

# The Economic Realities, Sustainable Opportunities, and Technical Promises of Biofuels

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The supply of petroleum transportation fuels appears to be increasingly finite, while demand only continues to grow. This disparate situation leaves sole dependence on petroleum as a transportation fuel unattractive for many countries, including the United States. As the United States looks to diversify its portfolio of available fuels, it has a number of emerging options. Ethanol and biodiesel have been the dominant fuels to-date, but new production methods and alternative feedstocks may bolster their suitability for wide-scale adoption. Other fuel types such as biogas and Fischer-Tropsch liquids may offer further options for countries to use to displace petroleum. This article inventories some of the emerging alternative fuel technologies and discusses the issues affecting their potential adoption.

**Key words:** biofuels, alternative fuels, innovation.

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## Forces Driving Change

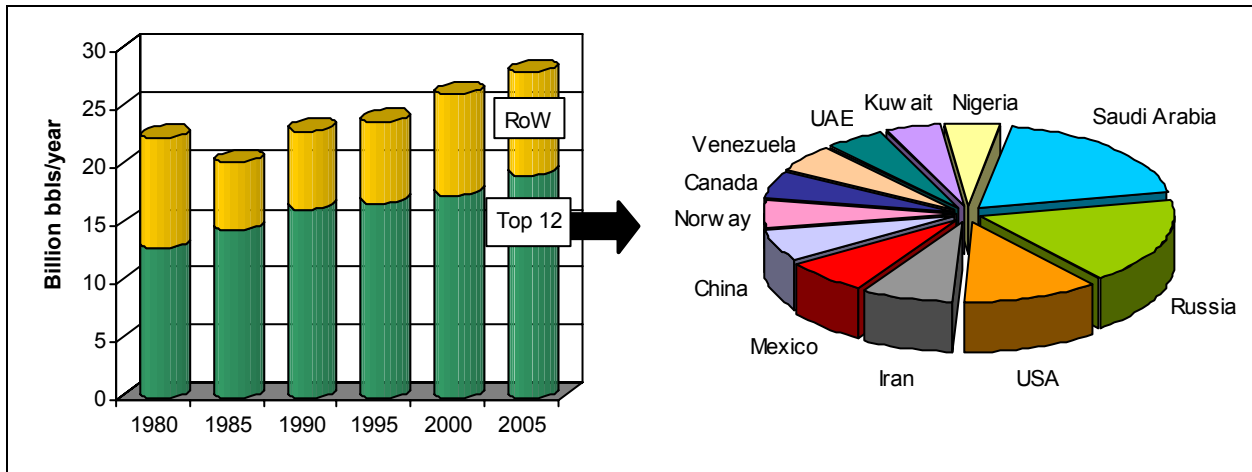
For the past 50 years, science and technology have allowed the creation of a more secure and convenient lifestyle, with high levels of mobility and convenience, within a growing economy. However, another consequence of such improvements in living standards is that we have become increasingly reliant on finite reserves of fossil fuels. In particular, crude oil is now the dominant feedstock for transportation fuels, contributes to heating energy, and provides a vast array of molecular structures for polymers, plastics, paints, chemical intermediates, and hundreds of other aids to modern life. Due to such reliance on a petro-based foundation for a large segment of the economy, we are facing increasingly intense pressure from a series of complex issues.

**Crude oil reserves are finite**, albeit with considerable debate as to the size of the recoverable reserves at an economically viable cost. Published volumes for crude oil reserves vary depending on the sources and assumptions used (United States Department of Energy [US DOE] Energy Information Administration, 2005; BP, Beyond Petroleum, 2006). There is considerable debate over proved reserves and “yet-to-be-proven” reserves, including the distinction between political volumes and physical volumes (Bentley, 2002). Irrespective of the volumetric number, the amount is finite in human time since new oil only forms in geological time-scales. For the purposes of this illustration in this article, an intermediate global reserve volume is taken as 1,200B barrels (bbls), based on the proved reserves (Figure 1) that are expected to be available using acceptable technology at economically viable costs (BP, 2006).

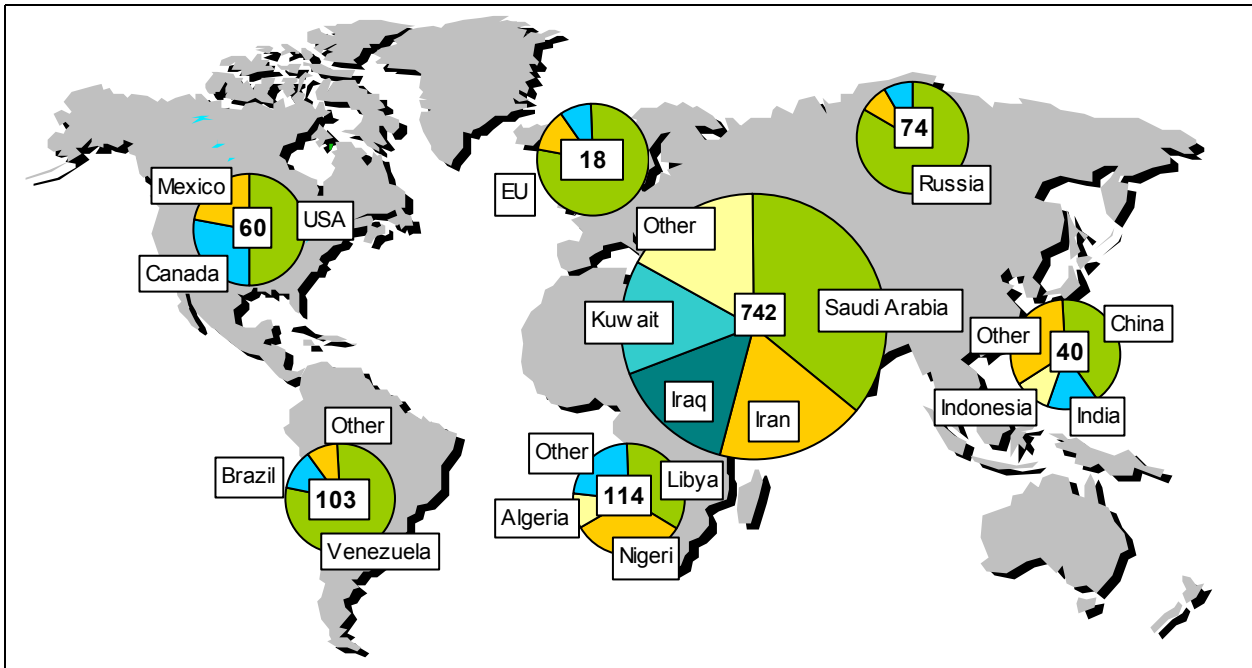
**Global production** continues to increase to meet current demand especially among the current top 12 countries, which account for 70% of the total world production (Figure 1). The production total mirrors the consumption total at approximately 30B bbls/year. On a mathematical basis, this rate of consumption will completely deplete proved reserves (1,200B reserves/30B consumption) within 40 years. In reality, this is unlikely to happen either due to additional reserves being found or, perhaps more likely, the price of oil will increase to levels where it is not economical for use in combustion engines. This sobering fact should be a large driver for discovering and developing alternatives fuels, on a global basis.

**Oil reserves are not uniformly distributed** around the globe (Figure 2) and are not located in the areas of highest utilization. For example, the United States, China, and Japan account for more than 40% of the total world consumption (BP, 2006), resulting in large volumes of crude oil being traded and redistributed on a competitive basis. The pressure on supplies will only increase as China continues to grow its economy at an unprecedented rate. Political uncertainty in the Middle-East adds additional pressure to the security of future supply for the major consumers.

**Energy intensity** is an important consideration. Decreasing the volume utilization in major consuming countries, such as Japan and the United States, is not simple and has several ramifications since these countries are engines for the global economy. Energy use and oil consumption tend to be platforms for growth and



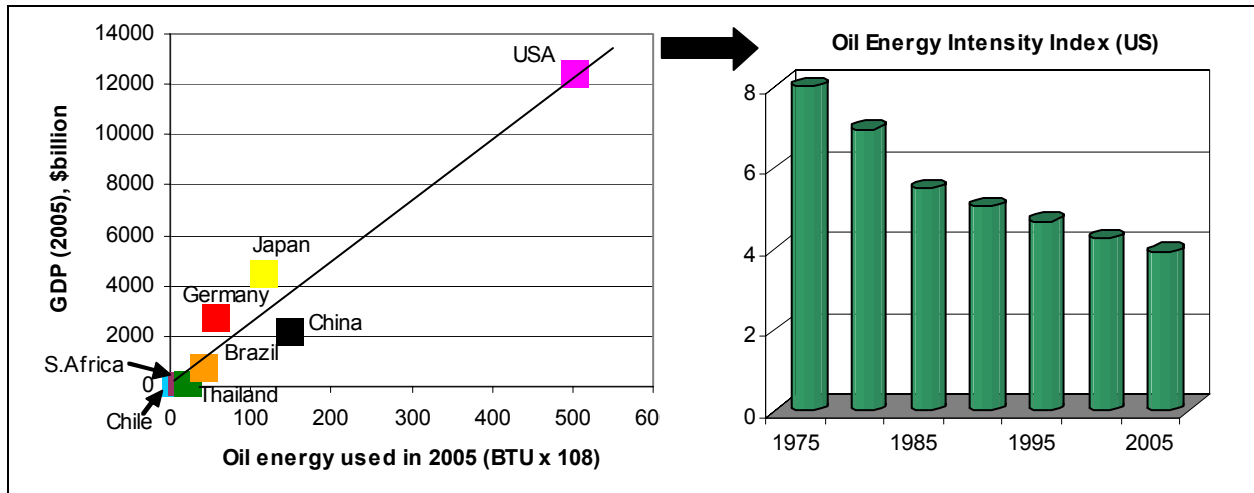
**Figure 1. Global crude oil production trends, between the current top 12 countries and the rest of the world (RoW).**  
 Note. The pie-chart shows the production split among the top 12 for the year 2005. Volume estimates were calculated from a combination of the raw data obtained from the US-EIA (US DOE, 2005a) and BP (2006).



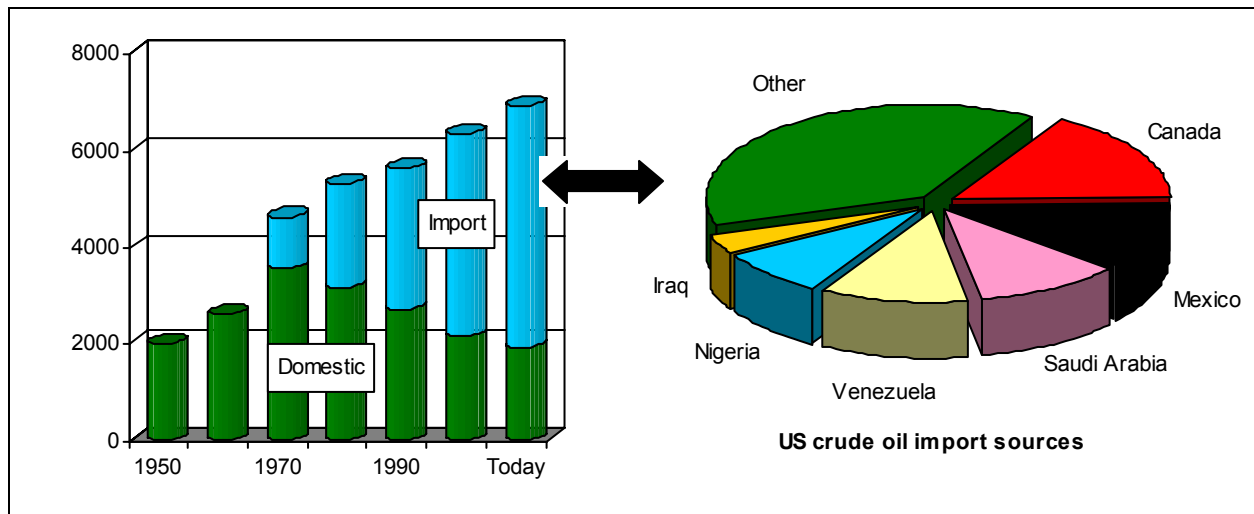
**Figure 2. Distribution of the approximately 1,200B bbls total world oil proved reserves.**  
 Note. The pie charts for each major location show the estimated proved reserve volume in billion bbls, and the proportion for the main countries is shown in the pie segments. Source: BP (2006).

productivity. Figure 3 shows that while the United States consumes much more oil energy than any country, that energy is used very effectively to generate much more national productivity. In addition, energy intensity, which is a measure of the efficiency of energy use for GDP, continues to improve in the United States.

**Security of future supply** is of particular concern to the United States, with uncertainty having potentially severe repercussions on the national economy. As mentioned above, the United States is the largest user of oil energy (albeit very effectively; see Figure 3) yet the current economically available reserves are relatively low (Figure 1). The solution to-date has been to rely on increasing imports of crude oil, of which a significant



**Figure 3. The relationship between oil energy used and gross domestic product (GDP) generated in 2005.**  
 Note. For clarity, only a selected number of countries are shown – covering the range of global values. The sub-chart shows the improvement in oil energy intensity (oil energy in 106 Btu used per unit GDP in billion dollars chained to the year 2000) for the US. The raw data used were obtained from US DOE (2005a), BP (2006), and the World Bank (n.d.).

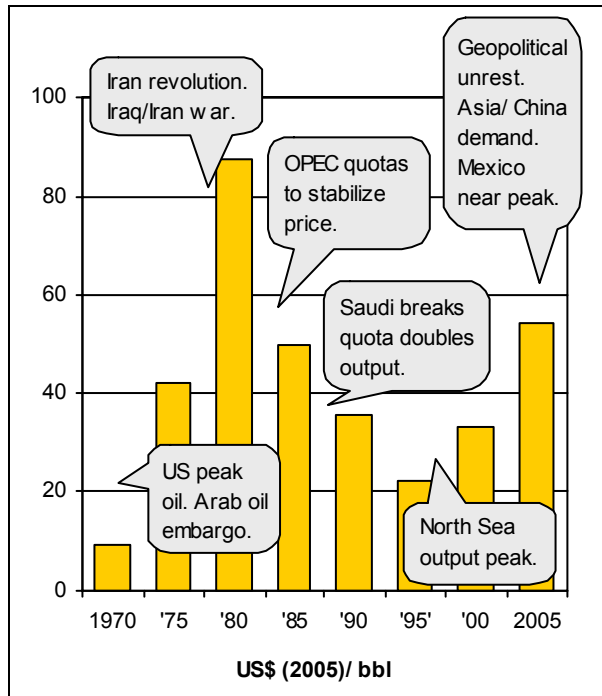


**Figure 4. US crude oil production and import volumes and sources of imports for 2005.**  
 Source: US DOE (2005a).

portion comes from politically unstable regions (Figure 4). Economic stability is also impacted by the price volatility (Figure 5), which is not expected to lessen with future intensity in competition for the limited resources available. Supply access and competitive demand are beginning to threaten global stability, as well as impacting the United States economy.

**Environmental consequences** are not entirely well-understood, but there is a growing concern around atmospheric emissions related to a more rapid extraction and utilization of the remaining crude-oil reserves. The utilization of fossil fuels results in increased carbon dioxide

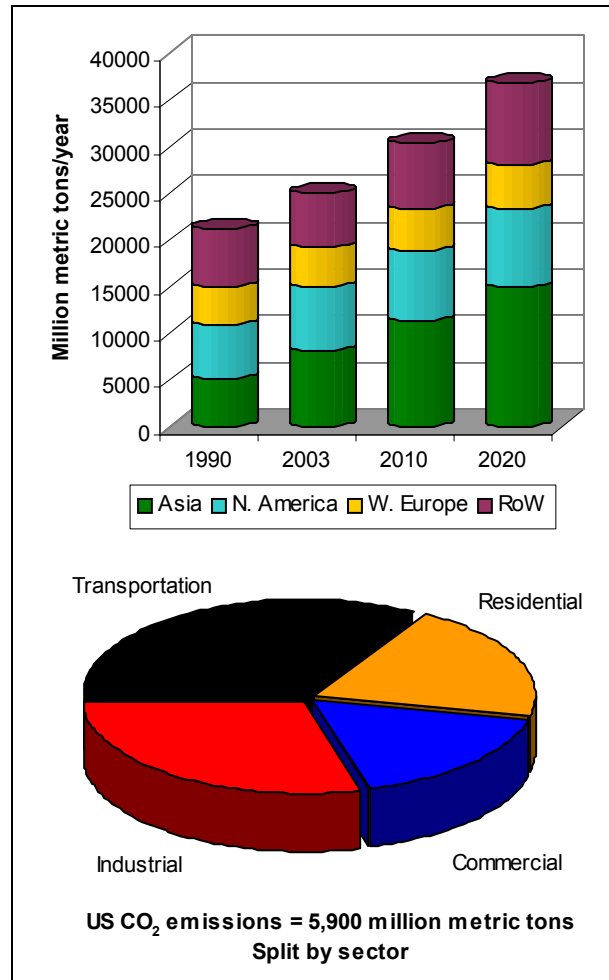
emissions to the atmosphere (Figure 6). While some uncertainty remains over global temperature effects and anthropogenic carbon dioxide (versus geological carbon dioxide or other planetary factors), there is a growing volume of evidence of some linkage to anthropogenic activities (Alley et al., 2007). Specific discussion of these issues is not presented here, except to note that carbon dioxide is increasing and is projected to increase with increased economic development which, in-turn, relies on the utilization of energy. Thus, decreasing the use of fossil fuels may lower carbon dioxide emissions, but without a compensating source of alternative energy the global economy would also crash. Additionally, the



**Figure 5. Crude oil average world price chained to 2005 dollars.**  
Source: BP (2006).

global situation is complex in that some regions are growing their economies while others have more mature, flatter growth rate economies – these situations have different consequences for energy use and carbon dioxide emissions in the future (Figure 6; cf Asia and Europe). Within the United States, the carbon dioxide emissions are found to occur across all sectors with transportation-related emissions generating about a third of the total (Figure 7). Generating a transport energy that was not based on crude oil would make a contribution to lowering the carbon dioxide emissions.

The issues discussed above and the background data (Figures 1-6) confirm the need for alternative solutions to the monopolistic use of existing fossil fuel, especially within the transportation fuels sector. On a scientific basis, several alternatives have theoretical possibilities but some are many years from practical application; for example, hydrogen can be used as an energy carrier but we have yet to develop the technology for the large-scale generation, storage, and distribution infrastructure (US DOE, n.d.A). Therefore, there is a need for near-term solutions that lead to practical, sustainable alternatives. Current biofuel systems are beginning to have an impact and, with continued improvement and the application of new technology, have the potential for significant contributions to the transport fuels sector.



**Figure 6. Emissions of carbon dioxide by world region and RoW.**  
Note. The pie-chart shows the typical breakdown of CO<sub>2</sub> emissions by sector within the US. The raw data were obtained from US DOE (2005a, 2005b).

### Target Market and Volume Requirements

The existing US transport-fuels market is very large and complex. Demand volume is currently around 140B gal/year for gasoline, and 48B gal/year for diesel (Figure 8). Given no change in the situation, the expectations are for volume demand to increase (US DOE, 2005a, 2005b).

Volume demand is a central issue in the fuels crisis. Recently, the President has called for a US national goal of “...reducing gasoline by 20% over 10 years...” (US White House, 2007). This would be a significant achievement, with volume being decreased to ~110B gal/yr instead of the projected ~155B gal/yr. Part of the decrease may come from more efficient combustion

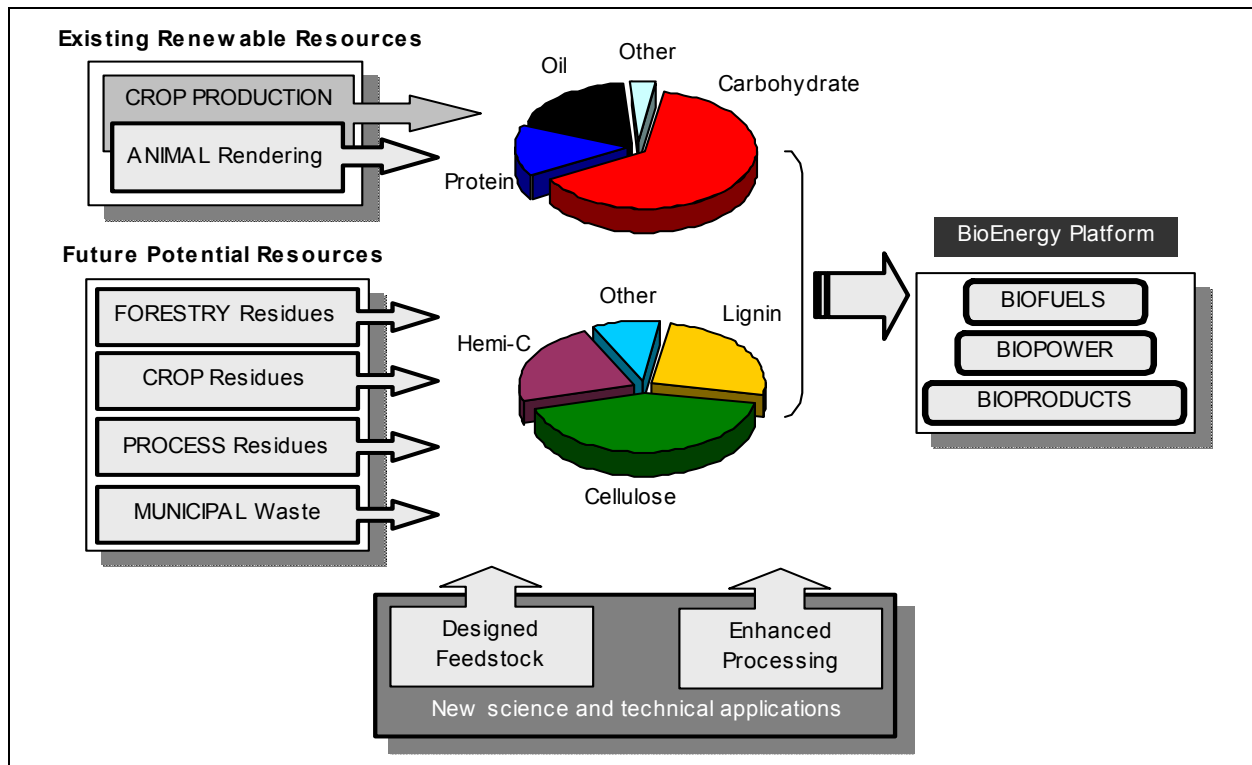


Figure 7. Outline of current and potential feed-stocks, and areas for improvement via biotechnology applications, to develop a sustainable bio-based energy platform.

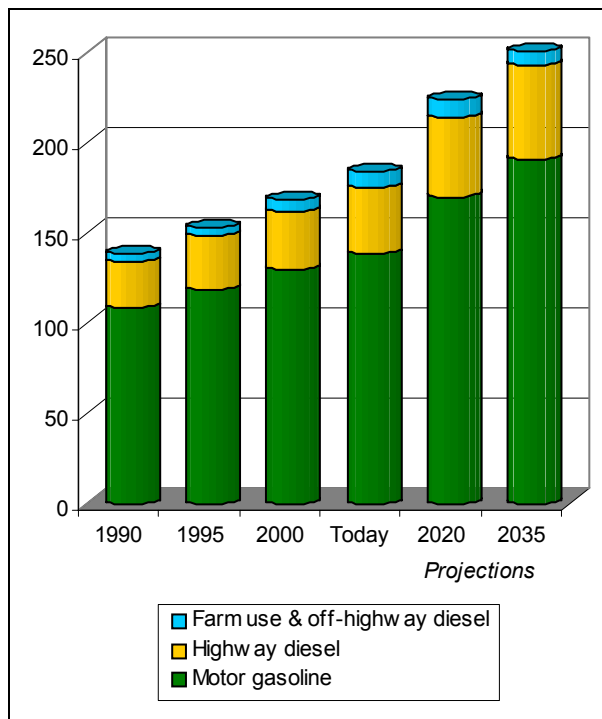


Figure 8. US transport-fuels market segments and demand trends and projections (billion gal/year).

engines and part from alternative fuels, among which biofuels are likely to make a significant contribution.

Beyond just volume demand, there are, ideally, several features required so that a fuel fits the fuel-handling and distribution systems, works optimally in modern combustion engines, and has specific environmental parameters both pre- and post-combustion. Acceptance of biofuels is a balance of economics, meeting the expected requirements and having at least one advantageous benefit.

### Current Biofuels and Benefits

There are a number of alternative fuels being explored (e.g., liquid/compressed natural gas, Fischer-Tropsch [FT] liquids) but these are not necessarily “biofuels”—a designation which typically depends on the feed-stock origin. At present, the only commercial biofuels in the transportation sector are ethanol and biodiesel. The characteristics of these fuels compared to the typical petro-analogs are shown in Table 1. For both ethanol and biodiesel, these characteristics result in certain benefits beyond just being produced from renewable bio-based feedstocks.

**Table 1. Characteristics for typical commercial conventional transport fuels and biofuels.**

	<b>Gasoline</b>	<b>Ethanol</b>	<b>Diesel #2</b>	<b>Biodiesel</b>
<b>Content</b>	C <sub>6</sub> -C <sub>12</sub> hydrocarbon	CH <sub>3</sub> CH <sub>2</sub> OH	C <sub>12</sub> -C <sub>20</sub> hydrocarbon	Methyl esters C <sub>16</sub> -C <sub>18</sub> FAs
<b>Octane*</b>	86-94	# = 100 Real: 112-115	--	--
<b>Cetane</b>	--	--	40 - 55	46 - 60
<b>Density lb/gal</b>	6.0 – 6.5	6.6	6.8 – 7.4	7.4
<b>Energy/gal LHV**</b>	115,000	76,000	130,000	120,000
<b>Source (typical type)</b>	Crude oil	Grain: Corn Biomass	Crude oil	Veg oils, fats, cooking oil
<b>Product (typical use)</b>	Gasoline formulations	Blends up to E10, E85	Diesel formulations	Blends: B2, B5, B20
<b>Value-added benefit</b>	--	<b>Oxygenate</b>	--	<b>Lubricity</b>

*Note.* \* Octane is a complex parameter, typically noted as average value of two test types and noted as (R+M)/2 on the pump: see ref. 11 for details. The octane number cannot be higher than 100 since it is defined as being relative to 100% iso-octane. The octane performance can be higher if the additive performs better than pure iso-octane. Ethanol octane "performance" is higher and varies around 112-115 depending on the denaturing agent.

\*\* Volumetric energy density is given as the lower heating value (LHV) since internal combustion engines do not have a mechanism to trap the latent heat of water (lost via tail-pipe emissions).

For ethanol, the volumetric energy density is lower than gasoline, which would mean lower mileage per gallon if all other parameters were equal. However, Table 1 also shows that the octane value of ethanol is higher than gasoline, because ethanol is an oxygenate (Hadder, 2000). The outcome is that ethanol-blended gasoline burns more effectively (acceleration improved) in high-compression engines, and is combusted more completely to give cleaner emissions. At lower-blend mixtures the oxygenate benefits of ethanol outweigh the lower energy density, resulting in about equal mileage performance.

For biodiesel (defined here as fatty-acid methyl esters [FAMES]), the energy density is lower than petrodiesel but only by ~7%, which is probably difficult to measure in practical use, especially given that the cetane value is higher for the biodiesel. Also, it should be noted that the recently required ultra-low sulfur petro-diesel leads to problems with poor lubricity. Adequate lubricity can be restored with as little as 1-2% biodiesel in the blend (National Biodiesel Board, n.d.).

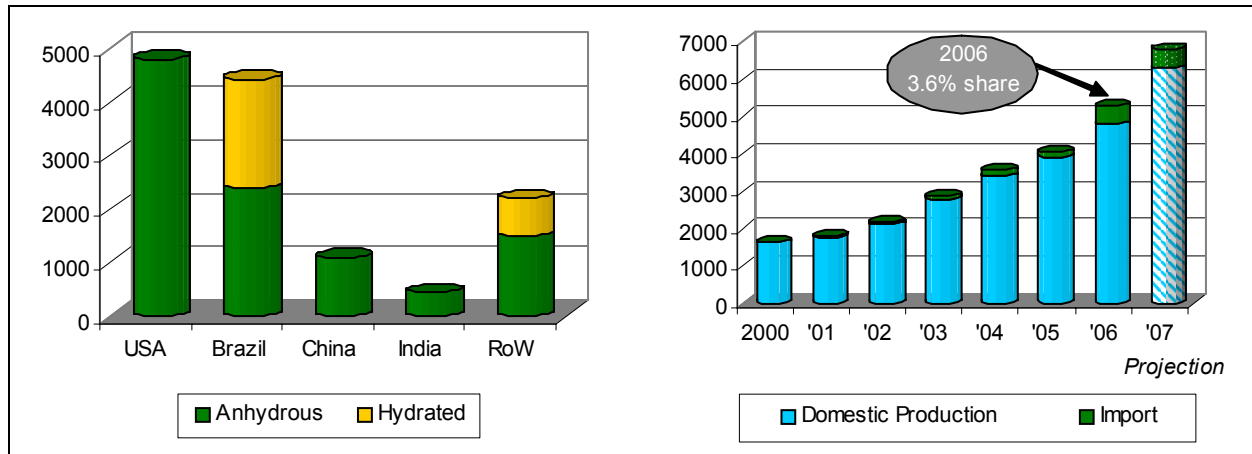
### **Ethanol**

Global ethanol production in 2006 was ~12.5B gallons, with the top countries being the United States (38% of total), Brazil (35% of total), and China following in a distant third (Figure 9). The main feedstocks for this commercial production of ethanol are cane sugar in Brazil and a mix of starch and sugar crops in other world areas. In the United States, the main feedstock is starch

arising from corn grain (~96%) and sorghum grain (~4%), with other feedstocks being less than 1%. The demand trends with production and import volumes are shown in Figure 9.

The projections are for a continued increase in ethanol production. The current capacity (2Q07) is around 5.5B gal/year, and investment in commercial facilities is underway to enable the production of over 10B gal/year by late 2008. The USDA has announced corn-planting intentions of over 90 million acres (up 12M acres from 2006). In 2006, roughly 15% of corn grain was used to produce 4.8B gallons of ethanol. An additional 12M acres should produce about 1,800M bushels of grain, which could be converted to another 5B gallons of ethanol. Thus, the feedstock supply could be capable of supporting up to 9.8B gallons for 2007, although the production capacity might not reach that until 2008.

The Congressional Energy Policy Act of 2005 established a federal mandate which was termed the Renewable Fuel Standard (RFS) and it required that consumption of biofuel should be 4B gallons in 2006, with an increase to 7.5B gallons by 2012. Clearly, the ethanol industry has succeeded in passing the biofuel goals set in 2005, and corn grain has been the driver. With continued application of new biotechnology traits to corn production, it is expected that yields will increase at an even faster rate than with previous conventional breeding (McLaren, 2005). Conservative calculations indicate that with 90M acres and the projected production gains, corn grain could easily provide the



**Figure 9. World ethanol production (million gal/year) for 2006, showing top countries and RoW (left). Production trend and imports (million gal/year) in the US (right).**

Note. In the US in 2006, 95% used as oxygenate and 5% as E85. The raw data were collected from The United States Department of Agriculture (USDA) Foreign Agricultural Service (2006), the US Department of Commerce, the Renewable Fuels Association (n.d.), and various industry sources.

starch feedstock for over 20B gallons of ethanol within 10 years and still have sufficient corn for the other existing-use segments, such as animal feed, fructose syrups, and industrial uses.

Relative to the transport fuels market, the highest-value use for ethanol is as an oxygenate in blends of around 10%. The gasoline market volume will be 110-160B gallons in 10 years—based on market demand volume (Figure 8) with a variable range related to potential success in generating improved fuel efficiency. Thus, corn grain can supply the oxygenate demand (11-16B gallons ethanol) and also be an alternative fuel for another 5-10% of the market. Building 15-20% share in the gasoline market is a major achievement and will make a substantial contribution to fuel security.

What lies beyond this level of market share for ethanol? It may be that alternative feedstocks can be developed to further grow the production. It may be that additional ethanol (beyond 20% of the total market) is not the optimum solution, and other molecules must be developed to fill the next segment needs. Some possible alternative solutions will be discussed under the “Future Potential” section.

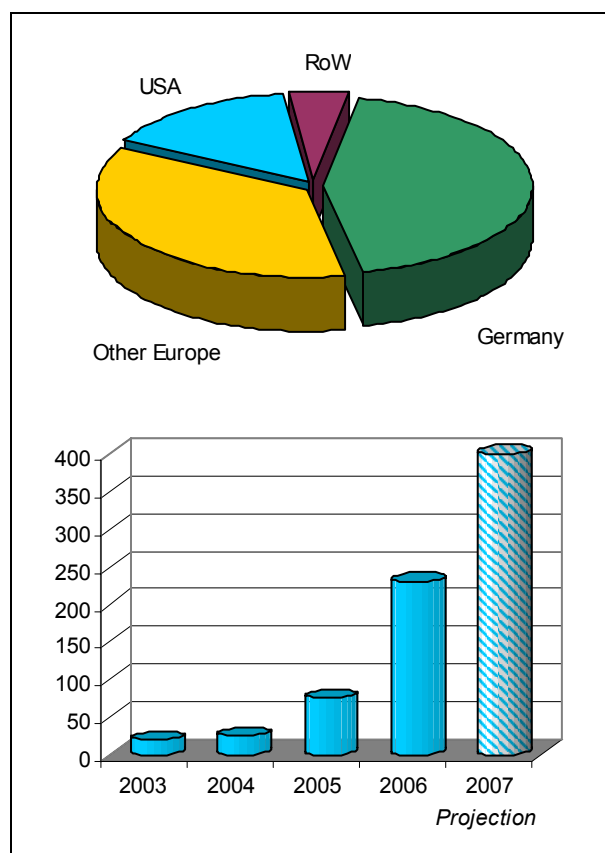
### Biodiesel

Global production of biodiesel in 2006 was ~1,490M gallons, or about 8 times lower than ethanol. The top producing countries are shown in Figure 10, and it is clear that Europe is the major producer (mostly from rapeseed oil) with a total of just over 1B gallons. The production trend in the United States has been upward

(Figure 10), but it is only in the past two years that significant increases have occurred (up to 230M gallons in 2006).

A major drawback for US biodiesel is that soybean oil has been highly successful in the edible oil market, resulting in very low excess production and a price that cannot be sustained by utilization for biodiesel alone. With soybean oil at \$0.32/lb, the feedstock cost alone is \$2.37/gallon biodiesel. The benefits of biodiesel, such as lubricity (Knothe & Steidley, 2005) and lower tail-pipe emissions (Knothe, 2006), may be worth the extra cost but that remains to be determined by a free market. The current biodiesel production is supported by the federal government via the American Jobs Creation Act and the Energy Policy Act of 2005 (EPACT 2005, #1344, Title XIII, Subtitle D), resulting in a tax credit valued at \$1.00/gallon.

There are options to enhance the production system for biodiesel. One is to utilize lipids other than soyoil, such as rendered animal fat and recycled cooking oils (Wyatt, Hess, Foglia, Haas, & Marmer, 2005). The feedstock costs are typically much lower, although additional cleaning costs and the removal of free fatty acids may be required (Kotrba, 2006). Also, animal fats tend to have fatty acids that are more saturated and, therefore, are more likely to generate cold-temperature problems with the fuel, unless pour-point depressants are added. Another option is to apply biotechnology tools to soybeans to increase the oil content of the seed, from the current ~22% up to ~45%. Several crops, such as sunflowers and peanuts, have oil contents over 40% so this may be biologically feasible for soybeans. Doubling the



**Figure 10. Biodiesel production total for the world in 2006 (million gallons) split by main country and RoW (top). Actual production trend in the US in million gal/year (bottom).**

Note. The raw data were collected from the US Department of Commerce and various US and European industry sources.

oil production per unit of land would allow sufficient oil volume for food uses and for conversion to biodiesel. Using feedstock other than from the major oil crops (i.e., soybean, rapeseed, palm) may be another alternative and some examples are discussed in the next section.

## Future Potential on the Horizon, and Beyond

### New Biofuels

Beyond ethanol and current biodiesel (FAMES), there are several possible biofuel compounds or formulations. Each has advantages and disadvantages in production, processing, distribution, environmental impact, or combustion performance. The possibilities of specific interest are discussed below.

**Butanol.** Good energy density, good vapor pressure, low water adsorption, produced via fermentation (Ramey & Yang, 2004), but currently the process is too costly to obtain pure butanol. DuPont and BP have a project to genetically engineer a microorganism to more efficiently produce relatively pure butanol. To test the product, a pilot production facility is running in the United Kingdom and the companies are planning on introducing butanol to the United States within the next few years (DuPont & BP, n.d.).

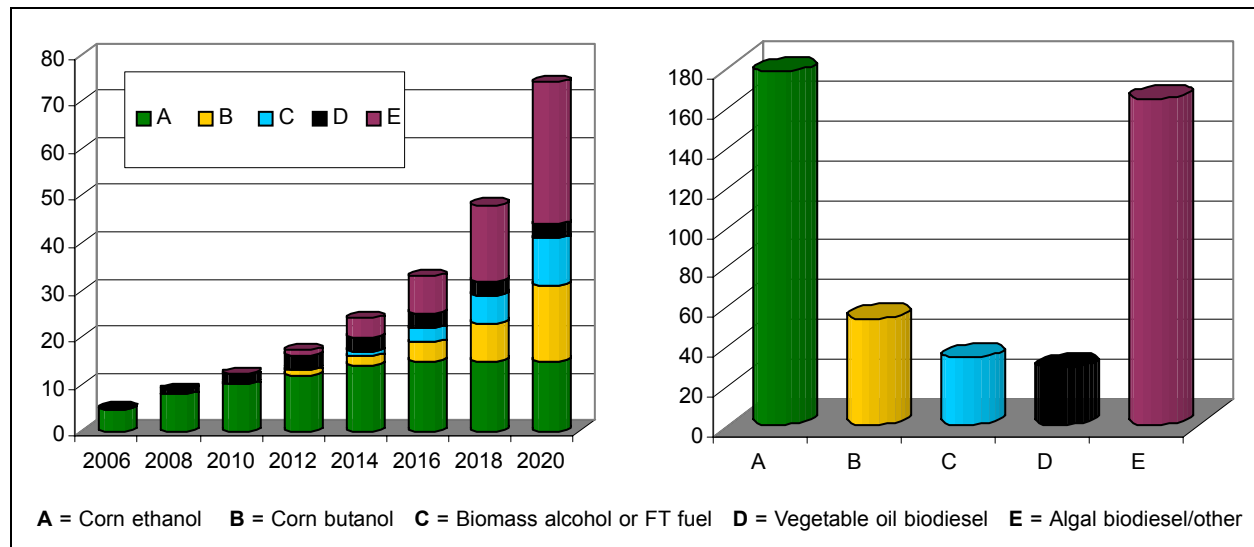
**Mixed Alcohols.** A mixture of microorganisms can be used to biologically digest biomass into a number of compounds, including carboxylic acids (e.g., acetic, propionic, and butyric). These acids can be subsequently converted to the corresponding alcohols (e.g., ethanol, propanol, and butanol). The system requires careful control of pH, and would involve massive amounts of biomass digested in “silage-like” piles. The process has been demonstrated at a pilot-scale level (Holtzapfel et al., 1999).

**Biogas (Methane).** Generated from anaerobic conversion of waste residues. In existing systems, the methane produced is typically combusted in a furnace to produce heat or steam. If liquefied natural gas were to become more common as a transport fuel, this source of methane would be a potential contributor.

**Fischer-Tropsch Liquids.** FT liquids can be generated from the catalytic conversion of syngas (carbon monoxide and hydrogen), which arises from gasification of solid material, such as biomass (Fischer-Tropsch, n.d.). The systems are also called BTL (biomass-to-liquid) and are essentially similar to the coal-to-liquid fuel gasification approach. FT liquids can be used directly in diesel engines. Alcohols and other types of synthetic fuels can be made from syngas depending on the catalytic process applied. The main hurdles, to-date, have been high capital cost and the need for improved catalysts.

It can also be expected that additional molecules will be selected and/or designed as future fuels. These will address the marketplace needs and will carry improved features to provide an overall advantage with longer-term benefits to the consumer. Such “sustainability” will include factors such as high-quality performance, being constantly and consistently renewable, economically viable, and environmentally acceptable.





**Figure 11. Realistic scenario based on current technology trends and potential in biofuels.**

Note. Over the next 15 years, several different feedstocks and fuel types will contribute, and at different times. Left chart units are B gal/year; right chart units are cumulative B gallons from 2006 to 2020.

### Feedstocks and Processing

Due to being renewable on an annual basis, feedstock resources generated by agricultural production methods are an attractive foundation for the development of a future bioenergy platform (Figure 7). Crops such as corn and soybeans, as well as animal processing residues, are being successfully used for biofuels today. However, there remains considerable potential for improvements in the processing methods and the types of feedstocks used.

New processing methods are continually explored, evaluated, and developed. In the corn ethanol industry, the rate of new capital inflow for new facilities allows a relatively rapid introduction of new technology. For example, fractionation technologies (Jessen, 2006), where the grain components are separated prior to various processes, are being applied to corn grain processing that change the dynamics of sustainability in several ways. There are additional advantages of matching a particular-designed corn composition with a particular-designed type of fractionation to elevate the portfolio of products, and the overall economic benefits—e.g., this approach is being developed with elevated-amino-acid corn and fractionation technology (Renessen, n.d.). The outcome of these types of approaches is that ethanol production efficiency and the quality of feed generated are both improved.

Other process improvements include a range of new enzymes for the liquefaction/starch breakdown step in ethanol production. For example, there are thermotoler-

ant amylase enzymes, discovered in organisms from deep-sea thermal vents and further improved via protein engineering (Ethanol Producer Magazine, 2005), being introduced to the ethanol industry. In another approach that allows lower heating energy costs at the front-end, enzymes that degrade starch directly from the granular form are being introduced (Galvez, 2005).

Within the existing crop feedstocks, considerable improvement is being gained due to the application of biotechnology. While a major advantage of an agricultural feedstock production system is that it is powered by solar energy, the natural level of energy trapping and conversion is very low (~2-4% incident radiation energy is captured). Beyond just overall biomass growth, composition of the harvested material is typically under genetic control and can have a large impact on the conversion to biofuel (Wu et al., 2007). Transgenic improvements in the overall photosynthetic efficiency of crop production, better crop protection traits, and enhanced composition of the harvestable parts are all in various stages of the development pipeline today. The first biotechnology applications have already moved the corn yield curve upwards (McLaren, 2005), and new traits from genomics projects will allow even further improvements (McLaren, 2006). The upside ceiling for yield improvement is difficult to predict, but, from the traits already on the horizon, it seems that the average corn grain yield will be at least double what it is today—and be combined with enhanced compositional traits for enhanced processing, and value in the utilization portfo-

lio. Similar improvements are likely to also occur in the major oil crops, such as soybeans and rapeseed.

The future contribution required from biofuels is of such a magnitude that existing crops (many of which are developing improvements) and additional sources of feedstock will be required (McLaren, 2006). At present, lignocellulose is being considered as a possible major feedstock resource for the future. Published calculations indicate that the US potential for total biomass (lignocellulose from crop stover, forestry, dedicated crops, plus existing crop grains and oils) could be in the order of 1.3B tons (Perlack et al., 2005). Lignocellulose has very high potential and, at theoretical rates of conversion of 85 gal ethanol/ton, could provide biofuels for ~65% of the transport fuel market. Unfortunately, the handling of such volumes of biomass and the technical operation of the conversion are not commercially viable today, but a significant amount of research (more than \$500M/year) is being funded in order to find the breakthroughs required to move lignocellulose forward as a viable feedstock (US DOE, n.d.B).

The research focused on a potential lignocellulose system is targeted at resolution of commercialization barriers in several areas.

- Production projections for lignocellulose include the concept of over 50M acres of dedicated energy crops, but it is unclear whether these crops will compete with existing crops for acres of productive land or will be able to utilize areas of lower agricultural productivity (Graham, 1994).
- If new, dedicated crops are used, there will be a need to generate cultural practice knowledge and experience, as well as crop protection programs for the massive areas to be introduced. Biotechnology applications to “dedicated” energy crops are being explored to evaluate production improvements and compositional design enhancements.
- Harvesting and handling methods (Hess et al., 2006) must be developed to allow movement and storage of massive volumes of material for conversion facility operation year-round. The possibility of a method to increase biomass density, prior to transport, is being explored since the existing infrastructure and cost system is not acceptable for the projected volume of material.

- Ethanol (or other alcohol) arises from the fermentation of glucose. Glucose can be obtained from the cellulose fraction in lignocellulosic biomass by the action of cellulase enzymes working as an enzyme complex (Himmel et al., 2007). However, the cellulose must first be separated from the matrix of other substances present in biomass. The R&D approach to-date has been to use a chemical pre-treatment to separate the lignin, hemicellulose, and cellulose. Typically, these pre-treatments are quite harsh and involve a combination of acid, heat, and pressure. Possible alternative methods are under investigation, including microbial and enzymatic methods, but the rate of action on the recalcitrant biomass remains a challenge.
- Since cellulose is only approximately 45% of the lignocellulosic biomass, the other components must be used in order to achieve any efficiency of utilization for the large volume of biomass transported to the processing facility. Lignin can be combusted for thermal energy in the facility, or gasified with perhaps FT liquids as a product. The other main component of lignocellulosic biomass is hemicellulose, which is a complex polymeric matrix of C5 sugars, such as xylose and arabinose. At a research level, organisms have been created that can use both C6 glucose-type sugars (from cellulose) and C5 arabinoxylose-type sugars (from hemicellulose) for conversion to ethanol (Potera, 2006). Some improvement in the conversion efficiency of these microbes is still required for implementation in commercial operations.

Resolution of these, and other technical and market hurdles, may come from scientific breakthroughs in the research that is already underway at many organizations. However, taking another parallel approach to the utilization of lignocellulose biomass may be prudent. For example, biomass can be used in a gasification system to produce syngas (e.g., Kavalov & Peteves, 2005, and described above). Syngas can be used to make electricity via driving a turbine and can be a source of hydrogen, or biohydrogen in this case, or can be used as the substrate for FT liquids, or other synthetic fuels. If the deconstruction route does not develop into a sustainable approach, then gasification of lignocellulose may still be a viable method for using the available biomass feedstocks.

Another concept with very high potential for a renewable feedstock is the use of algae (Sheehan, 1998). Thousands of species of algae exist, both fresh water and salt water types, and some can be metabolically altered to generate high concentrations of oil (with potential for approximately 50% w/w). There are calculated projections suggesting that an algal system, with appropriate light interception, heat controls, and fed from a carbon-dioxide-emitting process, could produce in excess of 6,000 gal biofuel/acre. If this remarkable potential were to be realized then the total US transport-fuel market could be satisfied with 25M acres of algal systems. Put into perspective, this area represents only 27% of the US area in corn today. While numerous patent applications have been filed on various photobioreactors and algal production devices, the containment, temperature control, and physical systems over 25M acres may present a considerable infrastructure challenge. The cost to develop such an infrastructure will be considerable and the investment-driven development rate will likely be a function of the rate of price increase in crude oil, and perhaps have carbon mitigation strategies as a second driver for investment.

The above overview of the future potential shows that there are multiple challenges in developing biofuel feedstocks and processes that go beyond positive results from laboratory research or theoretical computer model concepts. Taking new ideas from the research level and integrating these into a sustainable commercial practice may be the highest hurdle facing the emergence of additional biofuels; many new technical developments are driven by small start-up companies, while the biofuel challenge may require integration of technologies and consolidation of small companies.

The reality might be that new concepts take longer to develop into actual contributions (application, launch, and supporting infrastructure creation) than is currently being predicted. Experience of new product development timelines indicates that contributions from new approaches to biofuels will begin making a noticeable impact in the 10-15 years range. For example, the lignocellulosic technical hurdles are likely to take 5-8 years to resolve into investment-acceptable risk levels, and it will then take another 5-8 years to make enough investment to build a contributing infrastructure.

We have explored some realistic timelines, based on the current status of various technologies, research funding levels, and investment interest (Figure 11). This is one possible scenario where the main constraints in our model included

- Corn ethanol ceiling at 15B gallons by 2015.

- Butanol impact starts in 5 years—feedstock is initially corn, then may use other glucose inputs.
- Lignocellulose begins to impact in 6 years, which we believe is aggressive for resolution of the deconstruction approach, but we believe gasification to FT liquids will be utilized in some areas. Overall, the investment rate will be relatively slow due to transport storage and consistency uncertainties.
- Vegetable oil biodiesel is limited at 3B gallons by 2012.
- Algal systems take 4-5 years to resolve the immediate technical challenges, but then the high production rates drive relatively rapid investment in infrastructure.

Figure 11 shows the annual increase in production from each main combination of feedstock and biofuel, with a potential for over 70B gallons by 2020. A large proportion (>40%) of this volume would arise from success with an algal system, but several feedstocks and biofuels are also required to contribute. Given the first impact dates used and the volume ramp-ups projected, Figure 11 also shows the accumulated volume generated over the 2006 to 2020 timeframe. It is clear that, even with a limit placed on the upper volume produced from corn in our model, the cumulative contribution to the transport fuel market in the next 15 years or so is driven by corn ethanol. Thus, while we explore and develop new feedstocks, processes, and fuels, it may be prudent to ensure that the existing system is protected, stimulated, and managed as well as possible. The cumulative chart also shows the potential of having very high productivity on a unit basis, with lower uncertainty in consistency driving faster investment; the rate of increase provides a potential cumulative volume that almost catches the contribution from corn ethanol by 2020. The point is not that this scenario is real, but to use the outcomes (Figure 11) to highlight that we need several contributing systems for biofuels and that attention should be given to both the existing productive systems and a selection of future potential approaches. Ultimately, the time taken to reach a particular volume will be determined in part by the research results but also by the demand for alternatives; this, in turn, will be a function of crude oil prices combined with how the public values security and environmental stability.

Science and technology has provided viable solutions for progress over several hundred years now, and we can reasonably expect to overcome the existing technical hurdles to a biofuel future. It seems timely that, as

we embark into the 21<sup>st</sup> Century, biotechnology and related sciences are becoming an exciting platform that will support progress for the next 50-100 years. Biotechnology is based on tools and mechanisms that nature already utilizes. When applied in appropriate ways, the results can be beneficial for everyone. We only require the scientific capability to understand, optimize, and apply the existing rules of nature—and the political insight—to avoid romantic ideology that detracts from generating the best pathway to true sustainability.

If there can be a long-range plan for the future of mankind, then we should be setting the directions for that now. Surely the capture and utilization of solar energy (still free) must be a major foundation and, thus, the role of photosynthetic plants will be a central theme. The plan should call for the integration of the opportunities of biotechnology to generate large societal benefits via an affordable food supply, adequate renewable bioresources, economically viable bioprocessing systems, and consumer-friendly “performance” materials and products, all combined with a smaller anthropogenic footprint on the environment.

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