuel is spilled, the rapid biodegradation of ethanol reduces the degradation rate of benzene, toluene, and xylene in groundwater. The potential generation of methane during the degradation process can pose a hazard to structures in which gases may accumulate. EPA is developing modeling software for assessing the fate of various fuel blends in groundwater.

Fuel Use

New fuels, and even new blends of known fuels, need to be tested with existing or new engine and vehicle systems. These tests examine materials compatibility, assess vehicle operational performance and safety, and ensure that regulatory standards are met for exhaust, evaporative, and life-cycle emissions. In addition, models of transportation, emissions, and atmospheric processes should be used to examine potential impacts on ambient air quality and human health. For example, increased ethanol combustion resulting from EPA's RFS2 rule is expected to decrease exposures to certain pollutants such as carbon monoxide, but to increase others such as acetaldehyde (a suspected human carcinogen).[5]

Whole Supply Chain

On the broader scale, models are being developed that simulate the growth of all components of the biomass supply chain. Examples include the National Renewable Energy Laboratory's biomass scenario model (BSM),[13] and EPA's augmentations of the "MARKet Allocation" energy system model framework (MARKAL).[14] Such models can be particularly useful for identifying the largest barriers to market growth and for generating feasible scenarios for which environmental and socioeconomic impacts may be assessed.

To compare impacts among fuel alternatives and to evaluate sustainability, life-cycle assessment examines impacts such as greenhouse gas emissions, water use, and fossil fuel usage over the whole supply chain. Several modeling tools are available, many of which are originally derived from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed at Argonne National Laboratory.[15] While life-cycle assessments for biofuels report a wide range of results, many biofuels are shown to have net GHG savings over conventional fossil fuels, though the magnitudes depend on the elements of the supply chain and the scale of the comparison, including whether potential indirect land-use change impacts are considered.

Thorny Issues

Finding workable solutions to the transportation fuels challenge means overcoming a number of difficult hurdles. First, several questions of feasibility need to be addressed through technological innovation. Consumer acceptance of transportation fuels demands that they be abundant, readily available and affordable, have high quality, and provide the expected performance. This presents a huge challenge to the successful introduction of new fuels.

The United States has already made an enormous investment in the infrastructure used to produce, transport, store, and market today's transportation fuels. New fuels that can be accommodated within this infrastructure, such as those that can be co-mingled with existing fuels without adversely affecting the fuel properties, will find easiest acceptance, whereas those that are incompatible with existing infrastructure will face severe challenges with respect to cost, quality control, and consumer acceptance.

Mandates and incentives can help facilitate any large-scale transition, but still must take account of public acceptance and technological progress. As evidenced by EPA's relaxation of the year-2010 target for cellulosic biofuel (from the 100 million gallons originally proposed in EISA to the 6.5 million gallons finally required in RFS2), the technologies for producing advanced biofuels are not yet fully developed and commercialized. Competitive markets for feedstocks pose an added challenge; for example, wood waste probably will not be converted to liquid biofuels, regardless of feasibility, if there is a power plant with a biomass boiler nearby.

Other hurdles are primarily informational and need to be met through research. The amounts of feedstock that can be sustainably grown and harvested without harming soils or ecosystems, the potential invasiveness of new feedstock crops, and the potential benefits of using perennial biomass crops to stabilize erodible soils, need to be investigated. The potential implications for global trade and land-use of diverting large volumes of any material from an existing use to use for fuel must also be better understood.

Improved assessments are needed that reveal trade-offs between fuel alternatives in a comprehensive way. For example, we need to employ a landscape perspective to understand where cropping changes would be most ecologically beneficial and then inform our agricultural incentive programs accordingly.

We need rapid assessment methods that can quickly examine new fuel supply chains and screen out any that are probably infeasible or have harmful consequences, so that more resources will be available for complete analysis of the more promising alternatives.

Moreover, we need to better understand the potential environmental and socio-economic impacts of increasing oil extraction in the Arctic, offshore, and in shale oil deposits. All impact assessments, especially comparisons of fuel alternatives, will require a good understanding and definition of baseline or business-as-usual conditions. And given the wide range of pathways through the biofuels supply chain, the assumptions used in any particular analysis should always be made clear.

Making Good Decisions

Fuel choices are made or influenced by individual consumers, producers, entrepreneurs, investors, and nongovernment organizations, as well as by policy-makers. Decisions made in the public interest should be based on between-fuel comparisons that examine sustainability from economic, ecological, and social perspectives. Consensus-building exercises with multiple stakeholders, and formal optimization methods, can be used to help sort out the complicated trade-offs among these objectives. The general public does not have the luxury of conducting formal analyses, but their choices will be influenced by costs that reflect incentives for various fuels, as well as by popular reports about environmental and social factors. Fuel producers can also make decisions that are economically- and environmentally-beneficial by taking advantage of the growing body of research on biofuels.

We believe that these decisions, individually and collectively, will lead to more sustainable solutions to the extent that they:

- **Favor evidence over assertions.** *Scientific methods should be rigorous and transparent, and uncertainties should be acknowledged.*
- **Consider complete fuel cycles using life-cycle assessments.**
- **Consider a broad range of potential benefits and adverse effects.** *Analyses should examine issues such as economics, employment, energy security, land-use change, food security, GHG emissions, air quality, water quality, water availability, human health, and wildlife habitat.*
- **Compare alternatives.** *Alternative fuel scenarios should be compared with business-as-usual scenarios; for example, land conversion for biofuel feedstock production might have adverse consequences, but land that is not used for biofuels may be put to another use with effects that must be compared.*
- **Consider high consequence hazards.** *The risks of mining, shipping, or drilling accidents and pipeline leaks must be included in fuel cycle comparisons.*[16]
- **Adopt best management practices.** *For biofuels feedstock production, these may include shifting from annual to perennial crops, carbon sequestration, conservation of water, and recycling,*[17] *as well as finding ways to safely utilize marginal or abandoned agricultural lands rather than prime food-producing land.*[18] **em**

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