Biodiesel is unusual among biofuels in that it is almost interchangeable with conventional diesel fuel. (In what follows, the word petrodiesel will be used to denote conventional diesel fuel.) By contrast, the performance characteristics of ethanol are very different from those of gasoline, and wood is very different from coal, but the differences between biodiesel and petrodiesel fuel are so small that under many conditions one fuel could be substituted for the other, and the user would be none the wiser.

Biodiesel is not a new discovery. Its proponents include the inventor of the diesel engine, the German engineer Rudolph Diesel (1858–1913). Inspired by the writings of Sadi Carnot, Diesel sought to invent an engine that would be optimally efficient, and his efforts led him to build the first diesel engine. Diesel was also an early proponent of biodiesel, and some of the earliest diesel engines used biodiesel fuel. In 1900, for example, a diesel engine that ran on
peanut oil was famously displayed in Paris at the World’s Fair. But despite its early start, biodiesel was quickly displaced by petrodiesel, which was cheaper and more plentiful. Interest in biodiesel did not revive until after the oil crisis of 1973. Today, the market in biodiesel is growing quickly. It is generally blended with petrodiesel fuel for use either in diesel engines or in the home heating market. (Conventional heating oil and petrodiesel fuel are interchangeable and are sometimes referred to collectively as “number 2 distillate.”) This chapter describes what biodiesel is and how it is produced. It goes on to describe the economics of the biodiesel market.

**SOME PROPERTIES OF BIODIESEL**

To appreciate the properties of biodiesel, it helps to know something about the engine in which it is used. Diesel engines, unlike
the internal combustion engines found in most automobiles, have no spark plugs. Instead, air is drawn into a cylinder, and a piston compresses the air inside the cylinder, usually between 14 and 24 times atmospheric pressure. (These are higher compression ratios than those used in internal combustion engines.) The rapid compression causes the temperature of the air inside the cylinder to increase rapidly, rising to about 1,000°F (540°C). Fuel is then injected into the cylinder. Mixed with the hot air, the fuel ignites almost instantaneously. The pressure inside the cylinder soars along with the temperature, and the piston is forced downward. It is the downward motion of the piston that performs the work.

Diesel fuel must be able to “auto-ignite” at the temperature and pressure conditions prevailing inside the engine—that is, the fuel must combust spontaneously upon injection into the cylinder. (By contrast, the fuel in internal combustion engines is ignited by a spark from the spark plug.) The design of diesel engines makes them more accommodating in terms of the fuels that they burn—Rudolph Diesel even experimented with an engine that ran on coal dust—and engineers have found that in addition to petrodiesel, a variety of oils can make acceptable fuels for ordinary unmodified commercially built diesel engines, provided that the oils are properly processed. Some of the plants whose seeds have been used as feedstock include canola (outside the United States this plant is better known as rape-seed), sunflower, peanut, mustard, soybean, coconut, and oil palm. Biodiesel has also been successfully made from used cooking oil collected from restaurants and food processing facilities.

But in order to use any of these feedstocks, the resulting oil must be processed, a fact discovered by researchers in the 1970s. The modern era of biodiesel research began during the 1970s in response to the oil crises of that decade. First, researchers in Austria at the Federal Institute of Agricultural Engineering (Bundesanstalt für Landtechnik), and later at the University of Idaho and in South Africa, began to independently tinker with the idea of producing biodiesel. They all began by simply substituting plant oil for petrodiesel. In Austria
they operated a test engine using linseed oil, in Idaho they used safflower oil, and in South Africa they used sunflower oil. The result was the same in each case: At first, the engines ran smoothly, but the fuel left deposits that accumulated inside the cylinders. These deposits eventually destroyed the engines. The unprocessed oil was, they discovered, unsuitable for modern diesel engines. In retrospect, this is not surprising, because these engines had been designed to run exclusively on petrodiesel. The researchers were left with a choice: They could change the fuel, or they could change the design of the modern diesel engine.

Analyses and experimentation soon revealed that it was much easier and cheaper to change the fuel. Plant oils can be burned in commercially-built diesel engines without causing engine damage, provided the oils are chemically altered through a process called transesterification, which involves breaking up the larger oil molecules into smaller molecules. The result is biodiesel and a coproduct called glycerin (sometimes also called glycerol or glycerine).

Although alternative processing methods exist, most biodiesel refineries continue to use transesterification to produce biodiesel because it is relatively inexpensive and technologically simple. (Transesterification, which uses significant amounts of methanol, a toxin commonly used as a solvent, is simple enough that hobbyists sometimes use the process to manufacture their own biodiesel.) The energy demands of the biodiesel refining process are modest. Adding the energy used during refining to the energy expenditures required to produce common biodiesel feedstocks and dividing the result into the heating value of biodiesel yields a fairly high net energy balance. As a consequence, and in contrast to corn-based ethanol, there is, from an energy perspective, little controversy over the wisdom of biodiesel production. Accepted estimates for the net energy balance for biodiesel indicate that it is in excess of three—that is, more than three times as much energy is obtained by burning biodiesel as is used in producing it—and the balance
is rising as production efficiencies improve. (See the section “Net Energy Balance” in chapter 4 for a more detailed discussion of how this statistic is calculated.)

As previously mentioned, when it is properly processed, biodiesel has performance characteristics that are similar, although not identical, to those of conventional petrodiesel fuel. Five characteristics of particular interest are the heating value of biodiesel, biodiesel emissions, its cetane number (defined later), its pour point, which is the temperature at which biodiesel ceases to flow, and its lubricity, which is a measure of biodiesel’s value as a lubricant.

The heating value of biodiesel is comparable with that of petrodiesel. The lower heating values are 118,200 Btu per gallon (32.94 MJ/l) for biodiesel and 120,100 Btu per gallon (35.98 MJ/l) for petrodiesel—that is, the heating value of biodiesel is about 8 percent less...
than that of petrodiesel. (These values vary somewhat from sample to sample.)

Biodiesel greenhouse gas emissions are more difficult to calculate than those of petrodiesel. For petrodiesel, one needs to analyze the contents of the exhaust and the emissions associated with product transportation and refining. These computations are well understood and relatively straightforward, but for biodiesel such an approach would be misleading, especially with respect to greenhouse gas emissions. Growing the feedstock from which biodiesel is produced removes carbon dioxide from the air, just as burning the resulting fuel releases the carbon dioxide. It might seem, therefore, that between growing the feedstock and burning the biodiesel the net addition of greenhouse gases is zero, but while this is an oft-repeated claim, it is not correct. There are substantial greenhouse gas emissions associated with raising the biodiesel feedstock, harvesting it, transporting it, and manufacturing the fuel, and these should all be taken into account. Estimates for greenhouse gas emissions across the biodiesel production process, although they trend in the same general direction, are not uniform. These estimates are further clouded by uncertainties about current industry averages. That said, the U.S. Environmental Protection Agency estimates that across the “life cycle” of biodiesel—that is, greenhouse gas absorptions and emissions from production through consumption—net greenhouse gas emissions are reduced, relative to those of petrodiesel, by about two-thirds. (By way of comparison, corn-based ethanol achieves a reduction in greenhouse gas emissions of about one-fifth relative to gasoline.)

There are, of course, other emissions to consider besides greenhouse gas emissions. Most of these other measures of the impact of burning diesel fuel favor biodiesel over petrodiesel: Burning biodiesel reduces the emission of particulate matter by approximately 55 percent relative to petrodiesel; carbon monoxide emissions are reduced 45 percent, but nitrogen oxide emissions increase slightly (about 5 percent) when biodiesel is burned instead of petrodiesel.
(Nitrogen oxides are molecules produced during combustion, and they have a number of deleterious effects. Perhaps the most important are that they contribute to acid rain, and they contribute to the formation of ozone at ground level. Although ozone has environmental benefits when it forms high in the atmosphere, at ground level it can cause respiratory problems.)

It is important to keep in mind that these comparisons between pure biodiesel fuel and pure petrodiesel fuel represent laboratory tests. In fact, almost all biodiesel is consumed in petrodiesel-biodiesel blends in which the biodiesel component is 5 percent or less. In practice, therefore, the combustion of biodiesel results in very small changes in emissions because they are burned in fuel blends that consist almost entirely of petrodiesel. The same remark holds for all other properties considered in the chapter, except for lubricity, which is discussed later in this section. Differences between biodiesel and petrodiesel—even when they seem large in the abstract—generally make for very small differences in practice because of the highly dilute nature of the blends in which biodiesel is used.

Cetane number is a measure of the auto-ignition properties of a diesel engine fuel. All other things being equal, a higher cetane number indicates better fuel performance. For petrodiesel, cetane numbers vary from the low 40s in the United States to the middle 50s in Europe. For biodiesel, the cetane numbers vary from the high 40s to the high 50s.

The pour point for biodiesel, the temperature at which the fuel is no longer able to be pumped, presents a challenge for those using biodiesel in colder climates. The pour point for biodiesel fuel is higher than that of petrodiesel. This means that as temperatures fall, the fuel will thicken until it ceases to flow. It is not possible to give a single pour point for biodiesel, because the pour point depends somewhat on the feedstock used to produce a particular sample of biodiesel. Nonetheless, in all common types of biodiesel, pour points are higher than those for petrodiesel, which generally has a pour point of between -40°F and -30°F (-40°C to -34°C).
Biodiesel clouding up. Biodiesel ceases to flow at much higher temperatures than petrodiesel. (USDA ARS)
points for pure biodiesel samples generally are fairly close to the freezing point of water.

The final property of biodiesel discussed in this section is the lubricity of the fuel. Diesel engine fuel is also used as a source of lubrication for diesel engine fuel pumps. Biodiesel has somewhat better lubricity than low-sulfur petrodiesel fuel, long the standard fuel for diesel engines, but the difference was not large enough to affect consumption patterns. But low-sulfur petrodiesel has recently been phased out in favor of ultralow–sulfur petrodiesel, which has poor lubricity properties. By adding small amounts of biodiesel (1 to 5 percent by volume) to ultralow–sulfur fuel, the lubricity of the resulting blend is markedly improved. The demand for biodiesel is largely centered on the production of these low percentage blends.

THE BIODIESEL MARKET: DEMAND AND SUPPLY

Because some of the fundamental properties of biodiesel depend on the feedstock—the pour point and cetane number, for example—it might appear that there is not one biodiesel fuel but many. Differences in performance are, however, generally small. The real importance of the feedstock lies in its effect on costs, both economic and environmental. In the United States, most biodiesel is produced from soybeans. The reasons for this are largely historical.

In the early 1990s, there was only a small market for soybean oil in the United States, but there was a large market for other soybean products, particularly soybean protein for animal feed. As a consequence, there was a surplus of soybean oil. It was also at about this time that the first Gulf War caused a spike in energy prices. United States soybean farmers quickly identified the business opportunity created by simultaneously high petrodiesel prices and a large soybean oil surplus and organized to take advantage of it. To be clear, United States soybean farmers were not the first to create a biodiesel market—the European Union was the first to create a
booming biodiesel market—but these early efforts by U.S. farmers were responsible for the U.S. market.

In 1992, farmers formed the National Soy Diesel Development Board, which, two years later, was renamed the National Biodiesel Board (NBB). Growth was slow at first—output was only one-half million gallons (1.9 million l) by 1999—but the NBB successfully lobbied for government subsidies, and beginning in fiscal year 2000, the USDA began a program called the Commodity Credit Corporation Bioenergy Program with the goal of encouraging biodiesel (and ethanol) production. The program had a positive effect on biodiesel production because it offered generous cash payments to producers. By 2006, the year the program was slated to expire, the market had grown to about 245 million gallons (927 million l), a 490-fold increase. In addition to the cash payments, a one dollar per gallon biodiesel tax credit remained in effect until 2008 under the Energy Policy Act of 2005. But these types of incentives also indicate problems with the biodiesel market. If biodiesel were truly competitive with petrodiesel, the incentives would not be necessary.

The choice of biodiesel feedstock is important for two reasons. First, biodiesel is expensive to produce, and the main cost is the feedstock. Currently, the cheapest biodiesel is produced from yellow grease, a material produced by food processors and restaurants. But it is not possible to run a nation’s fleet of trucks on its supply of yellow grease. There is not enough of it. In the United States, estimates indicate that probably no more than 100 million gallons of biodiesel can be produced each year from yellow grease. For purposes of comparison, this is a small fraction of 1 percent of the U.S. diesel fuel market. Although soybeans remain the principal feedstock for the production of biodiesel in the United States, other nations use other feedstocks to supply their markets. No matter which feedstock is used, it remains true that at present no one knows how to make inexpensive biodiesel.

Despite the costs, governments worldwide continue to encourage biodiesel production and consumption through generous subsidies.
These subsidies are easy to maintain as long as the market does not become too large, but as consumption rises, the costs of biodiesel subsidies rise proportionately. The United States has not yet reached a point where the subsidies are so large that they are perceived as a large drain on the budget.

Another way to compare feedstocks is on the basis of how much biodiesel is produced per acre of land cultivated. This is an especially important statistic if the policy goal is to replace significant amounts of petroleum with alternative fuels. For example, the U.S. market in number 2 distillate, the term used to collectively describe petrodiesel and home heating oil, is very large relative to the yearly production of the nation’s biodiesel producers. In fact, biodiesel consumption remains at less than 1 percent of the total market. If, therefore, biodiesel production is to displace a large percentage of the number 2 distillate, it will require a very large shift in agricultural resources. One way to measure the shift is to calculate the amount of land needed to grow the necessary feedstock. The figures are daunting.

Soybeans yield only about 48 gallons of biodiesel per acre (450 l/ha). At that yield, there is not enough land in the United States to produce enough biodiesel to significantly change consumption patterns. This is not to suggest that soybeans should not be used to produce biodiesel. Soybeans were an important crop before the advent of the biodiesel market—soy protein is what made soybeans valuable originally, and soybeans remain important today for the same reason, as an excellent source of protein. Under these circumstances, the production of biodiesel as a soybean coproduct is efficient and profitable, but it is unrealistic to expect more than a small contribution to the diesel fuel market from soybean producers. The potential biodiesel market is simply too large to supply using soybean-based biodiesel.

The United States biodiesel market will, for the foreseeable future, be severely limited by the supply of biodiesel. In fact, it is mis-

(continues on page 94)
Biodiesel from Algae

One of the problems of biodiesel is that the production of large volumes of the fuel currently requires the use of large tracts of land. It is, in that sense, inefficient. Soybeans, for example, which comprise the main source of biodiesel fuel in the United States, produce only about 48 gallons of oil per acre (450 l/ha). This is a very low-density fuel source in the sense that if the soybean-based biodiesel obtained from a plot of land were spread uniformly across the plot on which the feedstock used in its production was grown, the oil would form a film about 0.002 inches (0.005 cm) thick. There is, however, at least in theory, an alternative that would completely change the biodiesel equation: the production of biodiesel from certain varieties of algae.

There are several advantages to using algae rather than higher plants for the production of biodiesel. First, the dry weight of some species of algae is as much as 60 percent oil. By contrast, it is sometimes claimed that some higher plants are 50 percent oil, but what is meant is that the seeds of the plant are 50 percent oil by weight. But the seeds are only a small part of the plant, and a great deal of energy is needed to produce the entire plant, which, in some cases, is grown solely for the purpose of harvesting the seed. That is certainly the case in soybean production, where only the bean is harvested. (The soybean plant minus its soybeans—often called the plant residue—is left on the field to prevent erosion and minimize soil depletion.) But with respect to algae, the 60 percent means exactly that—60 percent of the dry weight of the plant is in the form of molecules that can be converted to biodiesel.

Second, algae, because of their short generational time, are more susceptible to rapid genetic modification to improve plant characteristics and so improve yields.

Third, most conventional oil crops can be harvested just once or twice each year, but algae can be harvested much more rapidly. In fact, they can be harvested almost continuously.

Finally, because the algae would be grown inside enclosed structures, operators can manipulate the environment to optimize algal yields. Some early experiments have shown, for example, that diverting carbon dioxide—rich emissions from fossil fuel plants and sewage treatment plants to beds of algae accelerates the rate at which the algae grow. Even better, the algae convert the additional carbon dioxide into additional fuel. Such a system, if it could be brought to commercial development, would reduce greenhouse gas emissions while increasing energy availability. (It should be noted, however, that this scheme, if successful, would be more important to the algae producers than the power-plant operators, because the amount of carbon dioxide produced by coal- and natural gas–fired power plants far exceeds any conceivable capacity of agricultural operations to absorb more than a tiny fraction of it.)

Estimates of the amount of oil available per acre using algae as a feedstock vary widely. They reflect uncertainty about the productivity of a complex technology that is in its earliest stages of development, but one thing that all estimates have in common is that they are greater than the amounts of oil produced by more conventional feedstocks by roughly two orders of magnitude—that is, it is estimated that algae-based production methods will yield roughly 100 times as much oil per acre. Estimates range from 5,000 gallons per acre to 20,000 gallons per acre (47,000-190,000 l/ha). With such yields, algae cultivation could produce sufficient oil to replace substantial amounts of petroleum and do so without also monopolizing impossibly large amounts of agricultural land.

Intensive research into the following problems is under way:

1. identifying the most productive algal species
2. discovering the best ways to farm algae
3. creating efficient ways to harvest, dewater, and extract the oils

These are significant challenges, but they are the types of challenges that are amenable to intensive research. No nation is wealthy enough to maintain generous biofuel subsidies indefinitely while simultaneously increasing the size of its biofuel market. Germany, home of the world’s most advanced biodiesel market, began to decrease subsidies in 2008 with the goal of treating biodiesel and petrodiesel equally by 2012. “Death by installments,” is how Karin Ratzlaff of the Association of the German Biofuel Industry described the situation. She may be right. Biodiesel producers everywhere must become more efficient.
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leading to call biodiesel a transportation fuel, because that term mischaracterizes how most biodiesel is currently used. The most common biodiesel blends are B2 and B5. (Petrodiesel-biodiesel blends are identified with the letter “B” followed by a number that represents the percentage of biodiesel in the blend. B2, B5, and B20 are, respectively, blends consisting of 2 percent biodiesel and 98 percent petrodiesel, 5 percent biodiesel and 95 percent petrodiesel, and 20 percent biodiesel and 80 percent petrodiesel.) Because of the small volumes of biodiesel currently produced, only very modest amounts of B20 can be manufactured. But when sold as B2 or B5, biodiesel has little effect on the properties of diesel fuel because it is so diluted by petrodiesel. Only the lubricity of the fuel is significantly affected by the presence of the biodiesel in B2 and B5 blends. (As mentioned previously, ultralow–sulfur petrodiesel has poor lubricity properties, and so a fuel additive must be used to increase lubricity.) Even at 2 percent by volume, there is enough biodiesel in the fuel to lubricate those parts of the engine requiring lubrication from the fuel. At 2 (or even 5) percent, the other properties of the blend are similar enough to straight petrodiesel fuel that no other significant advantages are obtained by using the blend. It is no exaggeration, therefore, to say that at the present time, and for the foreseeable future, biodiesel really functions as a fuel additive rather than as a transportation fuel. It is valuable, but it is hardly a realistic alternative to petrodiesel.

In Europe, the biodiesel market is more fully developed than in the United States. In 2006, European sales of diesel-powered passenger cars exceeded those of gasoline-powered passenger cars for the first time. In France, in particular, almost three-fourths of all cars sold during 2006 were diesel-powered. This is, therefore, a much broader market for diesel fuel than exists in the United States. Furthermore, this market has been developed in a way that encouraged the rapid growth of biodiesel feedstock, while at the same time minimizing any immediate effects on food prices. Farmers in the European Union
(EU), for example, are bound by the EU’s Common Agriculture Policy. In particular, the policy prohibits farmers from growing food or feed crops on 10 percent of their arable land. Farmers are, however, permitted to grow “industrial” crops on this land. This policy reduces the initial impact on food and feed prices caused by shifting production from food and feed to energy crops, because, at least on the set-aside land, energy crops did not initially displace any food or feed crops. Coupled with substantial production subsidies, the result was an initial period of rapid growth in energy crops, especially canola, the biodiesel feedstock of choice. Oil yields with canola are substantially higher than those for soybeans, roughly 130 gallons per acre (1,200 l/ha), more than twice that attained with soybeans.

The use of canola as a biodiesel feedstock is an efficient way to use agricultural land in temperate climes—more efficient, at least, than other feedstocks grown in temperate regions. But in tropical regions, producers prefer coconut and oil palm for feedstocks. The difference is significant because coconut and oil palm plants have yields that are much higher than their temperate counterparts. Using coconut, growers can obtain yields of about 290 gallons of oil per acre (2,700 l/ha), and oil palm can yield 635 gallons of oil per acre (5,930 l/ha), which is an enormous improvement in per-acre yield over what can be achieved in temperate regions.

As worldwide biodiesel markets grow, developing nations have begun to aggressively increase biodiesel production capacity, and most of their production is for export. The boom in tropical energy farms has generated controversy on three fronts. First, some claim that large energy crop farming operations are displacing—or at least have the potential to displace—subsistence farmers and small-scale commercial farmers. These claims have attracted a lot of attention but, at least so far, little evidence has been presented to support them. The claims may or may not be true. Without research there is no way of knowing.

A second objection to the establishment of some large-scale energy farms has to do with the conversion of forests to farmland.
Biodiesel yields in gallons per acre for a variety of crops

This objection was raised by Achim Steiner of the United Nations Environment Programme, who, in November 2007, expressed concerns about the use of fire to clear Indonesian forests in order to create farmland to grow palm oil crops. The burning of these tropical forests releases large amounts of carbon dioxide, so much carbon dioxide that it may not be possible to recoup the emissions by the production of biofuels from these same lands. Mr. Steiner sought to give his argument an economic emphasis by expressing concern that once consumers become aware of the environmental havoc caused by the forest-clearing operations, they may refuse to buy biodiesel produced from these regions.

The forest-clearing operations have, however, continued unabated. After all, consumers have demonstrated little interest in the condi-
tions under which petrodiesel is produced, and the deleterious impact of oil production on some developing nations as well as the broader environment is well documented. Given that the motivation for the establishment of these tropical energy farms in the heart of large forests is economic and not environmental, and Mr. Steiner’s objections are fundamentally environmental and not economic, it is doubtful his remarks will be heard where it matters. Regardless of the outcome of the Indonesian controversy, it is clear that developed nations must increasingly look to international markets to satisfy increased domestic demand for biodiesel. For no matter which feedstock is used (see the sidebar “Biodiesel from Algae” for the one possible exception to this statement), producing enough biodiesel to replace a large fraction of petrodiesel consumption will require staggering amounts of land, amounts that often exceed what a large developed country can dedicate to its own fuel production.

The final objection to large-scale biodiesel production—and the same arguments apply to ethanol—rests with the surging price of grains. For the poor, an increase in price is the same as a decrease in supply. Sharp increases in grain prices have occurred as biofuel production has increased sharply, but the connection between the two is not entirely clear. Fossil fuels have also increased in price simultaneously with increased biofuel production, and fossil fuel prices have also caused an increase in grain prices. Disentangling the effects of these two factors on grain prices is not easy. And changing diets have also affected demand as the standard of living in many countries has improved. When hundreds of millions of people change from eating one meal per day to eating two, the effect on demand is substantial. And as the newly affluent eat more meat, the demand for grain must increase sharply as well. (It takes roughly two units of grain to produce one unit of beef and four units of grain to produce one unit of pork.) Biofuel production must, of course, contribute to grain shortages, but the principal factors may lie elsewhere. Not enough research has been done in this area to know for sure.
There are serious issues associated with converting land from food production or from forest to energy production, and these issues will come increasingly to the fore as worldwide biodiesel production continues to increase. There is no avoiding the discussion. To balance the supply of biofuels with the potential demand will involve creating an enormous new agricultural industry. The characteristics of that industry have yet to be determined.