NATIONAL RENEWABLE ENERGY LABORATORY

The Feasibility of Producing and Using Biomass-Based Diesel and Jet Fuel in the United States

A. Milbrandt, C. Kinchin, and R. McCormick
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-6A20-58015
December 2013

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Abbreviations, Acronyms, and Definitions

ATJ	alcohol-to-jet fuel
ASTM	American Society for Testing and Materials
CAFE	Corporate Average Fuel Economy
C&D	construction and demolition
DoD	Department of Defense
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
EPA	Environmental Protection Agency
EtOH	Ethanol
FAME	fatty acid methyl esters
FOG	fats, oils, and greases
FT	Fischer Tropsch
gge	gasoline gallon equivalent
GHG	greenhouse gas
ha	hectare
HEFA	hydrogenated esters and fatty acids
IPK	iso-paraffinic kerosene
LPG	liquefied petroleum gas
mpg	miles per gallon
MSW	Municipal solid waste
PADD	Petroleum Administration for Defense District
R&D	research and development
RFS	Renewable Fuels Standard
TAG	triacylglycerol
TEA	techno-economic analysis

Executive Summary

In recent years, growing concern about U.S. dependence on oil imports and greenhouse gas (GHG) emissions has resulted in greater interest in alternative fuels that can be produced from domestic renewable feedstock. Currently, diesel and jet fuel substitutes derived from biomass material—such as crop and forest residues, dedicated energy crops, and plant oils—are receiving increasing attention.

The purpose of this study is to evaluate the technical and economic feasibility of producing and using biomass-based diesel and jet fuel in the United States. To achieve this goal, data on production, capacity, cost, market demand, and feedstock availability were gathered and analyzed. Environmental considerations and legislative climate were not evaluated here, but these factors would contribute to an important follow-up study and provide a more complete picture of the biomass-based diesel and jet fuel potential in the United States.

Some of the key findings of this study include the following:

1. It is technically feasible to produce biomass-derived diesel and jet fuel substitutes in the United States. Many conversion technology options exist. Some are commercially available or in demonstrational stage; others are still in the research and development phase.

2. Biodiesel, consisting of fatty acid methyl esters (FAME) produced from lipids (fats, oils, and greases), is currently the predominant form of biomass-based diesel. Production reached a record 1.1 billion gallons in 2011 and kept at that level in 2012. It is expected to be higher in 2013. Biodiesel blends cannot yet be considered fully “drop-in” fuels because they cannot be transported in all petroleum product pipelines. For pipelines that transport jet fuel, there is a concern that the jet fuel will be contaminated with biodiesel, making it unsuitable for use. Ongoing research aims to determine what, if any, level of FAME can be tolerated in jet fuel.

3. In comparison, the current U.S. renewable diesel and jet fuel production capacity is small, about 225 million gallons per year. These fuels can be produced from various biomass resources and through several different approaches which all target hydrocarbon products that are similar to petroleum fuels in chemical makeup, and therefore may be considered “drop-in” fuels. It is anticipated that, as “drop-in” fuels, they can be blended with petroleum diesel/jet fuel at high levels, or possibly used in neat form.

   - Renewable diesel is produced at commercial scale primarily by hydroisomerization of lipid feedstock. Currently, there are two commercial facilities utilizing this process: Dynamic Fuels, a joint venture between Syntroleum Corporation and Tyson Foods (Geismar, Louisiana) and Diamond Green Diesel, a joint venture between Valero subsidiary Diamond Alternative Energy LLC and Darling International Inc. (Norco, Louisiana).
   - A number of processes are under development for production of renewable diesel from biomass-derived sugars (corn, sugarcane, and sorghum, as well as sugars from thermochemical or biochemical depolymerization of cellulose and hemicellulose).

- Processes are also being developed for direct conversion of lignocellulosic biomass by fast pyrolysis, gasification, and other thermochemical means. The first commercial plant is operated by KiOR in Columbus, Mississippi and became operational in early 2013.

4. The costs for producing renewable diesel and jet fuel are not well known and involve a high degree of uncertainty. The process economics for these fuels is highly dependent upon the cost of the feedstock, similar to biodiesel. Additionally, variables such as plant size and co-product credits can have a significant impact on the overall production cost. Hydroisomerization of lipids is performed commercially by Dynamic Fuels and Diamond Green Diesel and internationally by Neste Oil. The KiOR technology, utilizing pyrolysis, is at an initial commercial scale. Other technology routes are not yet commercial and display a wide range of estimated costs in public sources. As these technology pathways mature and become more widespread, more specific information regarding their economics will be available, which will enable a more detailed analysis and performance comparison.

5. From a feedstock perspective, enough lignocellulosic material is projected to be available in support of the Renewable Fuels Standard (RFS) mandate of 21 billion gallons of advanced biofuels. Crop and forest residues alone could yield about 8-24 billion gallons of biomass-based diesel/jet fuel in 2022 (assuming a conversion via fast pyrolysis).This potential could be larger if the conversion technologies achieve higher yields and if additional feedstock, such as dedicated energy crops, become available. However, there will be competition for lignocellulosic feedstock with the ethanol industry and renewable gasoline producers to meet the RFS mandate. Thus, it is unclear what share the renewable diesel/jet fuel would have in the total biofuels contribution. Ultimately, it will depend on the rate of commercialization of these technologies, selling price, and the transportation market demands.

6. Based on current statistics, and proven by the biodiesel industry, there is enough lipid feedstock to support the production of 1 billion gallons of biomass-based diesel mandated by the RFS. Today, roughly half of the biodiesel in the United States is produced from soybeans. The remaining portion consists of animal fat, used cooking oil, canola, and some other minor feedstocks. While soybean production is projected to grow in coming years, the biodiesel industry hopes to achieve higher output through advanced technologies for increasing oil supply and production of new feedstock. If algal oil becomes commercially available, as projected within the next 5-10 years, it would greatly benefit both biodiesel and renewable diesel/jet fuel industries. Given the right resources, algal oil productivity can be quite high. Algae are a potential aquatic oil crop, but may also yield carbohydrates that can be converted to sugar.

7. Demand for diesel and jet fuel in the United States is projected to grow. As easily recoverable crude oil resources are diminishing and as their prices rise, more substitutes are expected to enter the market.

   - Among the diesel consumers in the country, freight trucking has the largest share. The number of light-duty vehicles using diesel is projected to increase, the rate of which will depend on the market penetration of other alternatives such as hybrid and electric vehicles.

- Jet fuel is forming as a large and profitable market for the renewable fuels industry. Success in this area could stimulate a significant increase in the production of biofuels and associated feedstock. It is expected that jet fuel consumption by commercial carriers will continue to grow over the next years, whereas jet fuel consumption by the military will remain flat.

8. For biomass-based diesel and jet fuel to be successful among the trucking and aviation companies, they must be cost-competitive with petroleum-based fuels. It is uncertain what the future holds for these substitutes, but it is expected that the next several years, as more facilities come online, will answer many questions about the economic viability of these technologies. Much will depend on the rate of recovery of U.S. and world economies, oil prices, carbon market, and political climate.

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Introduction

In recent years, growing concern about U.S. dependence on oil imports and greenhouse gas (GHG) emissions has resulted in greater interest in alternative fuels that can be produced from domestic renewable feedstock. Currently, diesel and jet fuel substitutes derived from biomass material—such as crop and forest residues, dedicated energy crops, and plant oils—are receiving increasing attention.

The purpose of this study is to evaluate the technical and economic feasibility of producing and using biomass-based diesel and jet fuel in the United States. To achieve this goal, data on production, capacity, cost, market demand, and feedstock availability were gathered and analyzed. Environmental considerations and legislative climate were not evaluated here, but these factors would contribute to an important follow-up task to provide a more complete picture of the biomass-based diesel and jet fuel potential in the United States.

Overview

The Renewable Fuel Standard (RFS), a program introduced by the Energy Independence and Security Act of 2007 (EISA), defines biomass-based diesel as follows: (a) renewable fuel made from biomass; (b) meeting the definition of either biodiesel (mono-alkyl esters) or non-ester renewable diesel; (c) with lifecycle GHG emissions at least 50% less than the diesel fuel it displaces; and (d) which excludes renewable fuel derived from co-processing biomass with a petroleum feedstock[1] (EPA 2009). The jet fuel substitutes fall under the "additional renewable fuel" category of RFS2, defined as fuel produced from renewable biomass that is used to replace or reduce fossil fuels used in home heating oil or jet fuel (EPA 2009).

There are several technologies and processes that produce biomass-based diesel and jet fuel. Some of these technologies are in commercial or pre-commercial production while others are still in the research and development phase. The different technologies use a variety of feedstocks, including lignocellulosic biomass (such as wood and crop residues, dedicated herbaceous or tree energy crops), grains, sugar crops, vegetable oil (soybean, canola/rapeseed, etc.), animal fat (beef tallow, pork lard), and waste cooking greases. Table 1 summarizes the different processes used to create biomass-based diesel and jet fuel, as well as examples of companies involved in these technologies.

Biodiesel is currently the predominant form of biomass-based diesel. It is a liquid fuel made from recycled or virgin vegetable oils and animal fats through a chemical process (transesterification, described below) to produce chemical compounds known as fatty acid methyl esters (FAME). Biodiesel is the name given to these esters when they meet specifications such as ASTM D6751 or European Norm EN14214 for use as transportation fuel. Biodiesel is used in its pure form or in blends with petroleum diesel. Blends containing up to 5% volume are considered the same as conventional diesel and are fully compatible with all engines and infrastructure. Blends containing 6-20% volume biodiesel are accepted by many engine manufactures and are compatible with underground storage tanks. Fuel dispensers and related equipment that are compatible with B6 to B20 blends are available. Biodiesel blends cannot yet

[1] The EPA considers co-processing to occur if both petroleum and biomass feedstock are processed in the same unit simultaneously.

be considered fully “drop-in” fuels because they cannot be transported in all petroleum product pipelines. For pipelines that transport jet fuel, there is a concern that the jet fuel will be contaminated with biodiesel, making it unsuitable for use. Ongoing research aims to determine what, if any, level of FAME can be tolerated in jet fuel, and in the meantime, biodiesel is being shipped on pipelines that do not transport jet fuel. A few engine manufacturers approve of the use of B100 (pure biodiesel) in some engine models.

Renewable diesel refers to diesel fuel substitutes derived from biomass sources that chemically are not esters and thus are distinct from biodiesel. Renewable diesel and jet fuel can be produced by several different approaches (Table 1), which all target hydrocarbon products that are similar to petroleum diesel/jet fuel in chemical makeup and therefore may be considered “drop-in” fuels. It is anticipated that, as “drop-in” fuels, they can be blended with petroleum diesel/jet fuel at high levels or possibly be used in neat form. They are also expected to be transportable by pipeline.

Table 1. Conversion Processes for Biomass-based Diesel and Jet Fuel

Technology	Process	Fuel Produced	Companies
Lipids (fats, oils, and greases)			
	Transesterification	Biodiesel	Imperium Renewables, Renewable Energy Group, ADM, Amerigreen Energy, Inc., Cargill Inc., Direct Fuels, etc.
	Transesterification of microalgae	Biodiesel	Cellana, Solix, Seambiotic, LiveFuels
	Hydroprocessing	Diesel, Jet Fuel	Neste Oil, Dynamic Fuels LLC, Diamond Green Diesel LLC, UOP, AltAir, Emerald Biofuels LLC, etc.
	Hydroprocessing of microalgae	Diesel, Jet Fuel	Sapphare, Solazyme
Lignocellulosic Biomass/Sugars from Cellulose			
Biochemical	Conversion of cellulose via carboxylic acid	Diesel, Jet Fuel	Terrabon
	Synthetic Biology	Diesel, Jet Fuel	Amyris, LS9, Joule
Thermochemical	Gasification/Fischer Tropsch	Diesel, Jet Fuel	Choren, Flambeau River Biofuels, ClearFuels/ Rentech, TRI, Syntroleum
Hybrid Biochemical/ Thermochemical	Syngas fermentation	Diesel, Jet Fuel	Coskata, Lanztech, INEOS Bio
	Acetic acid production and lignin gasification	Diesel, Jet Fuel	ZeaChem
Depolymerization	Catalytic depolymerization of cellulose	Diesel, Jet Fuel	Covanta, Green Power
	Pyrolysis	Diesel, Jet Fuel	Envergent (UOP/Ensyn), Dynamotive, KiOR, RTI, GTI
	Thermal depolymerization	Diesel, Jet Fuel	Changing World Technologies Inc.
Other	Catalytic reforming of sugars from cellulose	Diesel, Jet Fuel	Virent
	Alchohol-to-jet fuel	Jet Fuel	Gevo, Cobalt

Note: The list of companies in the table is shown as an example and it is not meant to be complete. Some of the listed companies (such as Terrabon and Choren) were inactive at the time of writing. However, these companies are associated with either pioneering or further developing a process, and thus, they are included in this summary for illustrative purposes.

Biodiesel from Transesterification

The process of transesterification is used for the conversion of triglycerides (the main component of vegetable oils and animal fats) to biodiesel. In this process, the feedstock is chemically reacted with an alcohol (usually methanol) in the presence of a catalyst like lye. The products are glycerin and the biodiesel fuel or FAME. These separate into a bottom glycerin layer and a top FAME layer, which can then be physically segregated.

Renewable Diesel and Jet Fuel from Hydroprocessing of Lipid Feedstocks

Renewable diesel, sometimes referred to as "green diesel" or hydrogenated esters and fatty acids (HEFA), can be produced from fatty acids (fats, oils, and greases [or FOG]) by the traditional hydroprocessing and hydroisomerization technology used in petroleum refineries. Hydroprocessing is the process of reacting feedstock with hydrogen under elevated temperatures and pressures and in the presence of a catalyst in order to remove oxygen, sulfur, and nitrogen and saturate double bonds. For processing of triglycerides, some of the oxygen can also be removed as carbon dioxide by decarboxylation in some processes (Kalnes et al. 2007). While the feedstock can be hydroprocessed as a co-feed with petroleum, in order to qualify as a renewable fuel (according to the RFS) the diesel must be produced as a dedicated feed in a stand-alone process. The products consist predominantly of isoparaffins with some residual normal paraffins (Smagala et al. 2013). The degree of isomerization can be adjusted to lower the cloud point, and it is even possible to obtain cloud point in the jet fuel range (less than -40^{o}F). However, increased isomerization reduces the cetane number and leads to increased production of naphtha as a by-product. Nevertheless, for fuels with cloud points in the diesel fuel range, the cetane number will likely be over 80.

Renewable Diesel and Jet Fuel from Cellulose via Carboxylic Acid

Terrabon, a company involved in creating renewable fuels using carboxylic acid, describes the process as follows:

> It begins by treating the feedstock with lime to enhance its digestibility, and then fermenting the biomass using a mixed-culture of microorganisms to produce a mixture of carboxylic acids. Calcium carbonate is added to the fermentation to neutralize the acids to form corresponding carboxylate salts, which are then dewatered, concentrated, dried and thermally converted to ketones. The ketones are then hydrogenated to alcohols that can be refined into renewable gasoline, diesel or jet fuel blendstocks (*Ethanol Producer Magazine* 2011, ¶ 3).

Renewable Diesel and Jet Fuel Using Synthetic Biology

Synthetic biology modifies existing biological systems or builds new systems to produce novel substances. Amyris (2012) has developed genetic engineering and screening technologies that enable modification of the way microbes process (i.e., metabolize) sugar. By controlling these metabolic pathways, Amyris is able to design microbes, primarily yeast, to be living factories that convert plant-sourced sugars from crops such as sugarcane or sweet sorghum into target molecules. Using its industrial synthetic biology platform, Amyris develops yeast strains designed to produce a broad range of molecules. Amyris's building block molecule is Biofene (an Amyris-brand farnesene), a hydrocarbon molecule that can replace petrochemicals in a wide variety of products including transportation fuels such as diesel and jet fuel.

LS9 has focused on developing renewable petroleum products using a one-step fermentation process. In July 2010, the company announced the discovery of novel genes that, when expressed in *E.coli*, produce alkanes—the primary hydrocarbon components of gasoline, diesel, and jet fuel. This discovery is the first description of the genes responsible for alkane biosynthesis and the first example of a single-step conversion of sugar-to-fuel-grade alkanes by an engineered microorganism. A spokesperson for the company describes the process as a one-step sugar-to-diesel process that does not require elevated temperatures, high pressures, toxic inorganic catalysts, hydrogen, or complex unit operations (Greentech Media 2010). Similarly, the Joule process uses optimized microorganisms that act as living catalysts to produce fuel rather than first producing biomass and later extracting lipids or sugars for a subsequent multi-step conversion into fuel (European Biofuels Technology Platform [EBTP] 2012).

Renewable Diesel and Jet Fuel from Biomass Gasification (Fischer-Tropsch)

Another process for making renewable diesel and jet fuel is converting cellulosic biomass through high-temperature gasification into synthetic gas or "syngas", a gaseous mixture rich in hydrogen and carbon monoxide. Next, a Fischer-Tropsch (FT) process is used to catalytically convert the syngas to liquid and wax products that can be refined into synthetic fuels. The production of FT liquids is a commercial technology applied to coal and natural gas.

Renewable Diesel and Jet Fuel from Syngas Fermentation

This hybrid technology is currently used to produce ethanol. However, the companies involved in this process are working on diesel/jet fuel production as well. The strategy involves the gasification of biomass to syngas before processing it into ethanol using a biochemical fermenter. Coskata (2011) describes the process: during gasification, the biomass material is converted into syngas using well-established gasification technologies. After the chemical bonds are broken in the process, Coskata's proprietary microorganisms convert the resulting syngas into ethanol by consuming the carbon monoxide (CO) and hydrogen (H2) in the gas stream. Once the gas-to-liquid conversion process has occurred, the resulting ethanol is recovered from the solution using proven distillation methods.

Renewable Diesel and Jet Fuel from Acetic Acid Production and Lignin Gasification

Similar to the hybrid process above, this technology is currently used to produce ethanol, but the company involved in this process, ZeaChem Inc., has developed a platform capable of producing other fuels as well. After fractionating the biomass, the sugar stream (both xylose [C5] and glucose [C6]) are sent to fermentation where an acetogenic process is utilized to ferment the sugars to acetic acid without CO_2 as a by-product. In comparison, traditional yeast fermentation creates one molecule of CO_2 for every molecule of ethanol. Thus, the carbon efficiency of the ZeaChem fermentation process is nearly 100% vs. 67% for yeast.

The acetic acid is converted to an ester, which can then be reacted with hydrogen to make ethanol. To get the hydrogen necessary to convert the ester to ethanol, ZeaChem takes the lignin residue from the fractionation process and gasifies it to create a hydrogen-rich syngas stream. The hydrogen is separated from the syngas and used for ester hydrogenation, and the remainder of the syngas is burned to create steam and power for the process. The net effect of combining the two processes is that about two-thirds of the energy in the ethanol comes from the sugar stream and one-third comes from the lignin steam in the form of hydrogen (ZeaChem 2011).

Renewable Diesel and Jet Fuel from Catalytic Depolymerization of Cellulose

The catalytic depolymerization process uses heat and catalysts to break long chain polymers of hydrogen, oxygen, and carbon into short-chain petroleum hydrocarbons.

> The Green Power process catalytically depolymerizes cellulosic feedstocks at moderate temperatures into liquid hydrocarbon fuels. The feedstock is first ground to a size finer than 5 mm and then placed--along with a catalyst, a low loading of lime that serves as a neutralizing agent, and a fuel that provides a liquid medium--into a reactor and heated to around 662^{o}F. In the reactor, the feedstock is catalytically converted to liquid fuels which primarily fall within the gasoline and diesel fuel boiling ranges, although these

fuels may need further upgrading. The liquid fuels are separated from any solids which are present and are distilled into typical fuel streams including naphtha, diesel fuel, kerosene, and fuel oil (EPA 2010a, p. 42261).

Renewable Diesel and Jet Fuel from Pyrolysis Oil

Another technique for producing renewable diesel uses pyrolysis, the chemical decomposition of organic materials at elevated temperatures in the absence of oxygen. During this process, large polymers (i.e., cellulose, hemicellulose, lignin, and proteins of organic waste streams) are converted into smaller molecules and produce organic vapors, gases, and a solid residue containing carbon and ash. The vapors are condensed to produce pyrolysis oil (often referred to as bio-oil) that is then refined into diesel-like fuel. Yields of raw bio-oil as high as 75% of the initial dry weight of the biomass can be achieved (PNNL 2009).

Renewable Diesel and Jet Fuel from Thermal Depolymerization

Thermal depolymerization is similar to the geological processes thought to be involved in the production of fossil fuels—except that the technological process occurs in a timeframe measured in hours. Biomass is reacted in water at elevated temperature and pressure to form oils, gases, carbons, and ash. Hydrothermal conversion temperatures are typically 570°-660°F, with pressure sufficient to keep the water primarily as liquid (100-170 atm). The resulting bio-oil could be upgraded to a hydrocarbon product consistent with gasoline and diesel. The technology is being commercialized in the United States by Changing World Technologies (CWT). The National Advanced Biofuels Consortium (NABC) is working on further developing this process. NABC's researchers have achieved bio-oil yields of about 50% on a carbon basis from two feedstocks—wood residues and corn stover (NABC 2012b).

Renewable Diesel and Jet Fuel from Catalytic Reforming of Sugars from Cellulose

Catalytic upgrading of sugars to hydrocarbons involves separating sugars from biomass (e.g., milled corn stover) through a series of chemical and biochemical processes and catalytically upgrading it into hydrocarbon fuels. The process has been researched by Virent, Inc. Virent's BioForming process integrates the company's patented aqueous phase reforming (APR) technology with conventional catalytic processes. First, the lignocellulosic biomass is pretreated, followed by enzymatic hydrolysis (saccharification) of the remaining cellulose. Next is catalytic conversion of the resulting glucose, xylose, and other solubilized carbon components to hydrocarbon fuels in the gasoline, jet, and diesel fuel ranges (Biddy and Jones 2013).

Alcohol-to-Jet Fuel

Alcohol-to-jet fuel (ATJ) converts short carbon chain alcohols (such as methanol, ethanol, and butanol) to the longer C12/C16 alkanes of jet kerosene. The alcohol is produced conventionally (sugar/starch fermentation), thermochemically (e.g., gasification with upgrading), or through other pathways (industrial microbiology and algae). Several companies are exploring ATJ pathways, including Gevo and Cobalt. Gevo has developed a proprietary integrated fermentation technology (GIFT) consisting of a yeast biocatalyst that converts sugars into isobutanol. The alcohol is then converted into iso-paraffinic kerosene (IPK), a blendstock used in jet fuel, via additional reactions such as dehydration, oligomerization, hydrogenation, and distillation (Gevo 2011). Similarly, Cobalt has developed its own process for extracting sugars from biomass and converting them directly into bio n-butanol, a platform molecule for the production of a broad array of fuels and chemicals, including jet fuel (Cobalt 2013).

Capacity and Production

Current U.S. biodiesel production capacity is more than 1.8 billion gallons, with about 160 plants registered with the Environmental Protection Agency (EPA) under the RFS program (*Soybean Review* 2011). The industry struggled in 2010 due to increased feedstock prices and the expiration of a key $1.00/gallon blender tax credit at the beginning of the year. According to the Energy Information Administration (EIA), biodiesel production decreased from 678 million gallons (Mgal) in 2008 to 343 Mgal in 2010 (EIA 2012a). The revised RFS (RFS2, initiated in July 2010) mandates the blending of 1 billion gallons per year of biomass-based diesel; biodiesel produced from soybean oil, animal fat, waste grease, and several other feedstocks qualifies for meeting this mandate. Driven by the RFS2 mandate and reinstatement of the $1/gallon blender tax credit, biodiesel production reached a record 1.1 billion gallons in 2011, kept that level in 2012, and it is expected to be higher in 2013 (EPA 2013a).

In comparison, the current U.S. renewable diesel and jet fuel production capacity is small, about 225 million gallons per year (Mgy) (*Biofuels Digest* 2012, KiOR 2013). The industry is just starting out and most of the facilities are at pilot/demonstration scale, under construction, or in planning phase. At the time of writing, there were three commercial facilities as described below.

Dynamic Fuels, a 50/50 joint venture between Syntroleum Corporation and Tyson Foods is located in Geismar, Louisiana. The facility has a capacity of 75 Mgy and became operational in November 2010. The plant uses animal fats, greases, and vegetable oils as feedstock. In the summer of 2011, Syntroleum announced that Dynamic Fuels achieved a record production of renewable fuels, about 87% of plant's capacity (Syntroleum 2011). High production level (71% of plant's capacity) was kept in 2012 as well (*The City Wire* 2013a). However, the plant was idled in November 2012 because of deteriorating market conditions and the partners opted for replacement of a catalyst in the facility that would increase production efficiency. That catalyst was installed in June 2013 but the plant still remains idle today, mainly because the partners can't reach amicable restart terms (*The City Wire* 2013b).

KiOR's production facility in Columbus, Mississippi became operational in early 2013. It uses woody biomass as feedstock and has 13 Mgy capacity (KiOR 2013). Given that the facility produces both renewable gasoline and diesel, it is unknown at this time the share of renewable diesel in the final output.

Diamond Green Diesel, a joint venture between Valero subsidiary Diamond Alternative Energy LLC and Darling International Inc. is located in Norco, Louisiana. The facility has a capacity of 137 Mgy and became operational in the summer of 2013. The plant uses recycled animal fat and used cooking oil as feedstock.

It is projected that other companies will come online within the next several years, although some may produce renewable gasoline instead of, or in addition to, renewable diesel and jet fuel (*Biofuels Digest* 2012).

Production Cost

This section presents production cost estimates for several technology pathways. It is important to note that the costs presented here are production costs rather than final selling prices at the pump.

Very little data are available publicly on the production costs for renewable diesel and jet fuel. Some techno-economic analyses (TEAs) have been conducted for certain technology pathways, and other data from specific companies can be extracted from S-1 filings when a company goes public.

In an effort to make the production costs reported here as comparable as possible, only recent sources (2008 to 2011) have been cited, and care was taken to exclude estimates with unusual assumptions such as optimistic feedstock price. However, the cost estimates are still not perfectly comparable. Variables such as plant size and co-product credits can have a significant impact on the overall production cost. Also, each pathway is at a different level of technology maturity, which contributes to the uncertainty of the cost estimates. None of the analyses cited address costs associated with carbon capture and sequestration (CCS), and none benefit from GHG emission credits.

Biodiesel

An analysis of soybean biodiesel (Tao and Aden 2009) reports a production cost of $2.55 per gallon of biodiesel ($2.48 gallon-of-gasoline-equivalent or gge) in 2007 dollars at a feedstock cost of $0.30/lb of soybean oil. The feedstock cost is by far the most significant cost of biodiesel production, accounting for about 70% of the overall production cost, and 75%- 95% of the overall operational cost. Other publications confirm the significance of feedstock cost, estimating it accounts for as much as 80% of the overall production cost (Yusuf et al. 2011). A literature review in Tao and Aden (2009) revealed overall production costs ranging from $2.00-$2.50 per gallon ($1.94- $2.43/gge), although the cost years of the data points in the literature review are not provided. Current biodiesel production facilities use a caustic soda-based catalyst, sodium methoxide, which complicates product clean up. Enzymatic transesterification using a lipase biocatalyst is an attractive alternative due to reduced wastewater treatments needs, easy glycerol recovery, and absence of side reactions—although the production costs are significantly higher (Jegannathan et al. 2011). An economic analysis employing an immobilized lipase catalyst resulted in a biodiesel production cost of $8.04 per gallon ($7.81/gge), although no cost year is provided.

Hydroprocessing of Lipid Feedstock

Pearlson et al. (2013) is the only publicly-available, peer-reviewed journal article that could be found containing production cost estimates for HEFA fuels. It models diesel and jet fuel production via hydroprocessing of soybean oil for three production capacity scenarios: 31, 61, and 100 Mgy. Maximizing the process for diesel production (jet fuel and LPG are co-products) results in cost per gallon ranging from $3.82 to $4.39/gal ($3.61 to $4.15/gge). Catalytically cracking a portion of the diesel range products was modeled to maximize jet fuel production (diesel and LPG are co-products), which resulted in a jet fuel cost per gallon of $4.09 to $4.69/gal ($3.81 to $4.37/gge). No cost year is provided, although input costs for the model, such as electric power, natural gas, and purchased hydrogen, are cited in 2010 dollars.

An estimate of renewable diesel production cost via the HEFA technology pathway can be gleaned from Syntroleum Corporation financial disclosure statements. Dynamic Fuels produces renewable diesel, along with naphtha and LPG co-products, from animal fats and yellow grease. According to Syntroleum Corporation financial statements (Syntroleum 2013), the feedstock was \$3.62/gal of renewable diesel produced, and operating expenses were \$1.03/gal of renewable diesel produced for the quarter ending September 30, 2012 (Syntroleum 2013). Cost per gallon due to capital costs is not provided, but the Dynamic Fuels website reports the capital cost of the 75 Mgy production facility at \$150 million (Dynamic Fuels 2013). Assuming a 30-year project life and 10% discount rate, we can amortize a \$150 million overnight capital cost over the total amount of fuel produced over the life of the project. The resulting capital cost is \$0.22/gal. Adding the capital cost per gallon to the feedstock cost and operating cost results in a production cost of about \$5/gge. It should be emphasized that this cost was not reported by Syntroleum Corporation, Tyson Foods, or Dynamic Fuels. It was estimated in this study based on feedstock and operating costs provided by Syntroleum, and total capital cost (provided by Dynamic Fuels) amortized using financing assumptions common in scoping studies such as the National Renewable Energy Laboratory (NREL) techno-economic reports cited elsewhere in this section.

Algae

Davis et.al. (2011) recently published modeled costs for the co-production of diesel and naphtha from photosynthetic algae. In this analysis, both open pond and photobioreactor technologies are examined. In general, the costs for finished (hydro-treated) blendstocks range from \$9.84/gallon (\$9.30/gge) for open-pond systems to \$20.53/gallon (\$19.39/gge) in 2007 dollars for photobioreactor systems.

Algal biofuel production is a nascent technology at commercial scale. Therefore, previous analyses apply inconsistent assumptions, making comparison of results difficult. Consequently, the Department of Energy's (DOE) Bioenergy Technology Office (BETO) hosted a workshop at the University of Arizona, Tucson, from November 30–December 1, 2011, for the purpose of harmonizing assumptions used in previous algal biofuel TEAs, life cycle assessments (LCAs), and resource assessments (RAs). Due to the favorable cost estimates of open-pond systems over photobioreactor systems, only open-pond systems were considered for the harmonization exercise. Applying the harmonized assumptions resulted in a cost of \$19.60/gal (\$18.52/gge) in 2007 dollars. The increase in cost above the Davis et al. (2011) estimate is due largely to the addition of pond liners, a reduction of the baseline algae production activity from 25 g/m^2/day to 13.2 g/m^2/day, and accounting for location and seasonal variabilities (Davis et al. 2012).

Fischer Tropsch Diesel

Gasification and pyrolysis modeled costs have been most recently described in a series of papers from ConocoPhillips/Iowa State. Anex et al. (2010) estimate the production cost of diesel and gasoline produced via gasification of corn stover followed by FT synthesis at \$4.50 to \$5.00/gge in 2007 dollars, depending on the operating temperature of the gasifier. The National Energy Technology Laboratory (NETL 2009) estimates the production cost of diesel produced via gasification followed by FT synthesis as \$6.45/gallon (\$6.09/gge) in 2008 dollars. The NETL study assumes a 20% rate of return, whereas Anex et al. (2010) assume only a 10% rate of return.

Wright et al. (2008) explore distributed pyrolysis processing (on-farm and small co-op pyrolyzers) followed by centralized gasification and FT synthesis of the pyrolysis oil to FT liquids. The distributed processing scenario yields FT liquids for $1.43 to $1.56 per gge, although the analysis does not describe the composition of the FT liquid product. Additional separation and upgrading steps may be necessary. Additionally, transporting raw pyrolysis oil can be problematic due to its tendency toward phase separation. No cost year is provided for the estimate.

Non-Catalytic Fast Pyrolysis

Brown et al. (2011) perform a techno-economic analysis of a non-catalytic fast pyrolysis process that produces gasoline from corn stover for a selling price of $2.96/gal in 2007 dollars. Biochar and pyrolysis gas are also produced, but are consumed in the overall process for heat generation. The final price is most sensitive to bio-oil yield, followed by feedstock price. The same research group analyzed two fast pyrolysis pathways, one with on-site hydrogen generation for fuel upgrading, the other relying on merchant hydrogen (Wright et al. 2010). Results show selling prices of $3.09/gge for the on-site hydrogen production scenario and $2.11/gge with purchased hydrogen. Selling prices in 2007 dollars for pioneer plants are $6.55/gge for the on-site hydrogen production and $3.41/gge with purchased hydrogen.

Catalytic Fast Pyrolysis

The National Academy of Sciences (NAS) reviewed cost estimates made by Wright et al. (2009) and catalytic fast pyrolysis company KiOR, based on KiOR's Form S-1 filing to the Securities and Exchange Commission (NAS 2011). Using its own feedstock cost and financing assumptions, the NAS updates the estimated selling prices of $2.10/gge for Wright et al. (2009) and $3.24/gge for the KiOR catalytic fast pyrolysis process, although most details of the analysis are not provided, and it is unclear what year the costs are indexed.

Hydropyrolysis

Marker et al. (2012) modeled an integrated hydropyrolysis and hydroconversion process for gasoline and diesel production, called IH^2, developed by the Gas Technology Institute (GTI). Biomass is pyrolyzed in the presence of hydrogen to gas and liquid products. The gas phase proceeds to a hydro-conversion stage, which removes oxygen, resulting in deoxygenated gasoline and diesel products. The production cost of the finished fuel is $1.60/gal in 2007 dollars. A gge production cost is not provided, although the product mix is reported as approximately 75% gasoline and 24% diesel, which results in a gge production cost of approximately $1.56 in 2007 dollars.

Biojet Fuel

A review of biojet fuel cost produced several estimates, but only one peer-reviewed journal article. Agusdinata et al. (2011) estimates the cost in 2007 dollars of producing biojet fuel via gasification and FT synthesis at $4.00/gge from corn stover, $5.50/gge for switchgrass, and about $5.80/gge for short rotation woody crops (SRWCs). Several estimates found in trade journals and industry blogs are consistent with this cost range of $4 - $6, although these sources are not reviewed and do not provide supporting material. Agusdinata et al. (2011) also estimates the cost of producing biojet fuel from algae in open ponds to be about $17/gge.

Renewable Identification Numbers and the Renewable Fuel Standard

The RFS program was created to ensure that transportation fuel sold in the United States contains a minimum volume of renewable fuel. The EPA is responsible for implementing the RFS regulations. The obligation to meet the minimum volume falls on fuel blenders.

Renewable Identification Numbers (RINs) are the mechanism used by the EPA to track volumes of renewable fuel and verify blenders are meeting minimum blending requirements. Each volume of renewable fuel produced has an RIN attached to it. Each fuel blender must acquire enough RINs to cover its share of the mandate. RINs are tradable and can be purchased and sold. Therefore, a blender can meet RFS requirements by actually blending the mandated amount of biofuels, or by purchasing RINs from other fuel blenders who blend more biofuels than required and have excess RINs (FAPRI-MU 2009).

The RFS and RIN trading system do not affect the production cost of renewable fuels, but are worth mentioning here because they can serve as economic drivers to make renewable fuels competitive with petroleum-derived fuels (NABC 2012a) and aid in initial market penetration.

Demand

Diesel

Distillate fuel oils, a category that includes diesel and heating oil, are a general classification for one of the fractions obtained from petroleum distillation. These oils are used in all sectors of the U.S. economy and rank second behind gasoline as the most consumed liquid fuels (EIA 2012c). Diesel fuel (often referred to as No. 2 diesel fuel) is defined by EIA as a fuel that has distillation temperatures of approximately 500^{o}F at the 10% recovery point and no more than 640^{o}F at the 90% recovery point; it meets the specifications defined in ASTM Specification D 975.[2] No. 1 diesel fuel is a light distillate fuel oil that has distillation temperatures of no more than 550^{o}F at the 90% point and meets the specifications defined in ASTM Specification D 975. Both fuels are used in high-speed diesel engines found in trucks, buses, automobiles, and locomotives, as well as farm and construction equipment. No. 1 diesel exhibits a much lower cloud point than No. 2 diesel, so it is used neat, or it is blended with No. 2 in winter months.

Heating oil (often referred to as No. 2 fuel oil) is used for domestic heating and for moderate capacity commercial/industrial buildings. EPA defines it as a distillate fuel oil that has a distillation temperature of up to 640^{o}F at the 90% recovery point and it meets the specifications defined in ASTM Specification D 396.[2] No. 1 fuel oil is a light distillate fuel oil that has distillation temperatures of up to 400^{o}F at the 10% recovery point and no more than 550^{o}F at the 90% point; it meets the specifications defined in ASTM Specification D 396. It is used primarily as fuel for portable outdoor stoves and portable outdoor heaters and is commonly referred to as kerosene.

More than three-quarters of distillate fuel sales are used primarily for transportation: on-highway (by trucks, buses, and automobiles); railroad; vessel bunkering; and construction, farm, and military equipment (Figure 1). About 6% of distillate sales are for residential heating purposes, concentrated during the winter months. Table 8 in the Appendix provides a detailed breakdown of the different types of fuels used in each sector, as well as their volumes during the period 2007-2012. On-highway motor vehicles consume about 64% of distillate fuel oils, namely diesel, with freight trucks using most of the fuel. The states of Texas and California are the largest consumers of diesel in the country, accounting for about 20% of all sales (Figure 2). Diesel consumption by on-highway motor vehicles follows population distribution: the top consuming states are also the most populated. Table 9 in the Appendix provides information on the historic use of No. 2 diesel fuel by state.

[2] EIA. (2013). "Petroleum and Other Liquids - Definitions, Sources and Explanatory Notes," Accessed August 2011: http://www.eia.gov/dnav/pet/TblDefs/pet_cons_821dst_tbldef2.asp.

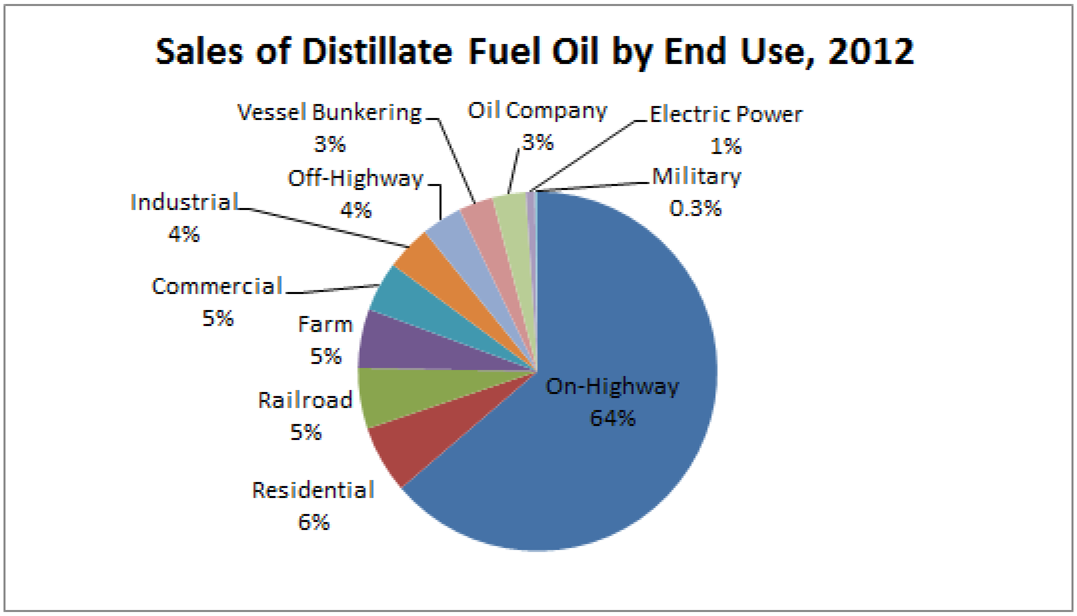

Figure 1. Sales of distillate fuel oil by end use, 2012

Data source: EIA 2013b

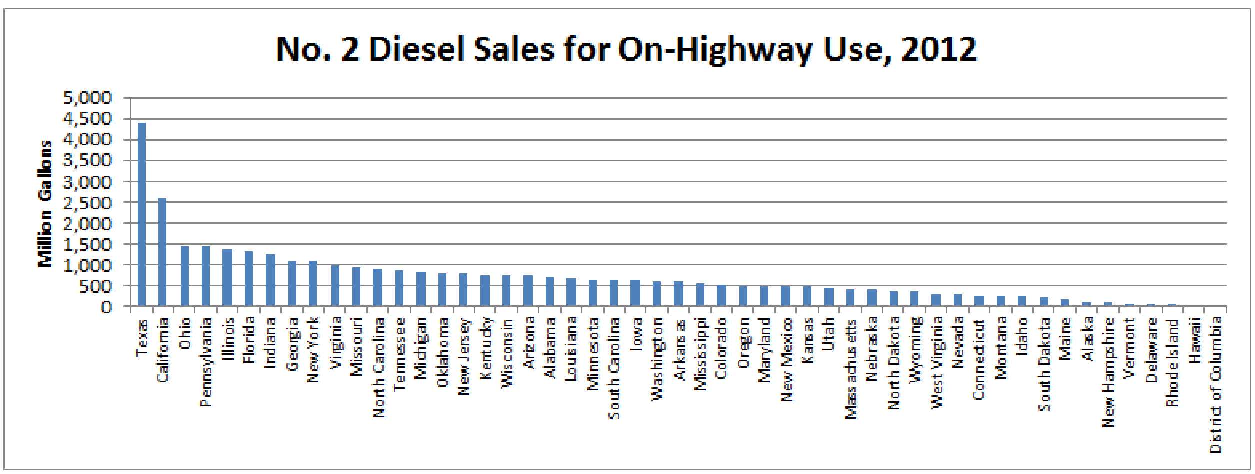

Figure 2. No. 2 diesel sales for on-highway use by state, 2012

Data source: EIA 2013b

Total distillate consumption was on the rise during the 1990s, and it reached a plateau during 2003-2007 (Figure 3). The growth was mainly due to increased use of diesel for transportation. From 2007-2009, low demand and a weak economy contributed to a downward trend. In 2010, this reversed to an upward trend, which experts believe is due to growth in manufacturing, usually associated with trucking demand.

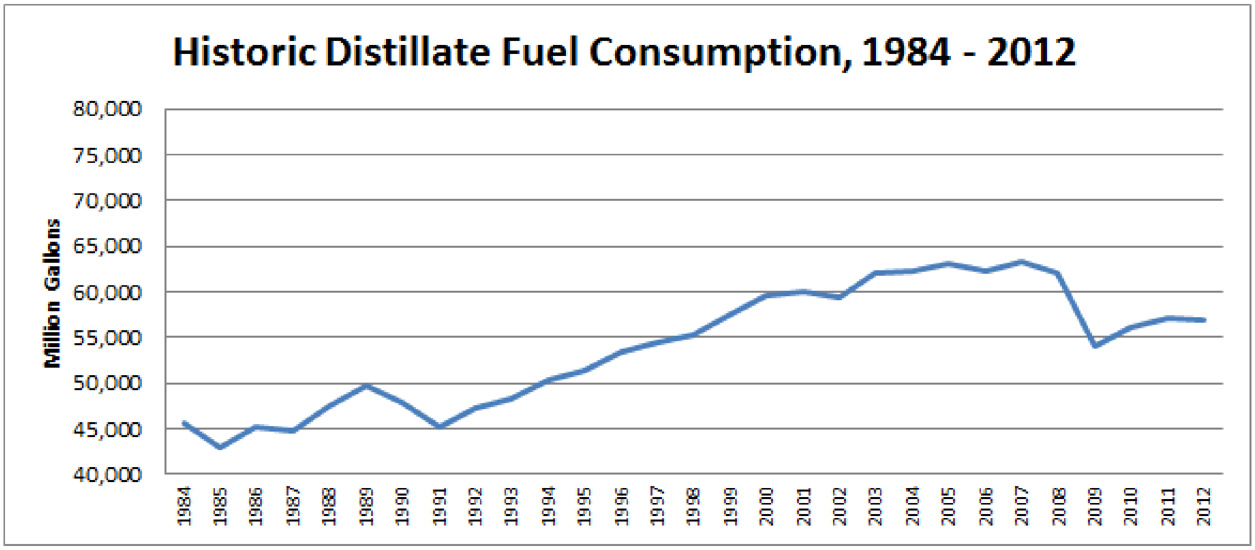

Figure 3. Total U.S. distillate retail deliveries, 1984 - 2012

Data source: EIA 2013b

Diesel consumption is projected to continue to grow, as illustrated in Figure 4. EIA notes that this growth results from both an increase in industrial output that leads to more fuel use by heavy trucks and an expansion of light-duty diesel vehicle sales to meet more stringent Corporate Average Fuel Economy (CAFE) standards.[3] As shown in Figure 5, freight trucks are expected to continue to dominate diesel consumption. Freight rail fuel use is expected to increase slightly while the consumption of diesel by the remaining market segments (such as commercial light trucks, shipping, school buses, etc.) remains almost flat over the years (Figure 6). An exception is the transit bus segment, which is projected to decrease its diesel use because of an increase in natural gas use. Historical diesel share of the transit bus segment declined relative to natural gas transit buses between 1995 and 2008, and this tradeoff is expected to continue.

[3] In July 2011, President Barack Obama proposed that the CAFE standards for cars and light trucks increase to 54.5 miles per gallon (mpg) by 2025 (currently 30.2 mpg for passenger cars and 24.1 mpg for light trucks), the biggest increase since the federal government started regulating fuel economy in the 1970s. The auto industry will be given time to adapt to the proposed 2025 standard. Under the supplemental notice of intent, passenger cars are required to increase fuel economy from 2017-2021 by 4.1% annually while light-duty trucks are required to have 2.9% annual improvements.

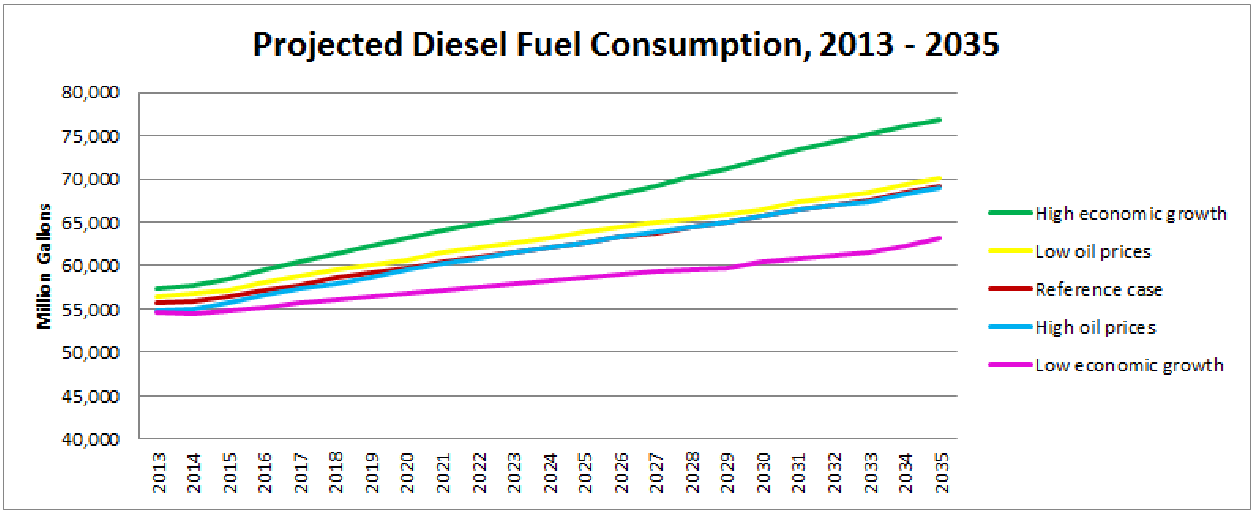

Figure 4. Projected diesel fuel consumption, 2013 – 2035

Data source: EIA 2011

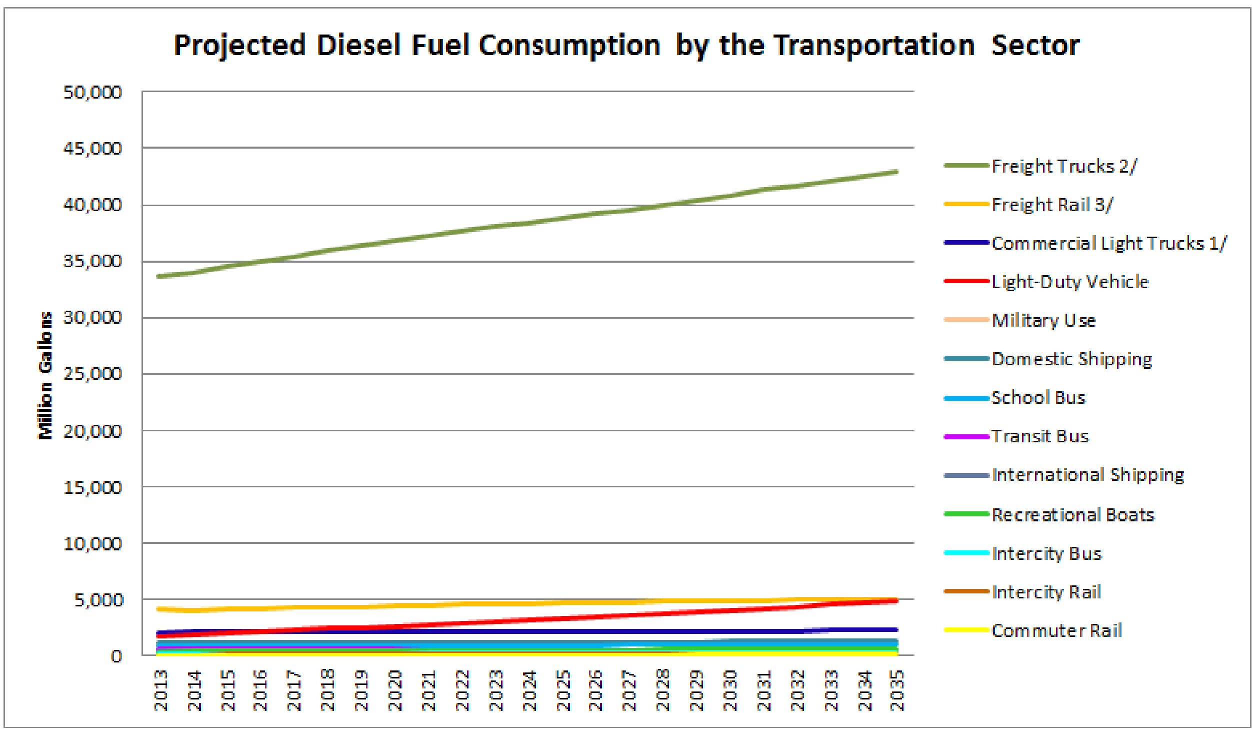

Figure 5. Projected diesel fuel consumption by the transportation sector

Data source: EIA 2011, Reference Case.

1/ Commercial trucks from 8,500 to 10,000 pounds.
2/ Does not include military distillate. Does not include commercial buses. 3/ Does not include passenger rail.

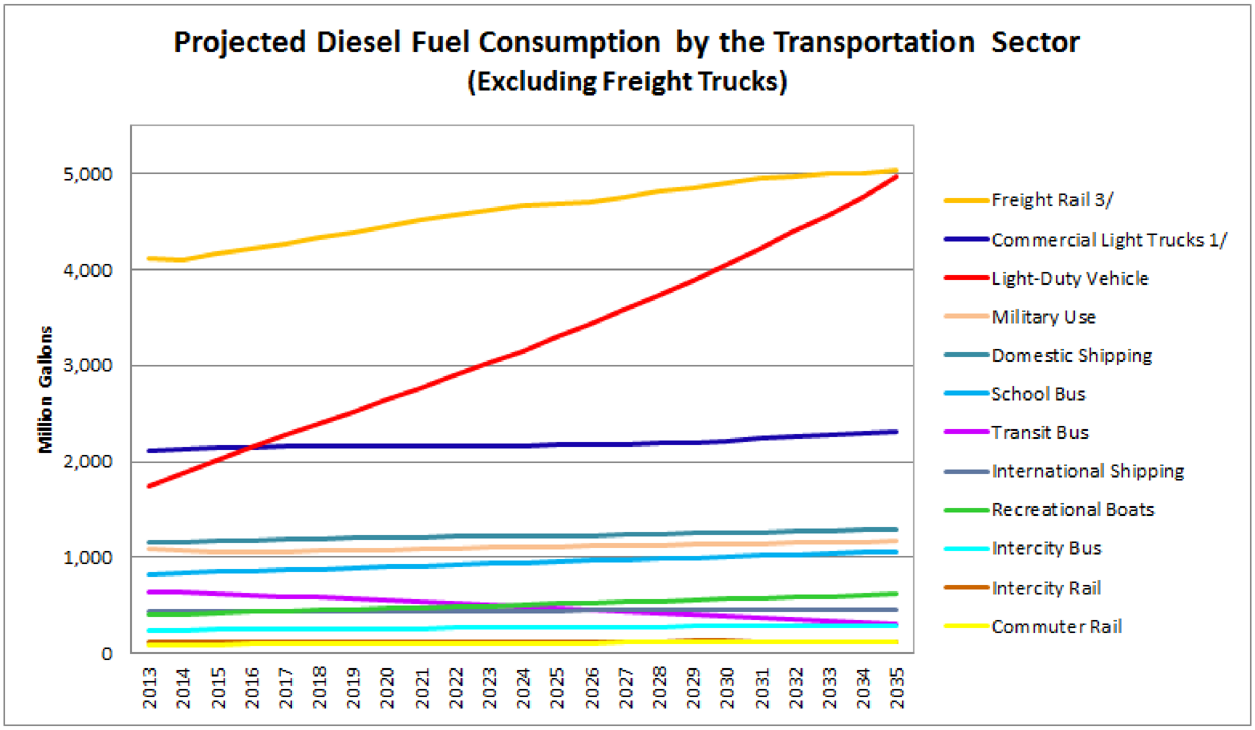

Figure 6. Projected diesel fuel consumption by the transportation sector excluding freight trucks

Data source: EIA 2011, Reference Case.

1/ Commercial trucks from 8,500 to 10,000 pounds. 3/ Does not include passenger rail.

Biodiesel

Biodiesel consumption was on the rise from 2005-2009, plummeted during 2010 due to low demand resulting from the economic downturn and the expired $1.00 per gallon blender tax credit, and was back up in 2011 mainly in response to RFS2 and the reinstated tax credit (Figure 7). Biodiesel is distributed through fueling stations nationwide. Low-level biodiesel blends such as B2 and B5 are used safely in any compression-ignition engine designed to use diesel fuel. There are several hundred major fleets in the United States that use biodiesel. These include municipal bus fleets; national park trucks and buses; federal, state, and local government fleets; school buses; and many commercial businesses, such as public utilities and refuse haulers (Hart Energy Consulting 2010). Off-road applications (tractors, boats, and electrical generators) also use biodiesel. EIA projects an annual growth of 7% for biodiesel consumption by 2035 (EIA 2011).

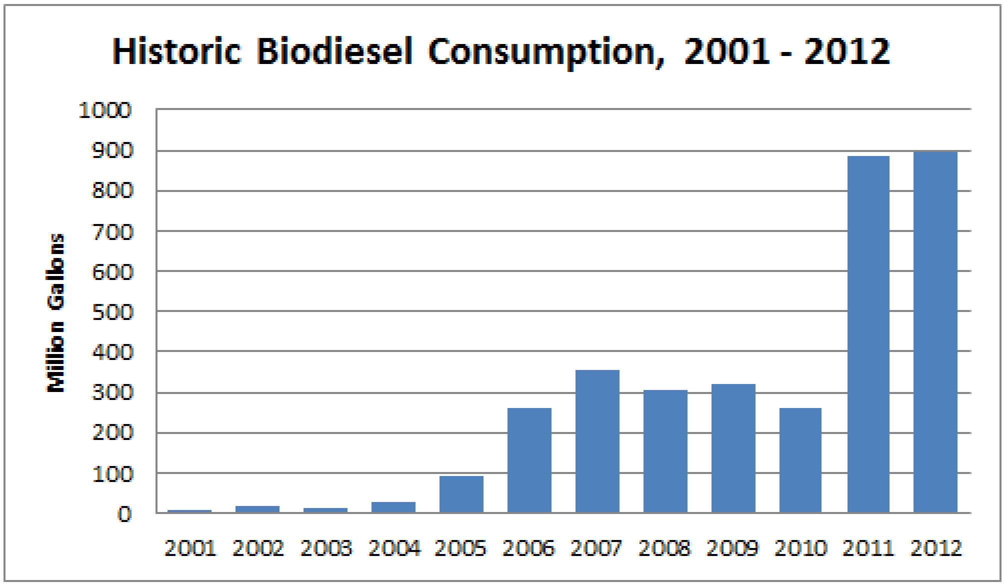

Figure 7. Historic biodiesel consumption, 2001 – 2012

Data source: EIA 2013a

Jet Fuel

Jet fuel is a type of aviation fuel designed for use in commercial and military aircrafts powered by gas-turbine engines. It is the third-most used fuel in the country after gasoline and diesel. EIA defines jet fuel as a kerosene-based product having a maximum distillation temperature of 400^{o}F at the 10% recovery point and a final maximum boiling point of 572^{o}F and meeting ASTM Specification D 1655 (JET A and JET A-1) and Military Specifications MIL-T-5624P and MIL-T-83133D (Grades JP-5 and JP-8).[4]

Jet fuel consumption was on the rise during the 1980s and 1990s and it reached a plateau during 2000 - 2007 (Figure 8). Since 2007, similar to diesel consumption, jet fuel consumption began a downward trend due to low demand and a weak economy. States consuming the most jet fuel include California, Texas, New Jersey, Florida, and Illinois (Figure 9); they are home to some of the busiest airports in the United States as well as large military bases.

[4] EIA. (2013). "Petroleum and Other Liquids - Definitions, Sources and Explanatory Notes," Accessed August 2011: http://www.eia.gov/dnav/pet/TblDefs/pet_cons_821dst_tbldef2.asp.

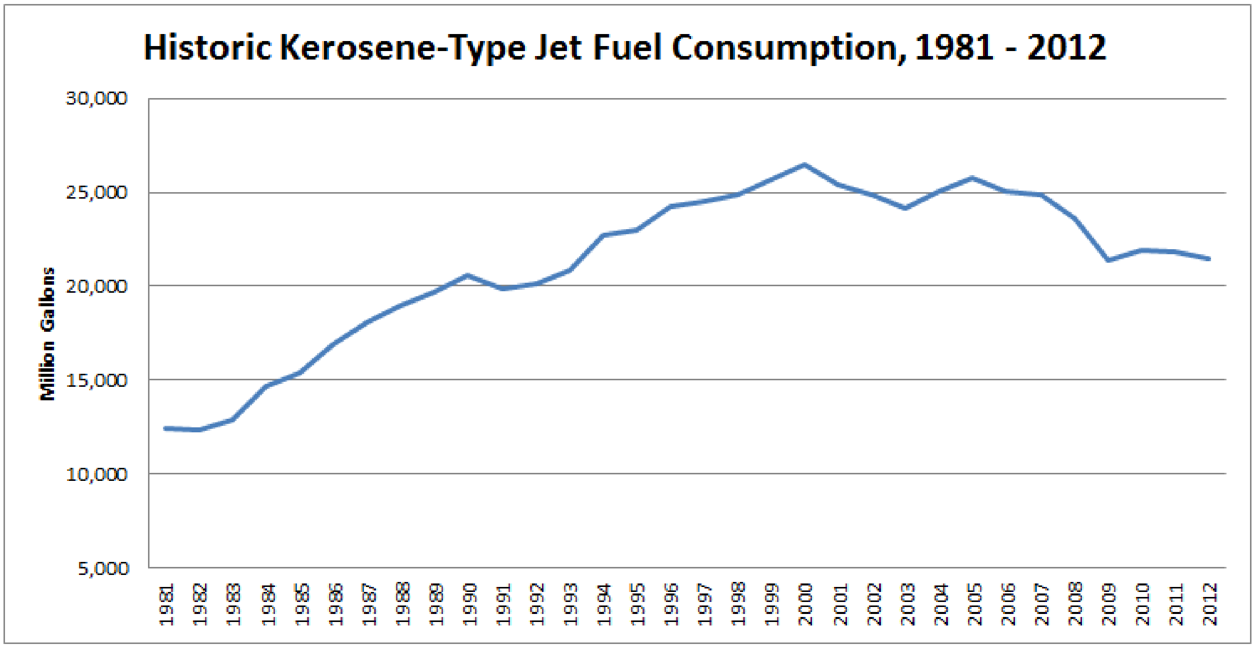

Figure 8. Historic kerosene-type jet fuel consumption, 1981 – 2012

Data source: EIA 2013c

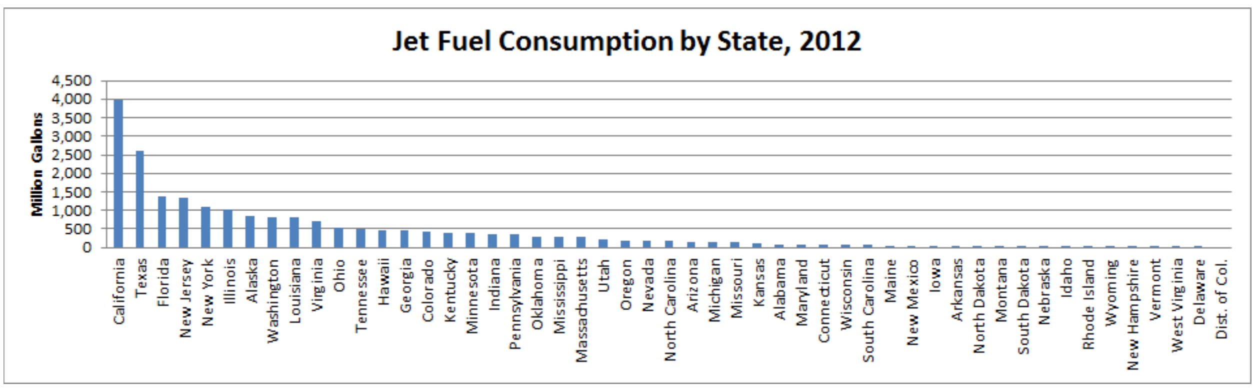

Figure 9. Jet fuel consumption by state, 2012

Data source: EIA 2013d

EIA projects that jet fuel consumption by commercial carriers will continue to grow over the next years, the rate of which will depend on economic growth and oil prices, whereas jet fuel consumption by the military will remain flat (Figure 10 and Figure 11).

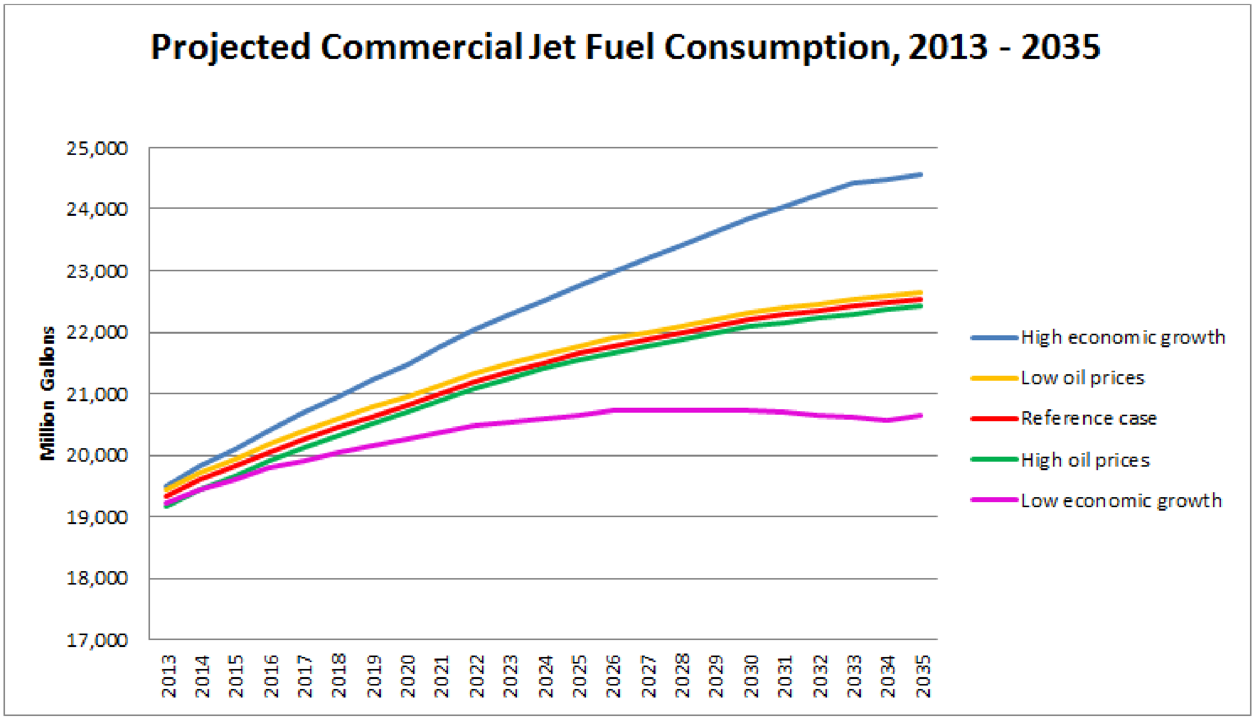

Figure 10. Projected commercial jet fuel consumption, 2013 – 2035

Data source: EIA 2011

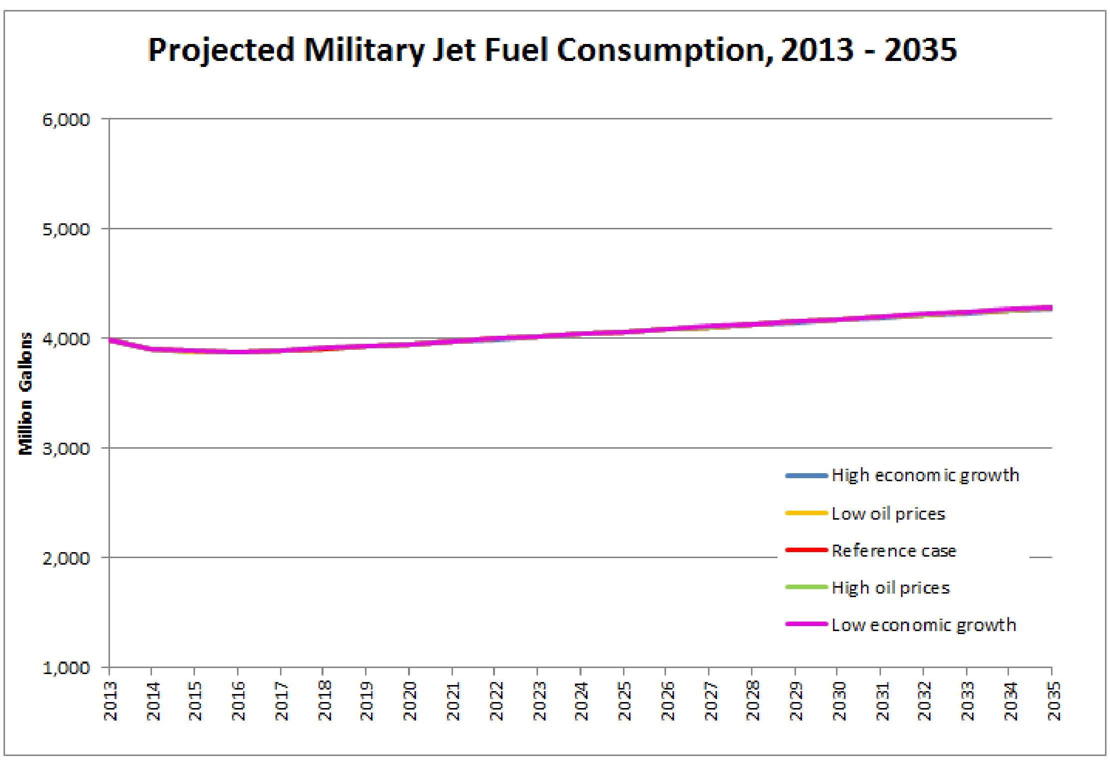

Figure 11. Projected military jet fuel consumption, 2013 – 2035

Data source: EIA 2011

Feedstock Assessment

Various biomass resources can be used for the production of diesel and jet fuel substitutes, as established earlier. These include lignocellulosic material such as wood waste, crop residues, and dedicated energy crops, as well as lipid feedstock such as vegetable and waste oils, animal fat, and algae. A recent study by the U.S. Department of Energy's Oak Ridge National Laboratory (U.S. DOE 2011), the Billion Ton Study (BTS), estimated the amount of currently available and potential biomass resources in the conterminous United States. The study included the following biomass categories:

1. Forest Biomass and Wood Waste
   - Forest residues (logging residues and thinnings) from integrated forest operations from timberland
   - Other removal residue[5]
   - Thinnings from other forestland[6]
   - Unused primary and secondary mill processing residues[7]
   - Urban wood wastes (woody component of municipal solid waste [MSW] and construction and demolition [C&D] wood)
   - Conventionally sourced wood[8]
2. Agricultural Biomass and Waste Resources
   - Crop residues from the major grain-producing crops (corn, wheat, barley, oats, and sorghum)
   - Secondary agricultural processing residues (sugarcane trash and bagasse, cotton gin trash and residues, soybean hulls, rice hulls and field residues, wheat dust and chaff, orchard and vineyard prunings)
   - Waste or tertiary resources (e.g., manures, waste fats, and greases)
3. Energy Plantations (perennial grasses, trees, and annual crops).

The BTS makes use of POLYSYS, an agricultural policy model, and data from the United States Department of Agriculture (USDA) to estimate supply/cost curves for each feedstock by county

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[5] These residues include unutilized wood volume from cut--or otherwise killed--growing stock from cultural operations, such as pre-commercial thinnings or from timberland clearing. This category does not include volume removed from inventory through reclassification of timber land to productive reserved forest land.

[6] Other forestlands are defined as incapable of producing at least 20 cubic feet per acre per year of industrial wood under natural conditions because of a variety of adverse site conditions including poor soils, lack of rainfall, and high elevation.

[7] Primary mill residues include wood materials (coarse and fine) and bark generated at manufacturing plants (primary wood-using mills) when round wood products are processed into primary wood products like slabs, edgings, trimmings, sawdust, veneer clippings and cores, and pulp screenings (USDA – Forest Service). Secondary mill residues include wood scraps and sawdust from woodworking shops such as furniture factories, wood container and pallet mills, wholesale lumberyards, and flooring.

[8] This category includes wood that has a commercial value for other uses but is used as an energy feedstock because of competitive market conditions.

for 2012-2030. Two scenarios are used: baseline and high yield. The baseline scenario assumes a continuation of USDA's 10-year forecast for the major food and forage crops, as well as a continuation in trends toward no-till and reduced cultivation. Energy crop yields assume an annual increase of 1% due to experience in planting and additional R&D. Forest residues are estimated using resource cost analysis with data from the USDA's Forest Service. The high-yield scenario assumes a greater proportion of corn in reduced and no-till cultivation and increased corn yields to about double the current rate of annual increase. The energy crop productivity increases at 2%, 3%, and 4% annually, not only due to experience in planting, but also to more aggressive implementation of breeding and selection programs. No high yield scenario was evaluated for forest resources except for the woody crops.

The forest resources are available over a wider price range than the agricultural resources–$20 per dry ton or less to $100 per dry ton or less for forest resources vs. $40 per dry ton or less to $60 per dry ton or less for agricultural resources–with increasing quantities at higher prices. Over the estimated price range, forest resource quantities vary from about 33 to 142 million dry tons currently (Table 2). Due to data limitations, there is little estimated change over the next 20 years. Another study looked at the currently available forest resources in the country, regardless of price, and estimated that there are about 92 million dry tons of woody biomass available in the country today (Milbrandt 2005).[9] A study by NAS reports a similar amount of currently available woody biomass, about 110 million dry tons, and projects that about 124 million dry tons could be available in 2020 (NAS 2009).

Table 2. Summary of Potential Forest Biomass and Wood Wastes in the BTS, 2012

Feedstock ($ per dry ton)	<$20	<$30	<$40	<$60	<$80	<$100
	Million dry tons					
Other Removal Residue	4.4	12	12	12	12	12
Composite Operations	9.5	30	36	40	42	43
Without Federal Land	8.3	26	31	35	36	37
Treatment Thinnings, Other Forestland	0	0	0	3.2	6.4	6.4
Without Federal Land	0	0	0	1.8	3.6	3.6
Mill residue, unused primary	1.3	1.3	1.3	1.3	1.3	1.3
Mill residue, unused secondary	6..1	6.1	6.1	6.1	6.1	6.1
Urban Wood Waste – C & D	4.4	11	14	22	22	22
Urban Wood Waste – MSW	7.7	8.7	9.2	10	10	10
Conventional Pulpwood to Energy*	0	0	0	1.5	19	40
Total – All Land	**33**	**70**	**79**	**97**	**119**	**142**
Total – Without Federal Land	*32*	*66*	*75*	*90*	*111*	*133*

Source: U.S. DOE 2011

Under the baseline scenario, agricultural resource quantities vary from about 59-162 million dry tons currently to about 126-265 million dry tons in 2030. About two-thirds of this quantity comes

[9] This volume includes logging residues and other removals, unused primary mill residues, secondary mill residues, and urban wood waste.

from crop residue and the rest is from various agricultural processing residues and wastes. Under the high yield scenario, the quantities vary from about 115-244 million dry tons currently to about 284-404 million dry tons in 2030 (Table 3). As a reference, Milbrandt (2005) reports about 157 million dry tons of crop residues available in 2002. This amount is one-third of the total crop residues, accounting for a portion that needs to be left on the field for soil protection, grazing, and other agricultural activities. NAS (2009) reports a lower amount of currently available agricultural resources[10]--about 106 million dry tons—and projects that about 148 million dry tons of agricultural resources could be available in 2020.

Table 3. Summary of Baseline and High Yield Scenarios in the BTS —Agricultural Residues and Waste Resources

	<$40 per dry ton				<$50 per dry ton				<$60 per dry ton			
Feedstock	2012	2017	2022	2030	2012	2017	2022	2030	2012	2017	2022	2030
	Million dry tons											
Baseline												
Corn	19	32	42	65	73	93	108	129	85	106	120	140
Wheat	6.7	7.8	9.1	12	18	22	26	31	23	26	31	36
Barley, Oats, Sorghum	1.0	1.3	1.6	2.9	2.4	2.5	2.4	3.6	2.8	2.7	2.6	3.7
Total primary residue	**27**	**41**	**52**	**80**	**94**	**117**	**136**	**164**	**111**	**135**	**154**	**180**
Secondary residues & wastes												
Rice field residue	6.5	6.9	7.4	8	6.5	6.9	7.4	8	6.5	6.9	7.4	8
Rice hulls	1.5	1.6	1.7	1.7	1.5	1.6	1.7	1.7	1.5	1.6	1.7	1.7
Cotton field residue	4.2	5.3	5.9	6.7	4.2	5.3	5.9	6.7	4.2	5.3	5.9	6.7
Cotton gin trash	1.4	1.6	1.7	1.8	1.4	1.6	1.7	1.8	1.4	1.6	1.7	1.8
Sugarcane residue	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Orchard and vineyard prunings	5.7	5.6	5.5	5.5	5.7	5.6	5.5	5.5	5.7	5.6	5.5	5.5
Wheat dust	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Animal manures	12	13	16	20	29	34	41	56	30	35	43	59
Animal fats	0	0	0	0	0	0	0	0	0	0	0	0
Total secondary residues & wastes	**33**	**36**	**40**	**46**	**50**	**56**	**65**	**82**	**51**	**58**	**67**	**84**
Total baseline	**59**	**77**	**92**	**126**	**143**	**174**	**201**	**245**	**162**	**192**	**221**	**265**
High-yield scenario												
Corn stover	71	132	157	221	143	200	228	264	153	209	234	271
Wheat Straw	9.8	12	13	16	60	35	38	42	35	39	42	46
Barley, Oats, Sorghum	1.5	1.5	1.4	1.7	3.6	3.4	2.8	3.1	4.0	3.6	2.9	3.0
Total primary residue	**83**	**146**	**171**	**238**	**176**	**239**	**269**	**309**	**193**	**252**	**279**	**320**
Total high-yield	**115**	**182**	**210**	**284**	**226**	**295**	**334**	**391**	**244**	**310**	**346**	**404**

Source: U.S. DOE 2011

Energy crops considered in the BTS include switchgrass, miscanthus, sugarcane, sorghum, poplar, willow, eucalyptus, and southern pine. The study estimates that between 3.7 and 101

[10] NAS (2009) evaluates corn/wheat residues and hay only, while Milbrandt (2005) considers residues from 18 major agricultural crops.

million dry tons of energy crops could be available under the baseline scenario in 2017 (Table 4). This wide range is due to uncertainty in crop yield and the rate of industry's development. The high yield scenario is simulated at three levels–2%, 3%, and 4% increase in annual crop productivity. Over the estimated price range, the quantity of energy crops varies between 13 and 180 million dry tons in 2017 to about 69 and 799 million dry tons in 2030. NAS (2009) reports that with current technologies and agricultural practices, about 104 million tons of energy crops could be produced today. Advanced technologies and practices could lead to increased production, potentially up to 164 million tons in 2020.

Table 4. Summary of Baseline and High Yield Scenario Availability of Energy Crops in the BTS

	<$40 per dry ton			<$50 per dry ton			<$60 per dry ton		
Feedstock	2017	2022	2030	2017	2022	2030	2017	2022	2030
Baseline scenario				*(Million dry tons)*					
Perennial grasses	3.0	12	30	41	77	129	90	188	255
Woody crops	0.0	0.0	0.1	0.9	40	67	5.7	84	126
Annual energy crops	0.7	1.8	4.2	3.8	7.3	14	5.0	10	19
Total	**3.7**	**14**	**34**	**46**	**124**	**210**	**101**	**282**	**400**
High-Yield (2% annual growth)									
Perennial grasses	11	43	57	67	152	239	122	253	319
Woody crops	0.0	0.1	4.2	1.9	78	127	10	145	207
Annual energy crops	1.6	4.1	7.4	5.5	8.7	12	6.9	11	15
Total	**13**	**47**	**69**	**75**	**239**	**378**	**139**	**409**	**540**
High-Yield (3% annual growth)									
Perennial grasses	24	71	107	85	213	329	138	296	390
Woody crops	0.0	1.5	43	9.3	101	186	14	168	251
Annual energy crops	2.4	6.6	11	6.2	10	14	8.0	12	18
Total	**26**	**79**	**162**	**101**	**324**	**520**	**160**	**476**	**658**
High-Yield (4% annual growth)									
Perennial grasses	35	100	202	106	270	406	154	338	462
Woody crops	0.1	5.3	45	12	118	199	16	212	315
Annual energy crops	3.4	9.0	14	6.8	11	18	9.4	14	22
Total	**39**	**114**	**261**	**124**	**399**	**622**	**180**	**564**	**799**

Source: U.S. DOE 2011

FOG is another resource category for the production of diesel and jet fuel substitutes. The United States produced about 18 million tons of FOG in 2010 (Table 5), which could theoretically be converted to over 5 billion gallons of biodiesel or renewable diesel. Another 3.7 million tons of oils were imported (mainly edible oils such as canola, palm, and coconut). Edible oil imports have increased from 13% of domestic edible oil production in 1998 to 27% in 2010 as a result of the shift from soy to low polyunsaturated oils (because of negative health effects of trans-fatty acids and rising U.S. food demand). However, not all of these resources are available for energy use. Roughly 85% were used for edible (baking or frying fats, margarine, salad or cooking oil) and inedible products (fatty acids, animal feed, methyl esters, etc.). In addition, about 1.5 million tons of edible oils (mostly soy) and 900,000 tons of animal fats were exported in 2010 (USDA 2012; U.S. Census Bureau M311K). The 1.1 billion gallon biodiesel production in 2011 consumed over 4 million tons of FOG, which is a significant increase from the 1.1 million tons consumed in 2010.

Table 5. U.S. Production of Fats, Oils, and Greases in 2010

Sources	Production ('000 tons)
Oils*	
Corn	1,258
Cottonseed	408
Peanut	82
Canola	576
Safflower	32
Soybean	9,518
Sunflower	314
Tall oil, crude**	672
Vegetable foot**	178
Fats	
Lard*	425
Edible tallow*	913
Inedible tallow**	1,650
Poultry fat**	709
Yellow grease**	702
Other grease**	660
Total Current Supply	18,092
Oils and Fats Import*	3,687

* Data Source: USDA, Oil Crops Yearbook 2011
** Data Source: U.S. Census Bureau, M311K

Algae are a potential aquatic oil crop, but may also yield carbohydrates that can be converted to sugar. This feedstock has received increased attention in recent years. Given the right resources– suitable climate, availability of water, CO2 and other nutrients – algal oil productivity can be quite high. A recent study suggests that under current technology, microalgae have the potential to generate 58 billion gallons of oil per year, equivalent to 48% of current U.S. petroleum imports for transportation (Wigmosta et al. 2011). The authors emphasize that this level of production requires 5.5% of the land area in the conterminous U.S. and nearly three times the water currently used for irrigated agriculture. The intensive water use for growing algae can be addressed in a sustainable manner by using low-quality water with few competing uses, such as brackish/saline groundwater, “co-produced water” from oil and natural gas wells, and wastewater discharged from domestic, industrial, and agricultural activities. Therefore, algal technology need not put additional demand on freshwater supplies.

Figure 12 illustrates the algal oil productivity at different locations in the United States. The pattern shows a strong linkage to climate and topography–locations with warm temperatures and flat terrain are most productive. The southern portions of the country exhibit the highest production rates ranging from 6,000 to 8,221 liters/ha/year (between 540-740 gallons/acre/year) of potential biofuel production. These areas are characterized with relatively warm temperatures year-round and longer hours of solar insolation in comparison to northern locations. Locations in the north and at higher elevations exhibit the lowest production rates, ranging from 2,291 to 4,000 liters/ha/year (206-360 gallons/acre/year). A long winter season in these areas contributes to a shorter growing season.

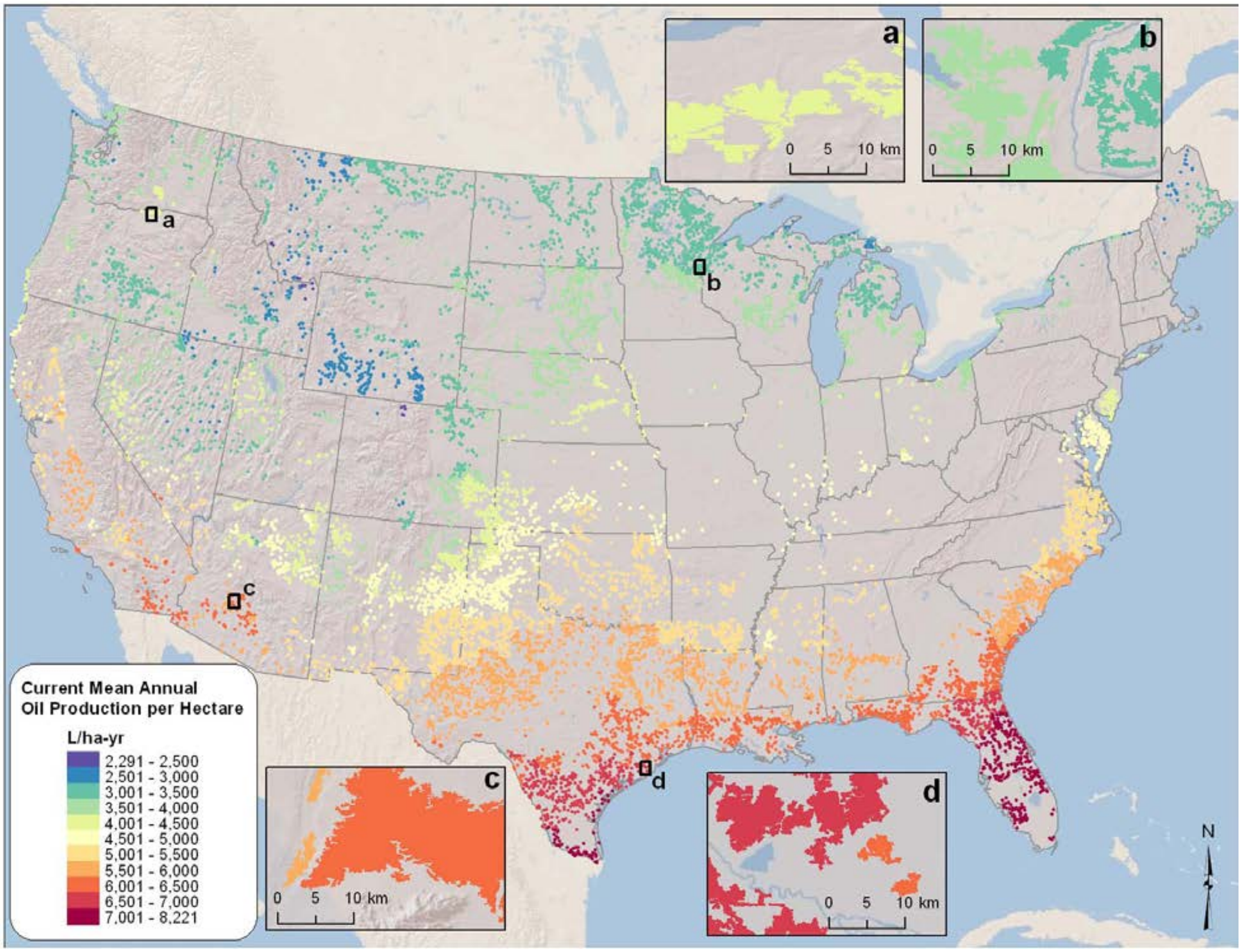


Figure 12. Mean annual algal oil production using current technology

Source: Wigmosta et al. 2011

Table 6 summarizes the biomass resource potential outlined above. Depending on the conversion pathway, different yields of biofuels can be achieved. Using current conversion technologies for lignocellulosic biomass, about 43.3 gallons of renewable diesel/jet fuel could be produced per dry ton via gasification/FT technology (Davis 2009) and about 65 gallons per dry ton via fast pyrolysis (PNNL 2009). For example, forest resources alone could produce about 1.4 - 6 billion gallons of renewable diesel via gasification/FT technology which could displace between 4% and 17% of current diesel consumption on highways (about 36 billion gallons of diesel fuel was used in 2011; see Figure 1 and Figure 3). Using fast pyrolysis, forest resources could yield even more "drop-in" fuels and displace between 6% and 26% of current diesel consumption. Renewable diesel and jet fuel yields from lignocellulosic biomass via biochemical conversion pathways are not readily available at this time.

On average, about 300 gallons of biodiesel, using a transesterification process, could be produced per ton of FOG. Thus, the 3.8 million tons of currently available FOG could yield about 1.1 billion gallons of biodiesel, which could displace about 3% of current diesel consumption on highways in the United States. About 245 gallons of “drop-in” fuel could be produced per ton of triacylglycerol (TAG) oil via hydroprocessing (Davis et al. 2012). Thus, about 931 million gallons of renewable diesel could be produced from the existing FOG in the United States, which could displace about 2.5% of current diesel consumption on highways in the country.

Table 6. Total Biomass Resource Potential

Feedstock	Current Potential (million tons)	Future Potential in 2022 (million tons)
Forest resources	33-142	34-150
Crop residues	59-162	92-221
Energy crops	n/a	14-282
Fats, Oils, and Greases*	3.8	4.1
Algae**	n/a	400

* Assumes 21% of FOG [about 85% of total FOG (18 million tons) is currently used for edible and inedible products, of which 6% is used in methyl esters (biodiesel)]. Future potential is estimated using population projections from the U.S. Census Bureau in 2022 (0.93 percent change) and applying the same ratio (21% of total).
** Assumes 1/5 of projected future potential.

It is unrealistic to assume that all of the biomass resources could be used for the production of diesel and jet fuel substitutes. There are other competing uses for these resources. For lignocellulosic biomass, these include the production of ethanol, renewable gasoline, chemicals and allied products, as well as power generation. For FOG, competing industries include the production of edible (baking/frying fats, cooking oil, etc.) and inedible (lubricants, paints, plastics, etc.) products. However, even if a small portion of the current biomass potential is dedicated to diesel and jet fuel substitutes, they can still play a role in diversifying the country’s energy portfolio. This role would be more significant if the projected future potential is realized and feedstock, such as dedicated energy crops and algae, become commercially available.

Discussion

The Congressionally mandated RFS2 goal is to use at least 36 billion gallons of biomass-based transportation fuels by 2022 (Figure 13). Of the total 36 billion gallons, 15 billion gallons are projected to come from conventional biofuel sources, such as corn ethanol, and the remaining 21 billion gallons from advanced biofuels divided into three categories: cellulosic biofuels, biomass-based diesel, and other advanced biofuels (EPA 2009, Table V.A. 2-1). Sixteen billion gallons are required to come from cellulosic biofuels (fuels, not necessarily ethanol, made from lignocellulosic biomass that also reduce GHG emissions by at least 60% relative to the gasoline or diesel fuel they displace). The contribution of biomass-based diesel to this goal can be no less than 1 billion gallons[11]: 0.81 billion gallons are projected to come from biodiesel and 0.19 billion gallons from renewable diesel. An additional 4 billion gallons of other advanced biofuels (any renewable fuel other than ethanol derived from corn that achieves 50% GHG emissions) is also mandated by RFS2.

Biomass-based diesel and jet fuel are considered to be advanced biofuels and can meet several RFS criteria. For example, renewable diesel derived from lignocellulosic biomass falls within the biomass-based diesel and cellulosic biofuels categories while jet fuel substitutes from biomass can meet the cellulosic biofuels and other advanced biofuels standards.

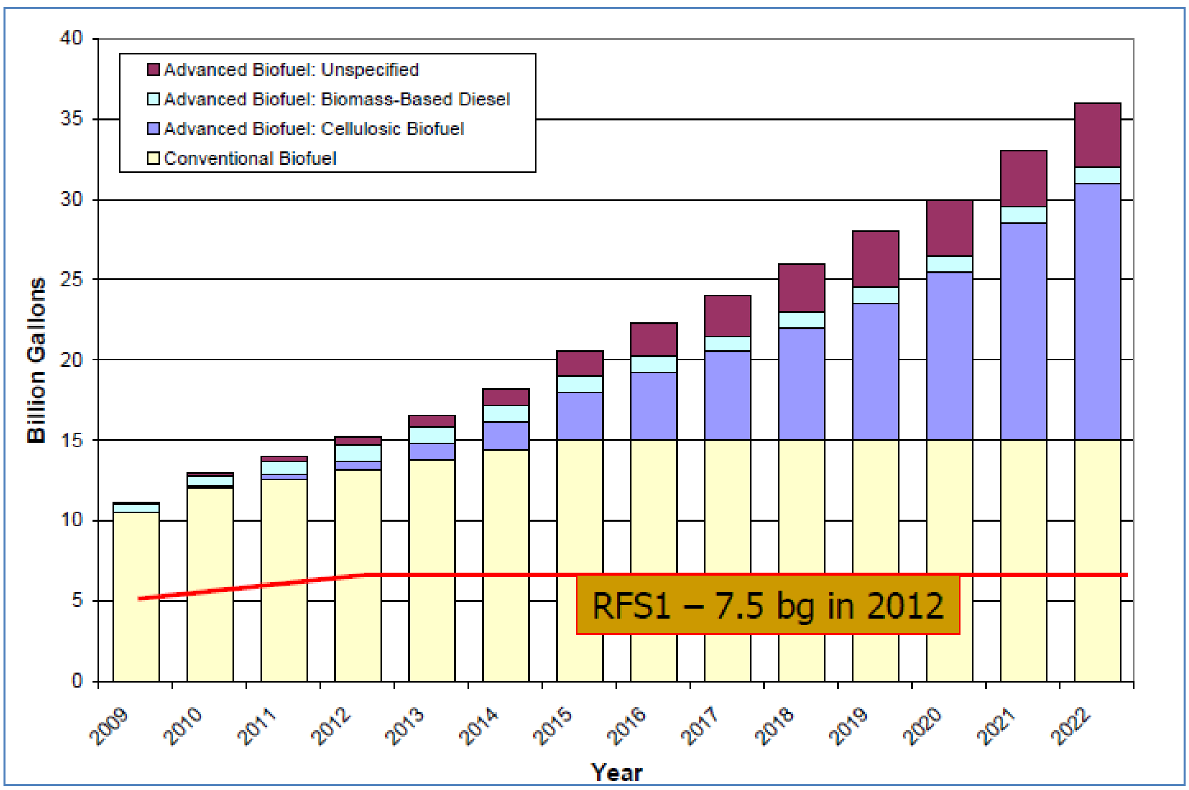


Figure 13. Renewable fuel volume requirements for RFS2 under EISA

Source: EPA 2010b

[11] In 2013, biomass-based diesel mandate was revised upwards from 1 billion gallons to 1.28 billion gallons actual volume (EPA 2013b).

During 2011 and 2012, the biodiesel industry proved that it has the ability to fulfill the entire biomass-based diesel volume requirements under RFS2. The mandate calls for at least 1 billion gallons of biomass-based diesel annually and biodiesel production was reported at 1.1 billion gallons during these two years. Production in 2013 is forecasted to be even higher. In addition to the RFS mandate, another factor for the industry's growth during the past three years was the extended tax credit. This key $1.00-per-gallon blender tax credit is scheduled to expire on December 31, 2013 and it is unknown at this point whether or not it will be extended. The industry could face significant setbacks if extension does not occur. In addition, EPA proposes to keep the biomass-based diesel standard at 1.28 billion gallons next year, the same volume set for 2013, which could further jeopardize the industry's further development (EPA 2013c). The next several months will reveal the biodiesel industry's future directions as these two legislative pieces get resolved.

Biofuels Digest (2012) projects that "drop-in" fuels capacity (inducing renewable diesel and jet fuel) will reach about 1 billion gallons in 2017. This projection is based primarily on companies' statements and media releases on planned facilities. Whether or not this capacity level is reached will depend on many factors, including commercialization of proven technologies (namely gasification, FT, and pyrolysis), success of trial technologies, feedstock availability, production cost, and diesel/jet fuel demand. As mentioned earlier, currently there are three commercial plants in the United States producing renewable diesel, although one of them (KiOR) produces other renewable fuels as well such as renewable gasoline. At present, Dynamic Fuels is idle and it is unknown when the facility will resume operation again. The other two plants, KiOR and Diamond Green Diesel are in an initial phase and thus it is difficult to evaluate the performance and economics of these plants. Neste Oil is the world's largest renewable diesel producer with about 572 MGY of installed capacity worldwide (*Biofuels Digest* 2012). It operates abroad in Finland, Singapore, and the Netherlands. While Neste Oil is using hydrotreating, a common practice in petroleum refineries, other technologies such as pyrolysis (employed by KiOR) and FT (utilized by Syntroleum) have yet to demonstrate their economic viability. The next few years will likely answer many questions about the feasibility and profitability of producing renewable diesel and jet fuel through the various conversion pathways.

Based on current statistics, and as proven by the biodiesel industry, there is enough lipid feedstock to support the RFS2 mandate. Today, roughly half of the biodiesel in the United States is produced from soybean oil. The remaining portion consists of animal fat, used cooking oil, canola, and some other minor feedstocks such as cottonseed oil, tall oil fatty acids, and corn oil recovered from corn ethanol dry mills. The Food and Agricultural Policy Research Institute (FAPRI) projects that soybean oil production in the United States will continue to rise over the next decade, from about 9.5 million tons today to about 11 million tons in 2022 (FAPRI-ISU 2012). One of the drivers for this increase is the anticipated volume required to meet the biofuels quota under the RFS2. Even if half of the projected soybean potential is used for biodiesel/renewable diesel production it would be sufficient to meet the mandate. Higher output could be achieved through advanced technologies for increasing oil supply (increasing crop yield and seeds' oil content, as well as recovering sewage and trap greases) and production of new feedstock such as oil from camelina (*Camelina sativa* L.) and field pennycress (*Thlaspi arvense*). Moreover, if algal oil becomes commercially available in the next 5-10 years, the biodiesel and renewable diesel production potential would increase substantially.

With regard to the lignocellulosic feedstock, enough material is projected to be available to support the RFS mandate of 21 billion gallons from advanced biofuels. Crop and forest residues in 2022 are projected to be between 126 - 371 million tons. Assuming a conversion via fast pyrolysis (with an average yield of 65 gallons/dry ton), this amount could yield about 8-24 billion gallons of biomass-based diesel/jet fuel. This potential could be larger if the conversion technologies achieve higher yield and if additional feedstock such as dedicated energy crops become available. The fuel produced from these resources would qualify under any of the advanced biofuels categories: cellulosic biofuels, biomass-based diesel, or other advanced biofuels. However, there will be competition for lignocellulosic feedstock with the ethanol industry and renewable gasoline producers to meet the RFS mandate, so it is unclear what share the renewable diesel/jet fuel would have in the total biofuels contribution. Ultimately, it will depend on the rate of commercialization of these technologies as well as the transportation market demands.

The costs for producing renewable diesel and jet fuel are not well known and include a high degree of uncertainty. Hydroprocessing of FOG is being done commercially by Dynamic Fuels, Diamond Green Diesel, and internationally by Neste Oil. The KiOR technology is at an initial commercial scale. Other technology routes are not yet commercial and publicized cost estimates vary widely. As these technology pathways mature and become more widespread, more specific information regarding their economics will be available, which would enable a more detailed analysis and performance comparison. Based on Syntroleum Corporation financial disclosure statements, we estimate the production cost for renewable diesel by Dynamic Fuels to be about $5/gge as of September 2012. As a reference, the average production cost of petroleum-derived diesel in the United States is about $2.87 ($2.59/gge) as of October 2013 (EIA 2013e).[12] As another reference, production cost for biodiesel is in the range of $2.00-$2.50 per gallon ($1.94-$2.43/gge). However, it should be noted that this range was documented in 2009; thus it is likely that biodiesel production cost is higher today given the increase in soybean and other relevant feedstock prices during the past several years (USDA 2013). As a reminder, this is the cost of production (feedstock and processing), not the price paid at the pump by the consumer. The price at the pump also includes distribution expenses, taxes, etc.

Biodiesel faces some technical limitations which may direct future industry decisions toward renewable diesel. While the lower-level biodiesel blends (B20 and below) can be used in traditional diesel vehicles without engine modifications, higher-level blends may require engine modifications and other usage considerations. More importantly, biodiesel is currently transported from the production sites to petroleum terminals where it is blended with petroleum fuels, via truck or rail and occasionally, by barge. These modes are much more expensive than transportation by pipeline, which is used for most petroleum fuels. The potential for biodiesel to contaminate jet fuel is preventing widespread pipeline transport. Hydrocarbon renewable diesel is likely to be easily transported in existing pipelines already utilized for petroleum-based fuels.

Renewable diesel and jet fuels produced by hydroisomerization of lipid feedstocks, gasification followed by FT synthesis, or biochemically using the approaches by Amyris, LS9, and other companies will consist entirely of paraffinic hydrocarbons (also known as alkanes). These are

[12] West Texas Intermediate crude oil price: $100.54/barrel.

completely miscible with conventional fuels and, from a purely combustion standpoint, they could be blended at any level or even used in neat form as long as they meet the requirements of the respective fuel standard specifications (ASTM D975 for diesel fuel and ASTM D1655 for jet fuel). For both diesel and jet applications, it is likely that fuel additives will be required to meet specifications for lubricity, conductivity, stability, and other properties. All of these additives are also commonly used in petroleum-derived fuels. However, fuel system elastomeric components for both ground transport and aviation have been conditioned over time in a significant level of aromatic compounds. When exposed to a zero aromatic fuel such as the renewable diesel and jet fuels described above, aromatics can be extracted from the elastomers, causing them to shrink and leading to fuel system leaks. To avoid this scenario in aviation applications, ASTM International has developed standard D7566 "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons," which allows no more than 50% volume paraffinic kerosene in jet fuel. The blended fuel is also required to contain a minimum of 8% volume aromatics. A similar situation could be envisioned for elastomeric components in diesel engine fuel systems, but to date, ASTM has not specified a minimum required aromatic level or a maximum allowable blend level of paraffinic components.

Other renewable diesel fuels, such as those produced by fast pyrolysis and related thermochemical processes, will likely contain significant levels of aromatics, and perhaps low levels of oxygenates. More data on the composition of these fuels will be required in order to assess any possible limit on blend level. For widespread application, biodiesel blending is limited to 20% volume due to lack of engine manufacturer approval and limited data on compatibility with infrastructure for higher blends.

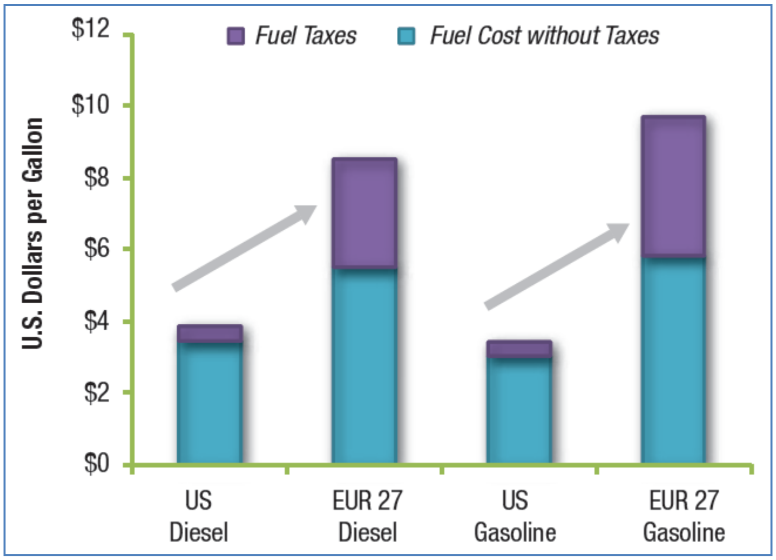
As noted earlier, on-highway motor vehicles consume about 64% of the diesel fuel in the country, with freight trucks being the largest consumer in this category. Therefore, the trucking industry could provide a strong business opportunity for biomass-based diesel producers. The American Trucking Association (ATA) is supportive of alternative fuels, evident from the fact that it currently supports biodiesel use in blends up to 5%. The organization highlights that renewable diesel has not been subjected to rigorous on-road fleet testing; however, preliminary information indicates that renewable diesel may have advantages over biodiesel for the end-user (ATA 2012). These advantages may include a higher energy content and better cold weather performance compared to biodiesel. Regardless, for any biomass-derived diesel to be a success among the trucking companies, the fuel price has to be equal to or less than petroleum-based diesel. Table 7 illustrates the top 25 U.S. trucking companies in 2012. By far, the two major package delivery companies UPS and FedEx lead the ranking in revenue. The e-commerce boom in recent years is the main contributor to the success of these companies.

Table 7. Top 25 U.S. Trucking Companies in 2012

2012 Rank	Parent Company	Primary Service	Subsidiary Portfolio/Services & Comments	Public/ Private	2011 Annual Revenue ($ million)	2012 Annual Revenue ($ million)	2011-2012 Percent Change
1	UPS	Parcel	*UPS Ground, UPS Freight*	Public	$24,752	$25,692	3.80%
2	FedEx	Parcel	*FedEx Ground, FedEx Freight, FedEx Custom Critical*	Public	$14,149	$15,416	9.00%
3	J.B. Hunt Transport Services	TL	*Truckload, Dedicated Contract Services, Integrated Capacity Solutions, Intermodal*	Public	$4,527	$5,055	11.70%
4	YRC Worldwide	LTL	*YRC Freight, YRC Regional*	Public	$4,869	$4,851	-0.40%
5	Con-way	LTL	*Con-way Freight, Con-way Truckload*	Public	$3,729	$3,898	4.50%
6	Swift Transportation	TL	*Truckload, Dedicated, Intermodal*	Public	$3,334	$3,493	4.80%
7	Schneider National	TL	*Schneider National, Schneider National Bulk Carriers, Schneider Intermodal*	Private	$3,170	$3,262	2.90%
8	Landstar System	TL	*BCO, TBC, Intermodal*	Public	$2,789	$2,952	5.90%
9	Old Dominion Freight Line	LTL	*Fastest-growing LTL carrier in Top 50 List*	Public	$1,883	$2,110	12.10%
10	Werner Enterprises	TL	*One-way Truckload, Dedicated, Cross-Border*	Public	$2,003	$2,036	1.70%
11	Arkansas Best	LTL	*ABF Freight System, Truck Brokerage, Panther Expedited*	Public	$1,756	$1,900	8.20%
12	U.S. Xpress Enterprises	TL	*Arnold Transportation subsidiary merged with LinkAmerica in December 2012*	Private	$1,670	$1,760	5.40%
13	Estes Express Lines	LTL	*Largest privately held LTL carrier*	Private	$1,640	$1,754	6.90%
14	Prime	TL	*Largest temperature-controlled carrier*	Private	$1,206	$1,372	13.80%
15	R & L Carriers	LTL	*R+L Carriers, R+L Truckload Services*	Private	$1,207	$1,250	3.60%
16	C.R. England	TL	*National, Regional, Dedicated, Intermodal, Mexico*	Private	$1,005	$1,146	14.10%
17	Greatwide Logistics	TL	*Merged with Cardinal Logistics in February 2013*	Private	$1,046	$1,105	5.60%
18	Saia	LTL	*Saia Motor Freight Line*	Public	$1,030	$1,099	6.60%
19	Kenan Advantage Group	TL	*Acquired Jack B. Kelley in September 2011*	Private	$988	$1,091	10.40%
20	CRST International	TL	*Acquired Specialized Transportation (STI) in July 2011*	Private	$846	$1,061	25.40%
21	Crete Carrier	TL	*Crete Carriers, Shaffer Trucking, Hunt Transportation*	Private	$942	$999	6.10%
22	Roadrunner Transportation	LTL	*Completed 8 acquisitions in 2012. Largest year-over-year growth in the Top 50 Trucking list*	Public	$768	$988	28.60%
23	Knight Transportation	TL	*Dry Van, Refrigerated, Brokerage, Port & Rail Services, Intermodal*	Public	$866	$936	8.10%
24	Southeastern Freight Lines	LTL	*Launched brokerage service in January 2011*	Private	$820	$875	6.60%
25	Averitt Express	LTL	*Revenue growth driven by LTL division*	Private	$769	$789	2.60%

Data source: JOC 2013

As illustrated earlier, diesel consumption by light-duty vehicles in the United States is relatively low, but it is projected to double over the next decade. The fuel is not as popular among U.S. passenger-car drivers as it is in Europe, but diesel vehicle sales show consistent double-digit increases over the last two years (*PR Newswire* 2012). Whether diesel cars remain niche vehicles in the U.S. market or enter the mainstream will depend on government policies, consumer demand, and fuel prices. The recently issued new CAFE standard of 54.5 mpg by 2025 is expected to have a positive effect on future clean diesel car sales. The Diesel Technology Forum (DTF), a non-profit educational organization dedicated to raising awareness about the economic importance and essential uses of diesel engines, issued a statement welcoming the new standards: “Because clean diesel autos are 20 to 40 percent more efficient than gasoline vehicles, diesel will be a major player in the nation’s effort to achieve the new mileage standards” (*Time* 2012, ¶ 8). Demand for gasoline is higher in the United States and fuel taxes favor gasoline, which makes gas less expensive. It is exactly the opposite in Europe where the fuel tax structure favors diesel (Figure 14). The U.S. diesel passenger vehicle market may expand as consumers are drawn more to diesels because they’re economical, offering greater fuel efficiency than comparable gas-powered cars. Moreover, if the U.S. fuel prices take off more abruptly than analysts predict, we could see a deeper penetration of diesel vehicles.



Fuel taxes for the United States include $0.184/gal for gasoline and $0.244/gal for diesel.

Figure 14. Comparison of fuel prices and taxes in the United States and Europe, 2007

Source: U.S. DOE 2010

Other transportation segments that could provide business opportunities for the biomass-based diesel industry are railroad; vessel bunkering; and construction, farm, and military equipment. While overall these segments do not consume as much diesel as freight trucks, they could still play a role at local levels. Tables 10-14 in the Appendix illustrate these sectors' diesel consumption by state. The rail network spreads throughout all states but certain areas such as Texas, California, Oklahoma, and Ohio report significantly more diesel consumption by the rail industry. The sector is strong in Texas and California due to a concentration of industrial and agricultural activities, in Oklahoma due to the state's somewhat central location, and in Ohio due to movements between eastern locations and markets in the Midwest. Diesel use by vessel bunkers is naturally high in coastal areas, while highly populated states (namely California and Texas) stand out as the largest consumers of diesel by the construction industry. About half of the country's diesel consumption in farm machinery is concentrated in the Midwest; large states with strong agricultural activities such as California and Texas also report high diesel use by this sector. As noted earlier, the military is not a heavy consumer of diesel; most activities are concentrated in states with large military bases such as Washington, Texas, North Carolina, and California.

Jet fuel is forming as a large and profitable market for the renewable fuels industry. Success in this area could stimulate a significant increase in the production of biofuels and associated feedstock. Successful test flights by commercial and military aircraft over the past few years led to the adoption of specification D7566 by the ASTM International in July 2011, which enables the use of 50% by volume paraffinic renewable fuels with conventional jet fuel. The blending level is restricted to 50% to ensure that the final blend contains a minimum level of aromatic compounds to prevent shrinkage of aged elastomer seals and subsequent fuel leakage. Since then, renewable jet fuel blends have been used by a number of airlines. The German airline Lufthansa began regularly scheduled commercial flights using Neste Oil's NExBTL renewable aviation fuel derived via hydrotreating vegetable oils and animal fats. This made Lufthansa the world's first airline to utilize biofuel in daily flight operations and Neste Oil the first company to provide the biofuel to be used on regularly scheduled commercial flights (Neste Oil 2012). In November 2011, Continental Airlines Flight 1403 from Houston to Chicago was the first U.S. commercial flight to run on a biofuel blend derived partially from genetically modified algae, which was provided by Solazyme. The parent company, United Continental Holdings Inc., plans to buy 20 million gallons per year of algae-derived biofuel made by Solazyme (*Seeking Alpha* 2012). Shortly after, Alaska Airlines and its sister airline Horizon Air started flights using a biofuel blend made from recycled cooking oil. More U.S. airlines are expected to join the effort to fly with renewable jet fuel in the following years.

The U.S. military is a promising client for renewable fuels given the fact that the Department of Defense (DoD) is the single largest consumer of petroleum in the country. The Defense Logistics Agency reports that it purchased about 4.7 billion gallons of fuel in FY 2012, of which 75% represented jet fuel (DLA 2013). Considering the approval of a 50% biofuels blend, this consumption represents a substantial potential demand for biofuels from the U.S. military in the near term. Among all services, the Air Force consumes the most energy and uses more than 2 billion gallons of aviation fuel annually. By 2016, it plans for half of its domestically purchased aviation fuel to be derived from renewable resources. Similarly, the Navy's goal is to use 50% of its energy consumption from alternative sources by 2020. This goal came as a result from successfully testing an F/A-18 fighter jet and helicopters on biofuel blends.

The military plays a very strategic role in the development and commercialization of advanced biofuels. It can afford research and testing of alternative fuels to determine their viability more easily than the private sector, which is somewhat limited by concerns about returns on investment. Also, it can purchase large volumes of fuel to create demand, which could lead to increased production and lower prices. Moreover, early adoption of advanced fuel technologies by the DoD provides certainty to investors that there will be a market for these products.

Conclusion

Our examination of the status, opportunities, and feasibility for biomass-based diesel and jet fuel in the United States leads to the following findings:

1. It is technically feasible to produce biomass-derived diesel and jet fuel substitutes in the United States. Many conversion technology options exist. Some are commercially available or in demonstrational stage; others are still in the research and development phase.

2. Biodiesel, consisting of FAME produced from lipids, is currently the predominant form of biomass-based diesel. Production reached a record 1.1 billion gallons in 2011, kept that level in 2012, and is expected to be higher in 2013. Biodiesel blends cannot yet be considered fully "drop-in" fuels because they cannot be transported in all petroleum product pipelines. For pipelines that transport jet fuel, there is a concern that the jet fuel will be contaminated with biodiesel, making it unsuitable for use. Ongoing research aims to determine what, if any, level of FAME can be tolerated in jet fuel.

3. In comparison, the current U.S. renewable diesel and jet fuel production capacity is small, about 225 million gallons per year. These fuels can be produced from various biomass resources and through several different approaches which all target hydrocarbon products that are similar to petroleum fuels in chemical makeup, and therefore may be considered "drop-in" fuels. It is anticipated that, as "drop-in" fuels, they can be blended with petroleum diesel/jet fuel at high levels, or possibly used in neat form.

    - Renewable diesel is produced at commercial scale primarily by hydroisomerization of lipid feedstock. Currently, there are two commercial facilities utilizing this process: Dynamic Fuels (Geismar, Louisiana) and Diamond Green Diesel (Norco, Louisiana).

    - A number of processes are under development for production of renewable diesel from biomass-derived sugars (corn, sugarcane, and sorghum, as well as sugars from thermochemical or biochemical depolymerization of cellulose and hemicellulose).

    - Processes are also being developed for direct conversion of lignocellulosic biomass by fast pyrolysis, gasification, and other thermochemical means. The first commercial plant is operated by KiOR in Columbus, Mississippi and became operational in early 2013.

4. The costs for producing renewable diesel and jet fuel are not well known and involve a high degree of uncertainty. The process economics for these fuels is highly dependent upon the cost of the feedstock, similar to biodiesel. Additionally, variables such as plant size and co-product credits can have a significant impact on the overall production cost. Hydroisomerization of lipids is performed commercially by Dynamic Fuels and Diamond Green Diesel, and internationally by Neste Oil. The KiOR technology, utilizing pyrolysis, is at an initial commercial scale. Other technology routes are not yet commercial and display a wide range of estimated costs in public sources. As these technology pathways mature and become more widespread, more specific information regarding their economics will be available, which would enable a more detailed analysis and performance comparison.

5. From a feedstock perspective, enough lignocellulosic material is projected to be available in support of the RFS mandate of 21 billion gallons of advanced biofuels. Crop and forest residues alone could yield about 8-24 billion gallons of biomass-based diesel/jet fuel in 2022 (assuming a conversion via fast pyrolysis). This potential could be larger if the conversion technologies achieve higher yields and if additional feedstock, such as dedicated energy crops, become available. However, there will be competition for lignocellulosic feedstock with the ethanol industry and renewable gasoline producers to meet the RFS mandate. Thus, it is unclear what share the renewable diesel/jet fuel would have in the total biofuels contribution. Ultimately, it will depend on the rate of commercialization of these technologies, selling price, and the transportation market demands.

6. Based on current statistics, and as proven by the biodiesel industry, there is enough lipid feedstock to support the production of 1 billion gallons of biomass-based diesel mandated by the RFS. Today, roughly half of the biodiesel in the United States is produced from soybeans. The remaining portion consists of animal fat, used cooking oil, canola, and some other minor feedstocks. While soybean production is projected to grow in coming years, the biodiesel industry hopes to achieve higher output through advanced technologies for increasing oil supply and production of new feedstock. If algal oil becomes commercially available, as projected within the next 5-10 years, it would greatly benefit both biodiesel and renewable diesel/jet fuel industries. Given the right resources, algal oil productivity can be quite high. Algae are a potential aquatic oil crop, but may also yield carbohydrates that can be converted to sugar.

7. Demand for diesel and jet fuel in the United States is projected to grow. As easily recoverable crude oil resources are diminishing and as their prices rise, more substitutes are expected to enter the market.

    - Among the diesel consumers in the country, freight trucking has the largest share. The number of light-duty vehicles using diesel is projected to increase, the rate of which will depend on the market penetration of other alternatives such as hybrid and electric vehicles.

    - Jet fuel is forming as a large and profitable market for the renewable fuels industry. Success in this area could stimulate a significant increase in the production of biofuels and associated feedstock. It is expected that jet fuel consumption by commercial carriers will continue to grow over the next years, whereas jet fuel consumption by the military will remain flat.

8. For biomass-based diesel and jet fuel to be successful among the trucking and aviation companies, they must be cost-competitive with petroleum-based fuels. It is uncertain what the future holds for these substitutes, but it is expected that the next several years, as more facilities come online, will answer many questions about the economic viability of these technologies. Much will depend on the rate of recovery of U.S. and world economies, oil prices, carbon market, and political climate.

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Appendix

Table 8. Distillate Fuel Oil and Kerosene Sales by End Use

	2007	2008	2009	2010	2011	2012
Residential						
Distillate Fuel Oil	5,141,642	5,568,066	4,103,881	3,930,517	3,625,747	3,473,310
No. 1	81,992	83,379	83,828	65,325	67,530	53,219
No. 2	5,059,651	5,484,687	4,020,053	3,865,192	3,558,216	3,420,091
Kerosene	325,320	157,505	205,136	215,587	137,232	57,316
Commercial						
Distillate Fuel Oil	2,718,674	2,850,895	2,785,246	2,738,304	2,715,335	2,557,543
No. 1 Distillate	64,089	80,322	83,323	70,671	63,982	60,588
No. 2 Distillate	2,475,571	2,630,528	2,559,629	2,545,205	2,524,697	2,384,977
No. 2 Fuel Oil	1,217,835	1,137,514	890,809	885,331	771,343	621,693
Ultra Low Sulfur Diesel	731,582	1,020,830	1,331,244	1,418,516	1,630,900	1,662,447
Low Sulfur Diesel	245,223	310,052	207,287	175,838	85,497	83,036
High Sulfur Diesel	280,932	162,132	130,288	65,520	36,958	17,801
No. 4 Fuel Oil	179,014	140,044	142,295	122,428	126,655	111,978
Residual Fuel Oil	481,368	403,972	415,107	356,343	316,713	226,150
Kerosene	67,960	32,857	31,291	35,716	23,648	8,909
Industrial						
Distillate Fuel Oil	2,466,906	2,593,750	2,159,428	2,045,164	2,179,953	2,325,503
No. 1 Distillate	37,787	35,510	26,931	32,532	63,588	39,364
No. 2 Distillate	2,371,370	2,534,715	2,054,633	1,948,268	2,055,831	2,215,033
No. 2 Fuel Oil	324,891	310,685	154,750	122,870	143,117	125,447
Low Sulfur Diesel	1,319,312	1,833,331	1,603,605	1,671,967	1,849,222	2,047,177
High Sulfur Diesel	727,167	390,699	296,278	153,432	63,492	42,410
No. 4 Fuel Oil	57,749	23,525	77,864	64,363	60,534	71,105
Residual Fuel Oil	1,187,319	1,043,883	726,210	667,672	772,676	484,957
Kerosene	88,372	22,445	25,536	45,145	22,557	12,920
Farm						
Distillate Fuel Oil	3,202,847	3,744,936	2,660,024	2,928,175	2,942,436	3,031,878
Diesel	3,147,431	3,698,265	2,620,378	2,895,104	2,912,647	3,007,499
Other Distillate	55,416	46,671	39,647	33,071	29,789	24,379
Kerosene	9,531	4,893	6,414	6,763	3,410	1,712
Electric Power						
Distillate Fuel Oil	669,951	615,525	581,386	548,144	506,603	461,694
Residual Fuel Oil	2,646,574	1,564,984	1,131,384	1,030,682	671,585	462,726
Oil Company						
Distillate Fuel Oil	774,984	1,066,688	760,877	951,322	1,381,127	1,710,513
Residual Fuel Oil	43,972	57,914	25,166	20,783	19,759	17,031
Total Transportation (Railroad, Vessel Bunkering, On-Highway)						
Distillate Fuel Oil	45,360,237	42,741,511	38,819,930	40,560,101	41,414,854	41,229,545
Residual Fuel Oil	6,326,931	5,257,810	4,589,049	5,142,573	4,560,070	4,819,508
Railroad						
Distillate Fuel Oil	3,634,512	3,229,625	2,759,140	2,974,641	3,121,150	3,118,150
Vessel Bunkering						
Distillate Fuel Oil	1,923,981	1,983,422	1,912,984	2,002,834	2,133,395	1,768,324
Residual Fuel Oil	6,326,931	5,257,810	4,589,049	5,142,573	4,560,070	4,819,508
On-Highway						
Distillate Fuel Oil	39,801,744	37,528,464	34,147,806	35,582,625	36,160,308	36,343,072
Military						
Distillate Fuel Oil	363,145	270,975	243,728	243,242	246,243	142,696
Diesel	202,873	254,537	213,643	215,218	223,841	126,268
Other Distillate	160,272	16,438	30,085	28,025	22,403	16,429
Residual Fuel Oil	17,719	9,250	14,609	9,851	14,653	10,324
Off-Highway						
Distillate Fuel Oil	2,512,394	2,605,660	1,985,592	2,148,677	2,070,260	2,088,157
Construction	2,206,899	2,248,506	1,749,599	1,809,806	1,810,394	1,852,241
Non-Construction	305,496	357,155	235,993	338,870	259,865	235,916
All Other						
Distillate Fuel Oil	0	0	0	0	0	0
Residual Fuel Oil	2,595	3,740	6,503	5,860	2,664	1,418
Kerosene	1,520	1,036	633	2,297	809	245

In thousand gallons. Data source: EIA 2013b

Table 9. No. 2 Diesel Sales for On-Highway Use

	2007	2008	2009	2010	2011	2012
U.S.	39,801,744	37,528,464	34,147,806	35,582,625	36,160,308	36,343,072
East Coast (PADD 1)	11,739,455	10,763,333	9,929,426	10,367,337	10,332,863	10,257,620
New England (PADD 1A)	1,123,563	1,062,422	1,044,171	1,052,933	1,064,679	1,063,943
Connecticut	303,570	292,688	266,121	267,948	271,070	266,474
Maine	181,010	180,284	176,004	178,774	176,241	173,717
Massachusetts	402,629	375,414	399,575	394,967	410,375	418,613
New Hampshire	97,695	97,837	92,882	93,381	91,778	91,143
Rhode Island	73,882	55,826	55,684	59,220	57,035	54,666
Vermont	64,777	60,373	53,905	58,643	58,180	59,330
Central Atlantic (PADD 1B)	4,232,345	3,956,845	3,629,109	3,796,971	3,883,499	3,898,410
Delaware	66,271	59,569	55,610	55,342	55,904	56,530
District of Columbia	10,710	15,887	11,944	11,975	8,742	8,535
Maryland	573,321	528,862	515,315	536,150	501,897	503,999
New Jersey	988,732	902,201	679,361	793,752	888,154	784,867
New York	1,118,505	1,120,424	1,064,997	1,083,536	1,082,247	1,100,897
Pennsylvania	1,474,806	1,329,902	1,301,882	1,316,216	1,346,555	1,443,582
Lower Atlantic (PADD 1C)	6,383,547	5,744,066	5,256,146	5,517,433	5,384,685	5,295,267
Florida	1,670,536	1,478,514	1,322,703	1,340,494	1,329,312	1,340,337
Georgia	1,508,118	1,325,065	1,197,220	1,260,672	1,187,538	1,121,051
North Carolina	1,076,721	968,520	886,949	940,838	954,190	920,147
South Carolina	722,868	667,949	641,944	715,795	715,136	647,447
Virginia	1,111,050	1,017,285	935,552	969,057	917,431	971,673
West Virginia	294,254	286,733	271,778	290,577	281,078	294,612
Midwest (PADD 2)	12,627,117	12,123,237	10,905,027	11,509,060	11,784,798	11,886,665
Illinois	1,516,293	1,436,180	1,364,571	1,340,323	1,454,548	1,387,514
Indiana	1,356,498	1,302,135	1,109,103	1,207,711	1,225,199	1,247,331
Iowa	648,924	643,923	601,324	633,299	641,795	643,505
Kansas	489,575	480,947	441,256	476,191	467,779	474,517
Kentucky	875,135	821,452	742,976	785,240	772,677	767,231
Michigan	906,538	838,960	780,954	819,342	820,526	837,612
Minnesota	673,758	663,548	584,807	610,447	639,520	653,051
Missouri	1,087,199	985,190	944,991	977,111	970,936	957,624
Nebraska	434,093	406,238	386,874	425,442	421,847	418,302
North Dakota	177,467	193,615	194,777	237,443	318,231	376,496
Ohio	1,597,741	1,494,384	1,323,991	1,437,404	1,455,547	1,448,059
Oklahoma	840,366	906,265	729,736	741,369	789,449	814,298
South Dakota	202,607	198,713	197,232	213,298	207,311	227,663
Tennessee	1,061,941	1,002,320	826,077	891,637	895,097	882,475
Wisconsin	758,982	749,367	676,358	712,803	704,336	750,987
Gulf Coast (PADD 3)	7,615,389	7,338,939	6,641,445	6,947,707	7,234,843	7,428,440
Alabama	848,402	736,640	657,070	711,371	717,466	705,904
Arkansas	673,079	627,835	592,469	618,731	605,275	605,758
Louisiana	703,016	690,551	694,073	732,017	749,400	667,605
Mississippi	625,746	623,455	553,866	562,673	552,909	578,156
New Mexico	531,013	473,827	432,794	472,924	495,600	495,026
Texas	4,234,133	4,186,631	3,711,173	3,849,991	4,114,193	4,375,991
Rocky Mountain (PADD 4)	1,999,274	1,891,875	1,693,227	1,768,306	1,800,630	1,854,474
Colorado	588,910	566,484	510,211	523,056	501,361	517,545
Idaho	275,706	243,868	225,624	254,417	254,007	255,815
Montana	263,696	250,069	235,067	243,660	251,686	259,418
Utah	480,993	446,071	399,528	401,810	474,895	462,240
Wyoming	389,969	385,383	322,797	345,363	318,681	359,456
West Coast (PADD 5)	5,820,509	5,411,080	4,978,681	4,990,215	5,007,174	4,915,873
Alaska	174,112	171,630	202,102	166,599	169,158	111,113
Arizona	865,536	792,698	739,863	741,588	757,789	742,679
California	3,091,491	2,838,723	2,591,988	2,602,646	2,633,352	2,603,546
Hawaii	52,692	56,394	46,847	50,187	45,792	47,897
Nevada	378,182	329,292	302,145	298,895	288,458	289,875
Oregon	560,598	534,041	498,335	513,521	513,970	507,784
Washington	697,898	688,302	597,401	616,779	598,655	612,979

In thousand gallons. Data source: EIA 2013b

Table 10. Diesel Sales for Farm Use

	2007	2008	2009	2010	2011	2012
U.S.	3,147,431	3,698,265	2,620,378	2,895,104	2,912,647	3,007,499
East Coast (PADD 1)	358,009	377,605	326,068	449,575	368,704	374,504
New England (PADD 1A)	18,818	20,214	11,470	10,956	14,953	13,938
Connecticut	1,798	2,160	987	1,091	1,515	1,880
Maine	6,509	7,547	2,350	3,713	4,335	4,399
Massachusetts	3,273	1,240	1,223	831	1,195	1,831
New Hampshire	2,229	2,622	2,083	772	1,263	1,295
Rhode Island	40	103	20	16	23	34
Vermont	4,970	6,543	4,808	4,532	6,622	4,499
Central Atlantic (PADD 1B)	96,794	113,257	90,495	99,578	104,693	99,395
Delaware	5,839	4,762	5,903	6,821	8,541	6,767
District of Columbia	--	0	0	0	0	0
Maryland	13,677	17,618	8,020	10,720	11,420	11,292
New Jersey	2,030	2,726	5,951	7,343	6,115	6,413
New York	39,923	43,886	30,246	20,092	29,844	30,636
Pennsylvania	35,325	44,266	40,376	54,603	48,773	44,287
Lower Atlantic (PADD 1C)	242,397	244,133	224,103	339,041	249,059	261,171
Florida	69,001	87,131	86,642	204,791	109,128	103,325
Georgia	68,172	47,824	69,053	62,281	63,725	79,470
North Carolina	49,930	50,645	41,443	39,454	38,571	42,955
South Carolina	20,374	20,058	8,176	9,379	12,217	10,832
Virginia	33,347	36,810	17,192	20,263	23,370	22,452
West Virginia	1,573	1,667	1,596	2,874	2,048	2,137
Midwest (PADD 2)	1,596,524	1,844,300	1,384,186	1,502,450	1,510,797	1,599,681
Illinois	175,985	210,548	119,015	142,946	152,491	151,626
Indiana	136,331	130,194	92,486	85,257	116,498	126,061
Iowa	155,346	201,338	178,089	200,458	191,678	202,588
Kansas	148,827	189,901	138,644	156,717	135,899	135,168
Kentucky	24,308	30,569	20,187	18,594	20,430	18,582
Michigan	47,329	53,828	49,200	56,779	60,122	50,302
Minnesota	114,924	131,577	153,716	166,789	158,840	157,524
Missouri	138,517	123,377	88,445	91,575	92,162	101,940
Nebraska	199,851	233,656	149,308	142,888	142,327	199,787
North Dakota	100,554	136,067	96,106	119,470	134,935	126,979
Ohio	107,688	130,449	95,777	106,136	87,699	106,475
Oklahoma	57,403	56,885	36,066	43,851	26,505	33,172
South Dakota	59,835	67,897	63,165	56,899	67,198	64,939
Tennessee	36,162	31,532	20,400	23,276	21,851	23,379
Wisconsin	93,464	116,481	83,583	90,816	102,163	101,158
Gulf Coast (PADD 3)	604,338	735,740	381,868	434,193	462,577	468,982
Alabama	32,659	44,138	17,882	19,881	24,518	24,503
Arkansas	212,255	222,990	68,641	92,965	83,323	87,118
Louisiana	51,507	58,838	41,219	42,255	48,056	45,753
Mississippi	50,123	41,385	41,080	57,087	52,559	81,878
New Mexico	15,472	20,028	11,277	14,821	10,950	12,816
Texas	242,322	348,361	201,769	207,183	243,170	216,915
Rocky Mountain (PADD 4)	207,302	227,081	203,467	167,704	175,686	159,171
Colorado	43,695	58,955	40,518	39,603	41,532	32,759
Idaho	54,577	55,455	53,759	66,442	70,724	61,287
Montana	94,618	96,116	93,447	44,921	44,840	47,207
Utah	5,885	5,110	6,786	5,831	6,794	7,031
Wyoming	8,526	11,445	8,957	10,907	11,797	10,886
West Coast (PADD 5)	381,259	513,539	324,788	341,182	394,882	405,161
Alaska	37	65	108	109	126	177
Arizona	19,184	35,197	35,893	34,514	39,760	35,964
California	268,177	349,107	187,956	205,254	244,358	258,004
Hawaii	4,102	3,570	4,175	3,493	3,483	3,074
Nevada	3,008	2,901	5,322	6,351	6,444	5,102
Oregon	26,982	30,579	33,964	33,174	46,209	47,498
Washington	59,769	92,119	57,371	58,287	54,502	55,342

In thousand gallons. Data source: EIA 2013b

Table 11. Sales of Distillate Fuel Oil for Railroad Use

	2007	2008	2009	2010	2011	2012
U.S.	3,634,512	3,229,625	2,759,140	2,974,641	3,121,150	3,118,150
East Coast (PADD 1)	580,632	500,071	459,324	482,929	514,418	492,156
New England (PADD 1A)	69,282	47,582	43,763	53,930	51,126	33,306
Connecticut	4,450	3,219	2,219	2,006	2,006	5,195
Maine	126	1,694	7,252	8,284	6,818	5,970
Massachusetts	63,896	40,378	24,852	33,130	32,647	12,307
New Hampshire	119	126	697	86	124	116
Rhode Island	13	72	4	24	3	133
Vermont	678	2,092	8,740	10,400	9,528	9,586
Central Atlantic (PADD 1B)	210,461	177,750	152,309	196,570	233,005	204,527
Delaware	1,404	1,120	1,096	879	126	149
District of Columbia	0	0	0	1,229	6,392	6,770
Maryland	11,546	3,214	17,035	34,717	36,283	20,384
New Jersey	15,616	15,055	8,071	1,778	1,660	1,325
New York	63,226	44,510	35,307	33,709	42,254	35,237
Pennsylvania	118,670	113,851	90,800	124,258	146,291	140,663
Lower Atlantic (PADD 1C)	300,889	274,739	263,252	232,429	230,287	254,322
Florida	74,409	64,963	33,651	42,353	46,461	66,711
Georgia	78,927	69,710	62,072	63,770	71,374	63,902
North Carolina	47,855	29,022	89,823	62,103	32,158	41,501
South Carolina	11,321	16,023	3,602	3,051	3,973	3,983
Virginia	72,611	79,606	63,960	49,503	63,611	67,769
West Virginia	15,766	15,416	10,143	11,650	12,711	10,456
Midwest (PADD 2)	1,561,277	1,420,396	1,144,926	1,223,206	1,215,528	1,195,263
Illinois	40,116	51,287	55,322	72,188	58,526	63,808
Indiana	65,820	51,232	37,773	50,736	63,437	68,061
Iowa	58,640	62,458	40,494	41,663	36,136	30,156
Kansas	92,323	129,141	147,106	78,143	80,404	99,475
Kentucky	170,042	94,124	48,002	42,101	67,347	61,840
Michigan	49,528	41,887	25,920	18,376	10,330	13,352
Minnesota	123,390	78,651	39,188	47,567	61,340	92,275
Missouri	27,467	13,281	19,765	36,396	51,179	44,914
Nebraska	12,732	27,507	75,064	214,176	181,421	166,060
North Dakota	124,832	58,667	12,849	8,983	9,839	43,907
Ohio	333,069	316,926	206,134	179,048	203,135	175,258
Oklahoma	348,832	395,252	352,301	349,077	313,806	245,376
South Dakota	8,572	10,024	5,730	5,860	7,182	10,826
Tennessee	76,692	41,676	53,391	54,332	58,125	52,522
Wisconsin	29,222	48,285	25,886	24,559	13,321	27,434
Gulf Coast (PADD 3)	699,882	631,796	542,036	573,037	694,053	729,109
Alabama	59,852	42,588	44,546	42,465	97,177	125,439
Arkansas	20,237	27,693	25,148	18,302	26,907	43,494
Louisiana	43,862	32,201	18,345	25,425	32,515	28,110
Mississippi	46,730	31,617	24,727	17,936	37,741	29,848
New Mexico	6,152	2,092	245	1,780	1,707	19,123
Texas	523,049	495,604	429,026	467,128	498,006	483,096
Rocky Mountain (PADD 4)	262,644	222,054	212,571	228,200	245,446	214,160
Colorado	4,014	5,422	47,830	66,510	71,365	77,038
Idaho	21,070	14,622	9,678	31,307	30,448	25,068
Montana	107,710	94,818	68,520	58,543	65,919	41,901
Utah	44,721	24,643	21,178	24,774	33,371	24,216
Wyoming	85,129	82,549	65,365	47,065	44,344	45,938
West Coast (PADD 5)	530,077	455,308	400,283	467,270	451,704	487,461
Alaska	6,419	6,120	5,899	5,399	5,754	5,564
Arizona	11,940	7,230	8,200	10,566	9,698	20,624
California	317,292	261,225	219,854	252,057	255,313	258,354
Hawaii	4	6	5	37	4	4
Nevada	6,874	7,101	11,594	7,446	8	44
Oregon	82,369	94,925	91,305	104,445	87,470	114,507
Washington	105,180	78,701	63,425	87,321	93,458	88,364

In thousand gallons. Data source: EIA 2013b

Table 12. Sales of Distillate Fuel Oil for Off-Highway Use

	2007	2008	2009	2010	2011	2012
U.S.	2,512,394	2,605,660	1,985,592	2,148,677	2,070,260	2,088,157
East Coast (PADD 1)	833,519	883,356	605,884	615,812	634,470	621,261
New England (PADD 1A)	92,754	113,790	81,453	102,263	102,751	75,212
Connecticut	21,159	19,948	14,456	16,124	16,435	10,683
Maine	12,193	15,262	14,483	15,495	16,622	18,373
Massachusetts	39,016	56,006	27,388	43,133	43,432	19,129
New Hampshire	11,495	14,814	8,898	12,689	11,421	10,558
Rhode Island	4,540	2,129	5,652	3,821	3,725	3,057
Vermont	4,352	5,632	10,576	11,000	11,116	13,413
Central Atlantic (PADD 1B)	226,685	252,027	186,785	187,163	213,795	208,407
Delaware	3,149	3,210	2,578	2,201	2,306	1,812
District of Columbia	1,988	1,223	1,043	357	920	892
Maryland	35,368	37,065	15,198	14,402	23,521	21,838
New Jersey	65,404	65,491	48,769	47,895	62,894	59,809
New York	51,681	48,869	37,033	34,272	38,054	35,089
Pennsylvania	69,096	96,169	82,164	88,035	86,101	88,967
Lower Atlantic (PADD 1C)	514,080	517,539	337,646	326,386	317,924	337,641
Florida	124,123	135,397	112,263	110,675	104,005	109,119
Georgia	124,009	111,648	75,856	79,376	76,496	81,370
North Carolina	53,366	52,272	43,755	53,910	51,483	42,119
South Carolina	51,781	57,191	36,537	35,998	29,800	41,179
Virginia	138,601	139,537	59,539	38,195	46,783	56,139
West Virginia	22,201	21,494	9,695	8,231	9,357	7,715
Midwest (PADD 2)	686,931	716,068	544,191	557,179	524,627	554,255
Illinois	110,067	108,788	60,997	59,541	56,167	66,746
Indiana	33,460	50,166	52,110	41,855	49,234	49,992
Iowa	24,765	28,979	29,836	30,989	26,475	30,634
Kansas	21,572	17,213	28,999	30,359	25,422	19,184
Kentucky	26,757	34,351	31,866	27,906	25,590	21,723
Michigan	47,782	52,039	35,267	34,737	35,147	33,514
Minnesota	57,964	86,484	45,198	54,211	62,268	55,294
Missouri	68,262	64,660	50,840	61,485	41,060	31,435
Nebraska	44,362	11,846	26,223	18,344	14,586	19,173
North Dakota	11,741	11,056	25,623	27,802	25,811	44,192
Ohio	68,156	74,876	56,113	56,694	49,976	60,223
Oklahoma	44,661	45,228	25,704	24,332	24,912	27,796
South Dakota	10,282	9,260	9,622	7,239	15,484	10,211
Tennessee	65,938	68,110	31,117	43,251	37,539	43,024
Wisconsin	51,163	53,012	34,676	38,436	34,954	41,115
Gulf Coast (PADD 3)	480,332	486,148	360,795	382,691	370,941	417,101
Alabama	62,743	80,762	61,501	58,051	58,172	69,907
Arkansas	48,044	30,752	23,210	29,752	22,773	22,622
Louisiana	76,131	82,523	48,510	68,889	44,130	42,719
Mississippi	59,253	53,833	17,862	18,404	20,889	26,199
New Mexico	3,235	16,705	5,729	24,907	24,865	29,454
Texas	230,926	221,572	203,983	182,689	200,112	226,200
Rocky Mountain (PADD 4)	149,317	138,282	139,107	121,101	125,195	113,299
Colorado	48,550	47,759	52,113	48,837	56,745	45,876
Idaho	23,362	18,349	14,912	11,780	11,916	10,317
Montana	22,325	28,642	20,985	19,520	14,700	14,814
Utah	35,219	29,871	26,922	19,952	26,754	20,749
Wyoming	19,860	13,661	24,176	21,012	15,080	21,543
West Coast (PADD 5)	362,295	381,807	335,615	471,893	415,027	382,242
Alaska	16,599	22,832	14,334	14,738	10,126	13,962
Arizona	66,808	76,168	49,894	60,142	65,414	66,025
California	135,327	127,748	146,296	195,299	208,632	183,553
Hawaii	9,414	8,570	9,806	7,839	7,920	9,578
Nevada	29,733	29,091	43,385	124,123	44,879	37,652
Oregon	22,925	33,848	34,306	30,108	34,562	36,028
Washington	81,488	83,550	37,593	39,644	43,493	35,443

In thousand gallons. Data source: EIA 2013b

Table 13. Distillate Fuel Oil Sales for Vessel Bunkering Use

	2007	2008	2009	2010	2011	2012
U.S.	1,923,981	1,983,422	1,912,984	2,002,834	2,133,395	1,768,324
East Coast (PADD 1)	466,132	461,533	276,013	259,319	296,947	283,254
New England (PADD 1A)	43,014	69,102	45,147	30,589	32,414	38,891
Connecticut	6,654	5,683	3,914	1,898	1,502	2,838
Maine	8,298	6,815	15,611	4,207	4,128	13,349
Massachusetts	21,336	48,094	19,193	17,529	17,132	13,612
New Hampshire	2,740	2,552	2,327	1,110	1,395	1,815
Rhode Island	3,987	5,958	4,101	5,824	8,257	7,243
Vermont	0	0	0	21	0	35
Central Atlantic (PADD 1B)	147,629	129,789	104,487	67,726	76,446	74,154
Delaware	615	919	582	485	1,658	615
District of Columbia	11	7	5	13	15	17
Maryland	21,380	16,507	8,240	8,335	2,662	7,300
New Jersey	87,549	74,725	68,321	37,276	61,990	55,842
New York	12,339	10,814	8,497	6,869	4,453	7,089
Pennsylvania	25,735	26,816	18,842	14,748	5,669	3,290
Lower Atlantic (PADD 1C)	275,489	262,642	126,379	161,005	188,087	170,209
Florida	145,269	180,514	84,718	118,991	142,198	131,685
Georgia	14,016	10,831	10,765	12,904	12,387	11,300
North Carolina	8,009	8,280	5,957	8,231	5,613	4,177
South Carolina	18,795	15,892	8,094	8,043	5,865	4,966
Virginia	43,971	18,558	16,745	12,731	21,562	18,063
West Virginia	45,429	28,568	99	105	461	18
Midwest (PADD 2)	386,653	428,712	385,719	370,587	389,493	354,341
Illinois	71,805	101,851	85,117	56,575	56,000	59,508
Indiana	29,805	24,226	17,165	19,849	22,319	8,139
Iowa	4,867	4,151	4,523	5,381	5,163	5,609
Kansas	0	0	0	0	0	0
Kentucky	91,516	104,387	102,305	98,294	104,160	96,669
Michigan	8,900	7,585	7,585	17,875	19,825	20,792
Minnesota	7,551	18,987	9,811	7,638	4,111	1,649
Missouri	34,158	42,760	44,967	49,922	42,388	40,858
Nebraska	0	0	0	0	0	0
North Dakota	0	0	0	0	0	0
Ohio	12,122	17,733	24,586	27,668	30,684	23,532
Oklahoma	10,764	10	8	9	6	7
South Dakota	0	0	0	0	0	0
Tennessee	114,703	106,326	88,312	85,786	103,077	95,856
Wisconsin	461	696	1,339	1,591	1,760	1,723
Gulf Coast (PADD 3)	613,864	721,875	827,977	1,010,776	1,026,408	677,343
Alabama	36,334	63,100	61,852	65,017	41,339	25,542
Arkansas	420	49,384	47,557	47,769	55,246	425
Louisiana	351,726	399,347	378,642	481,453	564,650	382,462
Mississippi	93,581	106,799	141,302	93,384	58,285	58,505
New Mexico	0	0	0	0	0	0
Texas	131,803	103,245	198,625	323,153	306,887	210,408
Rocky Mountain (PADD 4)	27	26	19	6	2	17
Colorado	2	2	1	1	2	2
Idaho	25	25	18	5	0	15
Montana	0	0	0	0	0	0
Utah	0	0	0	0	0	0
Wyoming	0	0	0	0	0	0
West Coast (PADD 5)	457,306	371,275	423,256	362,147	420,545	453,369
Alaska	127,614	119,460	104,126	115,129	118,900	136,681
Arizona	1	1	0	1	2	1
California	104,583	88,088	163,438	96,015	115,772	127,038
Hawaii	129,743	58,786	71,496	63,757	88,652	86,663
Nevada	25	22	7	6	6	7
Oregon	20,502	24,003	24,143	22,626	21,728	22,450
Washington	74,838	80,915	60,046	64,613	75,485	80,528

In thousand gallons. Data source: EIA 2013b

Table 14. Diesel Sales for Military Use

	2007	2008	2009	2010	2011	2012
U.S.	202,873	254,537	213,643	215,218	223,841	126,268
East Coast (PADD 1)	43,728	57,003	47,877	42,842	58,296	35,470
New England (PADD 1A)	8,260	15,028	3,342	3,427	5,656	2,836
Connecticut	1,660	997	207	236	622	501
Maine	3,551	6,915	1,094	2,495	1,300	774
Massachusetts	2,125	3,182	500	343	3,101	271
New Hampshire	815	3,178	1,225	292	143	83
Rhode Island	19	399	35	21	468	1,091
Vermont	90	357	282	40	22	115
Central Atlantic (PADD 1B)	12,921	15,306	10,429	9,111	13,076	8,293
Delaware	99	88	122	75	168	70
District of Columbia	598	291	165	265	693	300
Maryland	3,950	4,772	2,807	3,249	3,646	1,162
New Jersey	3,951	4,562	2,331	2,127	2,408	3,323
New York	3,058	3,656	3,288	2,460	2,394	785
Pennsylvania	1,265	1,939	1,715	936	3,767	2,654
Lower Atlantic (PADD 1C)	22,547	26,669	34,106	30,304	39,564	24,342
Florida	4,444	6,115	4,370	5,481	6,323	6,043
Georgia	2,502	2,936	3,644	3,282	3,357	2,957
North Carolina	3,848	5,265	18,456	16,839	12,133	2,794
South Carolina	6,479	8,859	4,029	1,911	1,436	636
Virginia	4,812	3,460	3,259	2,611	16,167	11,630
West Virginia	462	33	347	179	148	281
Midwest (PADD 2)	7,549	8,934	8,526	7,053	7,483	5,948
Illinois	266	316	329	728	1,415	239
Indiana	12	225	46	121	31	45
Iowa	38	37	50	50	154	43
Kansas	812	614	586	436	341	87
Kentucky	919	944	470	1,110	1,022	467
Michigan	1,184	2,147	889	267	807	1,270
Minnesota	292	454	257	167	225	322
Missouri	1,738	1,939	1,881	1,596	2,226	1,748
Nebraska	48	118	178	111	116	107
North Dakota	367	422	1,361	1,576	446	661
Ohio	72	707	1,186	325	268	192
Oklahoma	452	312	295	80	125	457
South Dakota	927	131	171	20	53	24
Tennessee	181	95	630	270	81	15
Wisconsin	240	473	197	194	173	273
Gulf Coast (PADD 3)	45,555	38,923	33,652	40,713	35,803	10,729
Alabama	1,369	793	2,014	2,203	2,124	1,649
Arkansas	284	421	283	447	458	329
Louisiana	11,319	940	1,619	3,892	2,900	1,648
Mississippi	722	105	769	845	1,280	1,726
New Mexico	839	548	582	306	859	572
Texas	31,023	36,115	28,385	33,020	28,183	4,805
Rocky Mountain (PADD 4)	950	1,230	1,063	2,267	2,537	663
Colorado	553	761	715	922	1,166	365
Idaho	247	23	40	17	9	0
Montana	145	424	130	109	8	1
Utah	6	23	96	917	1,097	101
Wyoming	0	0	81	303	257	197
West Coast (PADD 5)	105,090	148,447	122,525	122,342	119,723	73,457
Alaska	6,835	7,305	7,875	6,369	7,234	5,748
Arizona	1,237	1,611	1,291	1,649	330	284
California	11,984	10,093	16,107	56,828	36,038	44,068
Hawaii	75,189	1,940	8,939	48,583	2,141	1,557
Nevada	1,868	1,560	1,684	1,745	1,983	1,205
Oregon	2,027	1,948	2,198	2,388	1,469	1,940
Washington	5,950	123,989	84,431	4,781	70,527	18,657

In thousand gallons. Data source: EIA 2013b