

What's the Difference between Biodiesel and Renewable (Green) Diesel? or What Renewable Fuels Can Be Used in Compression Ignition Engines?

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Advanced Biofuels USA

Advanced Biofuels USA
507 North Bentz Street
Frederick, MD 21701
www.AdvancedBiofuelsUSA.org

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List of Abbreviations

ACRE	Advanced Catalyst Reduction and Economization	GTL	Gas-to-Liquid
APR	Aqueous Phase Reforming	H₂	Hydrogen
ASTM	Formerly American Society for Testing and Materials	HDRD	Hydrogenation-derived Renewable Diesel
BTL	Biomass-to-Liquid	HOF	High Octane Fuel
CARB	California Air Resources Board	HRD	Hydroprocessed Renewable Diesel (HRD)
CI	Compression Ignition Engine	HTL	Hydrothermal Liquefaction
CME	Canola Methyl Ester	HVO	Hydrotreated Vegetable Oil
CN	Cetane Number	IDL	Indirect Liquefaction
CO	Carbon Monoxide	ILUC	Indirect Land Use Change
CO₂	Carbon Dioxide	IRS	Internal Revenue Service
COA	Certificate of Analysis	LEO	Lignin Ethanol Oil
DEF	Diesel Emission Fluid	LPG	Liquid Petroleum Gas
DME	Dimethyl Ether	NBB	National Biodiesel Board
DOE	U.S. Department of Energy	NTDE	New Technology Diesel Engines and New Technology Diesel Exhaust
EGR	Exhaust Gas Recirculation	MSW	Municipal Solid Waste
EPA	U.S. Environmental Protection Agency	MTG	Methanol-to-Gasoline
EU	European Union	NO_x	Nitrous Oxides
EWABA	European Waste-to-Advanced Biofuels Association	OEM	Original Equipment Manufacturer
FAME	Fatty Acid Methyl Esters	P_c	Critical Pressure
FFA	Free Fatty Acid	PME	Palm Oil Methyl Ester
FOG	Fats, Oils and Greases	PPO	Pure Plant Oil
FT	Fischer-Tropsch	RD	Renewable Diesel
FTC	Federal Trade Commission	rDME	Renewable Dimethyl Ether
GHG	Greenhouse Gas	RME	Rape Methyl Ester
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model		

SAE	Society of Automotive Engineers
SCF	Supercritical Fluid
SME or SOME	Soybean Oil Methyl Ester
SVO	Straight Vegetable Oil
T_c	Critical Temperature
TERI	The Energy and Resources Institute
TME	Tallow Methyl Ester
UCO	Used Cooking Oil
ULEV	Ultra Low Emission Vehicle
ULSD	Ultra-Low-Sulfur Diesel
VOCs	Volatile Organic Compounds
WTW	Well-to-Wheels

1. Introduction

Diesel (compression ignition (CI)) engines are all around us, from delivery trucks to construction and farm equipment to long haul trucks to boat and locomotive engines. They are likely to remain with us for a long time, not only because they are so useful for efficient freight transportation and heavy duty work. but also because they last for many years. Also because economically replacing diesel engines with electric powered-alternatives will take quite a while since only about a third are expected to be replaced by other drivetrains by 2035 [174,175]. Currently, about 22% of US transportation fuel is diesel.[200]

What is the quickest, least expensive way to decrease the carbon footprint and mitigate air pollution from these diesel engines? Advanced renewable, sustainable fuels! Coupled with advanced engine design.

This paper begins by explaining briefly how CI engines work and how they are different from spark ignition engines which use gasoline or gasoline-alternative renewable fuels like ethanol, biobutanol, methanol and others. Next, and in greater detail, it focuses on exploring advanced renewable, sustainable fuels that are currently available or in development for use in CI engines.

The first version of this paper published in 2011 asked “What is the Difference between Biodiesel and Renewable Diesel?” because those were the two renewable fuels available at the time. This revision updates information on those fuels and adds others that have been



commercialized or are in development since that initial publication.

This paper is organized by fuel, including how the fuel is made, what feedstock may be used to make it, its properties, specifications, and environmental impact.

Renewable alternative fuel options discussed in this review include:

- Biodiesel
- Renewable diesel which goes by many names including:
 - Hydrotreated vegetable oil (HVO)
 - Hydrogenation-derived renewable diesel (HDRD)
 - Hydroprocessed renewable diesel (HRD)
 - and others
- Co-processed diesel
- Straight vegetable oil (SVO)
- Renewable dimethyl ether (rDME)
- Ethanol
- Lignin ethanol oil (LEO)

In the course of this discussion, we will also briefly address diesel generators (gen sets),

stationery (non-mobile) diesel engines, "marine diesel," and some renewable options for those uses.

Interest in renewable fuels for shipping and maritime use has increased due to the International Maritime Organization's regulations intended to reduce sulfur dioxide, nitrogen oxides, and other pollutants from global shipping exhaust. Some of the renewable fuels included in this paper are being studied as replacements for bunker oil and other marine applications to meet these requirements [176].

This paper is designed to help the general public better understand renewable fuel options for CI engines. It should be particularly useful for fleet managers and those working on incorporating transportation and equipment into corporate, government, and regional sustainability programs as well as for those interested in investing in renewable fuels.

This should also be a useful reference for people working on or reporting on policy

and legislation to defossilize transportation systems, such as the Transportation and Climate Initiative being discussed in the mid-Atlantic and Northeast [177] and the Midwestern Clean Fuels Policy [178].

This paper may also be used as a CI engine renewable fuels introduction or overview by teachers, faculty, and students of engineering, science, environmental studies, automotive mechanics courses, and others. This is not intended to be an SAE study or academic treatise.



2. Background

Combustion of fossil fuels has raised concerns regarding climate change, energy security, and pollution control, among others. Even with the promotion of electric vehicles to address these concerns, we anticipate continued use of diesel (compression ignition) engines especially for long-haul, heavy duty purposes, for locomotives, for construction, for agricultural and industrial equipment, and for other applications long into the future [174,175].

The other common internal combustion engines, spark ignition engines, rely on a spark instead of compression to ignite the fuel. In the US, most light duty vehicles have spark ignition engines and can run on fossil-based gasoline and alternative renewable fuels including blends using ethanol, biobutanol, methanol, etc.

CI engines use compression instead of sparks to cause rapid, uncontrolled combustion. Due to the characteristics of

this type of combustion, special after-treatment of exhaust to decrease soot and other pollutants is required.

Click on or follow these reference links to see videos that compare compression ignition and spark ignition engines, demonstrating these characteristics [179] and an animation of an engine that uses a combination of compression ignition and spark ignition fueled by gasoline [180].

The high sulfur content of petroleum diesel fuel makes its exhaust difficult to treat or clean to meet pollution standards. Not until January, 2001 were US low sulfur diesel standards finalized. Oil companies had seven additional years to comply [181]. Renewable low sulfur fuels used in CI engines enable them to have a lower life-cycle carbon footprint and improved life-cycle emissions.

These positive attributes are particularly important in the wake of “dieselgate,” and of continuing distrust of compression ignition engines to be able to meet pollution control regulations.

“Dieselgate” is the criminal scandal in which Volkswagen (VW) and others admitted that for years, they had cheated on diesel emissions tests with “defeat devices,” software masking excessive nitrogen oxide pollution.

These defeat devices were used in 11 million Volkswagen, Porsche, Audi, Seat and Skoda diesel vehicles worldwide. The defeat devices enabled the cars to meet US exhaust pollution standards when monitored in tests, but in everyday use, their emissions exceeded the limits. Tests carried out in the wake of the scandal found that diesel engines by other carmakers were also polluting more on the road than during testing. Investigators found that some cars spewed out up to 40 times more harmful nitrogen oxide—linked to respiratory and cardiovascular diseases—than legally allowed [182,181,183,184,185,186].

Work continues to address CI engine emissions including research on exhaust remediation catalysts which may reduce the emission of nitrogen oxides which remain a problem in biodiesel exhaust [187].

U.S. transportation energy sources/fuels, 2019 1

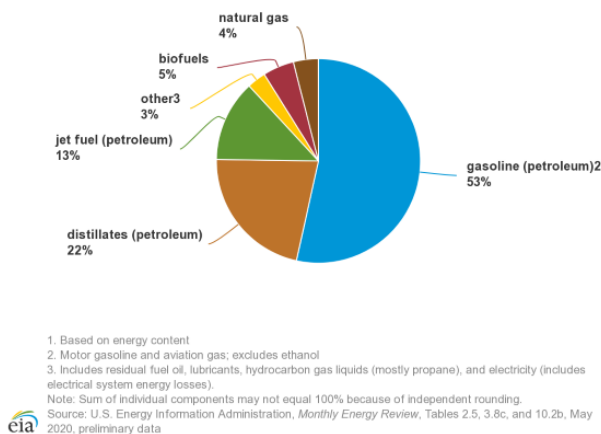


Figure 1: U.S. Transportation Energy Sources/Fuels [200]

3. Diesel (Compression Ignition) Engines

A. Overview of Diesel (Compression Ignition) Engines

From the transportation of people and consumer goods, to electric power

generation, the compression ignition (CI) or diesel engine plays a vital role in the global economy. Known as a “diesel fuel system” or “compression-ignition engine”, the diesel engine uses heat produced by compressed intake air to initiate fuel combustion. Figure 1 outlines the various stages of this process, a thermodynamic cycle developed by Rudolf Diesel in 1897 [1].

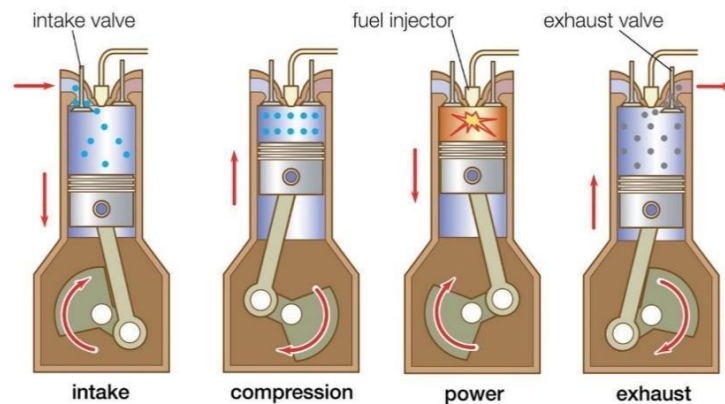


Figure 2 Stages of the Diesel Engine Cycle [2]

The operation of the diesel (compression ignition (CI)) engine begins by compressing air into a combustion chamber before fuel is atomized. The spray pattern of the injectors is critical to maintain engine performance measures. This compression-injection “action” can be observed from the “intake” to initial “power” stage as depicted in the first three stages of the figure above.

The high temperature of the compressed gases in the chamber causes air to mix with fuel vapor until it reaches its auto-ignition temperature. At this stage, the fuel ignites,

releasing the energy stored within it which drives the piston down creating power as exhaust is expelled from the chamber and the piston prepares to repeat the cycle.¹ The period of uncontrolled combustion, leads to the pollution characteristics of CI engines.

B. Production of Fossil-Based Diesel

The term “diesel fuel”, is also known as “petroleum distillate fuel oil”, “petroleum diesel”, “#2 diesel”, “petrodiesel”, “gas oil”

¹ Compare to spark ignition engines which, instead of compression, rely on spark to ignite the fuel, such as fossil-based gasoline

and alternative renewable fuels including blends using ethanol, biobutanol, methanol, etc.

in EU regulations, or simply “diesel” and commonly refers to any fossil-based fuel for a CI engine.

Diesel is traditionally refined from crude oil via a process called fractional distillation.

By increasing the temperature of the pre-processed crude, different hydrocarbon products are separated from each other, each classified by their boiling fraction. Diesel, a medium distillate fraction, is produced within a boiling range from 150 to 370 degrees Celsius [3].

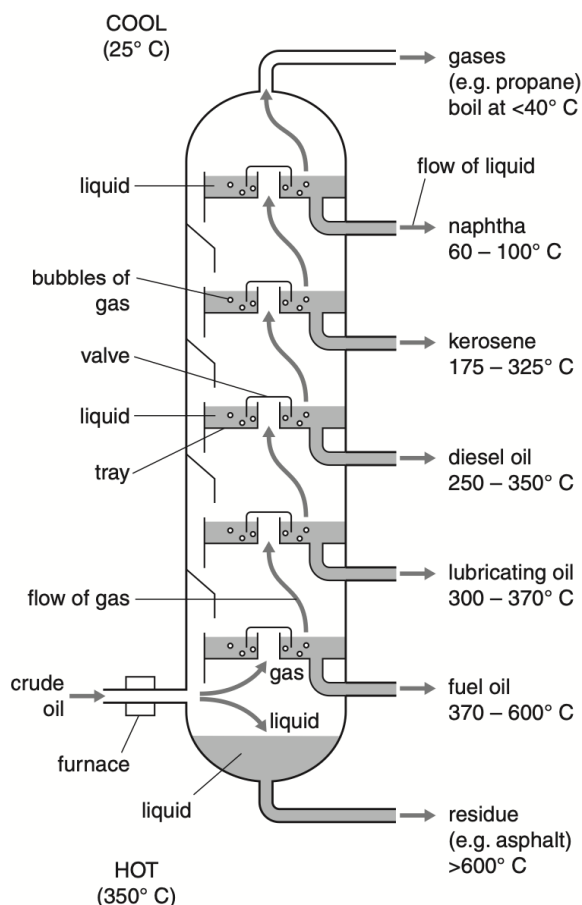


Figure 3: Crude oil separated into hydrocarbon-based products via fractional distillation [3]

In order to comply with government environmental regulations to lower particulates, sulfur dioxide (SO₂), and other emissions, as well as to comply with engine manufacturers' fuel requirements for newer diesel engines, undesirable elements such as sulfur, nitrogen, and oxygen must be removed after fractional distillation. The ultra-low-sulfur diesel (ULSD) that meets these standards contains 97% less sulfur than low-sulfur diesel [4]. ULSD was developed to allow the use of

improved pollution control devices that reduce diesel emissions more effectively because these devices can be damaged by sulfur[5]. The “dieselpgate” scandal described above grew from these difficulties in meeting pollution standards with a diesel engine [181].

Diesel may also be made from fossil natural gas in a gas-to-liquid (GTL) process. In the first stage synthesis gas, a mixture of hydrogen and carbon monoxide, is

manufactured from natural gas by partial oxidation. Impurities are removed from the syngas. A second stage converts the synthesis gas into liquid hydrocarbons using a catalyst. In this stage, a liquid is formed which looks and feels like wax at room

temperature. The final stage is cracking and isomerisation, which “tailors” the molecule chains into products with desired properties. This yields liquids such as diesel, kerosene and lubricant oil. [201] [202]

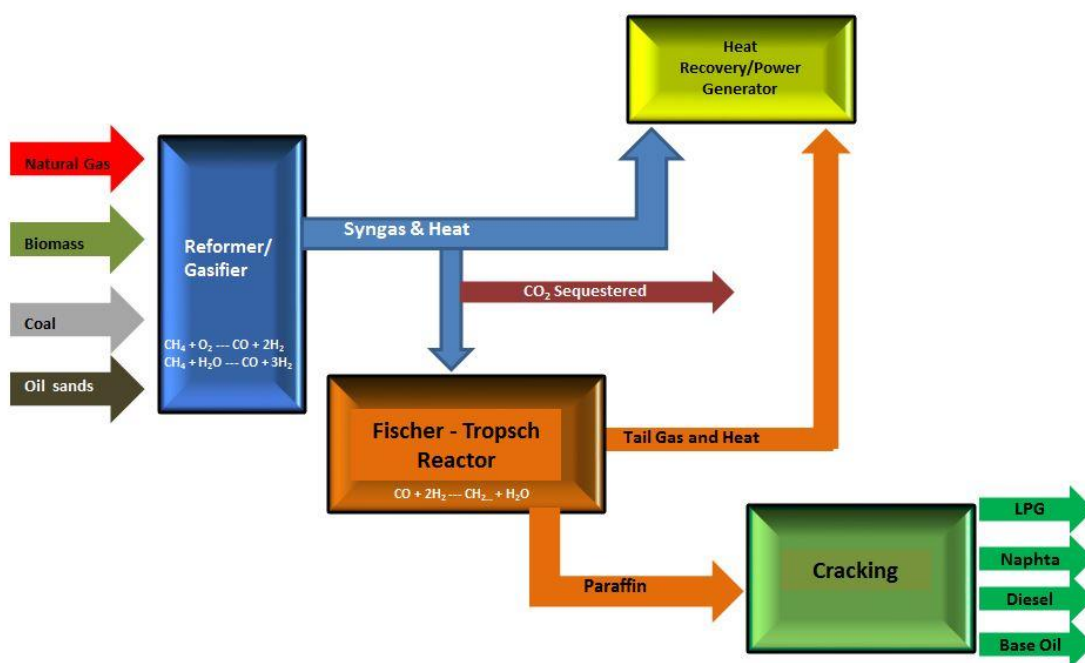


Figure 4: GTL Technological Process with Fischer-Tropsch Synthesis Reactor [203]

C. Fossil-Based Diesel Fuel Properties

Low temperature operability is an issue with middle distillate fuels such as diesel. Due in part to the straight- and branch-chained hydrocarbons that constitute these fuels, paraffin waxes can solidify at ambient winter temperatures. This may plug fuel filters or completely gel the fuel, making it impossible for the fuel system to deliver fuel to the engine [6]. A diesel fuel that commonly has good ignition quality also improves cold start performance; the smoothness of operation, misfire, smoke emissions, noise, and ease of starting are

also dependent on diesel's ignition quality, known as its cetane number.

Additives are used to manipulate fuel properties after manufacturing in a fuel distribution system and by the end-user. More specifically, fuel additives aid in handling, improve fuel stability, protect engine systems, and manipulate the combustion process while having a minimal impact on inherent physical properties such as density, viscosity, etc. [7].

Shell Oil describes its GTL Fuel as having broadly similar physical characteristics to

crude diesel derived from crude oil, with a much higher cetane number, a higher mass calorific value, lower levels of sulphur and aromatics, and a lower density. [201]

D. Fossil-Based Diesel Fuel Specifications

Diesel specifications are defined internationally by the ASTM D975 standard and by the EN 590 standard in Europe (amongst others). ASTM International's specification is a specification that describes multiple tests and the acceptable limits which a diesel fuel must meet at the time of delivery [8]. Diesel fuel purchasers generally verify compliance by asking their fuel supplier for a Certificate of Analysis (COA), rather than by sending a fuel sample to a laboratory for testing [8]. The EN 590 standard is observed by all fuel suppliers in Europe [9].

ASTM D975 allows up to 5 percent of the fuel to be biodiesel, and the US Environmental Protection Agency (EPA) and Federal Trade Commission (FTC) allow sales of such blends, without requiring special labeling or notification to purchasers [10]. EN 590 allows up to 7 percent FAME (fatty acid methyl esters) without special labeling or notification to purchasers [9].



E. Environmental Impact of Fossil-Based Diesel Fuel Use

Diesel exhaust contains substances that can pose a risk to human health and to the environment. Containing more than 40 toxic air contaminants [11], the exhaust itself is a complex mixture of thousands of gases and fine particles. These include many known or suspected carcinogens and other harmful pollutants. Older diesel engines in particular are substantial emitters of particulate matter (PM) and nitrous oxides (NO_x), but relatively small emitters of carbon monoxide (CO) and volatile organic compounds (VOCs). New emissions controls reduce all types of emissions and pending US regulations will reduce NO_x potentially by another 90% [6].

In addition, exhaust emissions depend on how a diesel engine is operated (i.e., duty cycles). Another challenge associated with improving emissions from diesels arises from their long service life. As a consequence, it may take many years for new emissions regulations to have a significant impact while older, high-emissions engines are gradually replaced by newer low-emissions engines [6].

Because these vehicles remain in use for so long, using renewable fuels that burn with fewer harmful pollutants even in older engines helps reduce their harmful environmental impact.

This paper describes renewable fuels and biofuels in commercial production and in development that can be used in compression ignition/diesel engines.

4. Biodiesel Fuel

A. Overview of Biodiesel Fuel

Biodiesel fuel is made, usually by a process called transesterification or esterification, from renewable sources such as vegetable oils, animal fats, and recycled cooking oils. It can be used on its own (with some precautions or restrictions discussed below) or blended with conventional diesel or renewable diesel [25].

Engine manufacturers design their engines for use with specific fuels and will recommend the use of that fuel in owners' manuals. The National Biodiesel Board (NBB), the trade association for the biodiesel and renewable diesel industry in the US, includes on their website a comprehensive list of original equipment manufacturers (OEMs) and the engines that they make that are supported when used with various blends of biodiesel [12].

Biodiesel blends are identified by the letter "B" followed by the corresponding level of biodiesel such as B2 (2 percent), B10 (10 percent), B20 (20 percent) and so on. According to NBB, all major OEMs producing diesel vehicles for the U.S. market support at least B5 and lower blends. Gross Vehicle Weight Classes 5-8 are vehicles that account for 92% of on-road diesel fuel use, the vast majority of the medium- and heavy-duty trucks. OEMs permit up to B20 (20% biodiesel and 80% petroleum diesel) for these vehicles.

The biodiesel component must meet ASTM D6751, and the B20 blends must meet

ASTM D7467 specifications. Many OEMs also recommend the use of BQ-9000 producers accredited for complying with a combination of the ASTM standard for biodiesel, ASTM D6751, and a quality systems program that includes storage, sampling, testing, blending, shipping, distribution, and fuel management practices [188].

Some fleets have successfully experimented with higher blends such as B30 in Indonesia [99] and B35 in Florida [13].

A two-tank system has been developed that enables use of B100 by using diesel equivalent fuel during startup and shutdown in order to manage cold temperature performance without paraffinic buildup [14].



B. Production of Biodiesel Fuel

The major elements required to produce biodiesel are: feedstocks, conversion technologies, and product purification.

1. Feedstocks Used for Biodiesel Fuel

Different feedstocks produce biodiesel with distinct qualities depending on their type of fatty acid chain [15,16]. The choice of fats or oils to be used in producing biodiesel is both an economic and process chemistry decision.

Plant oils and animal fats are commonly used in various combinations to make biodiesel. They include: soybean, cottonseed, canola, carinata, corn,

rapeseed, and palm oil, as well as recycled cooking greases such as yellow grease or animal fats such as beef tallow, pork lard, poultry fat, and fish oils. Use of oils from pennycress [17], camelina [18], cuphea, brown grease [19], various strains of algae, and others are also being developed [20].

Depending on the feedstock, biodiesel may be referred to by a number of more specific terms and corresponding acronyms such as:

Table 1: Biodiesel terms and acronyms

Soybean oil methyl ester	SME or SOME
Rape methyl ester	RME
Canola methyl ester	CME
Palm oil methyl ester	PME
Tallow methyl ester	TME

Also under development are algae strains that are able to thrive in wastewater [20,21], and that increase lipid-production when stressed [22]. These may serve not only as biofuel feedstock, but their cultivation may also solve other environmental problems such as treating waste water, cleaning up industrial emissions, and using nutrients in agricultural run-off.[198]

Fats, oils and greases (FOG), including used cooking oil (UCO), are prime examples of potentially mixed feedstock. Although they are usually mostly plant based they may also contain animal fat.

Using FOG to make biodiesel mitigates problems that can be caused by the disposal of UCO and greases in drains and sewerage systems [23] and prevents public health problems associated with the re-sale of the potentially unhealthy “gutter oil” in informal markets [24].

To begin, UCO must be purged of any impurities such as dirt or charred food before it can be processed for fuel. Also, some feedstocks may contain high levels of free fatty acids (FFAs), and other components that require special pretreatment [25].

Most vegetable oils have a low percentage of associated FFAs; however,

crude or unrefined vegetable oils contain some FFAs and phospholipids [25]. Animal fats and yellow grease have much higher FFA levels. For some processing, though, FFA content is not as significant an issue due to the advent of semi-continuous biodiesel plants able to process any feedstock having higher FFA content at a low capital cost [26].

Raw or refined plant oils, fats, or recycled greases that have not been processed, such as straight vegetable oil (SVO), are not biodiesel [25] and require special accommodations when used as fuel, and use for fuel is not recommended.

Because the feedstocks have different properties, the resulting biodiesel fuel also has variations in characteristics that may affect performance [16].

Table 2: Select properties of biodiesel by feedstock and ultra-low sulfur diesel [16,189]

Feedstock	Cloud Point (°C)	Cetane Number
Soybean Oil	0.9	47
Canola Oil	-3.3	55
Choice White Grease	7.0	64
Yellow Grease	6.0	58
Inedible Tallow	16.0	62
Ultra-Low Sulfur Diesel	-45 to -7	40 in.

2. Making Biodiesel Fuel: Commercialized Conversion Technologies [25]

The National Renewable Energy Laboratory uses the term esterification to cover all biodiesel production scenarios because 'esterification' is rigorously chemically correct. This term covers basic transesterification, which almost all producers use, and also covers acid esterification pre-steps to convert free fatty acids into fatty acid methyl esters (FAME) prior to converting fats or oils into FAME, and also would be correct for enzymatic

catalysts which may do both chemical processes using a single catalyst [95].

a) Transesterification

The transesterification process is a reversible reaction carried out by the mixing of fatty acids, short-chain alcohols (commonly methanol or ethanol), and catalyst. Generally, a strong base, acid, or enzymatic material can be used as a catalyst such as sodium- and potassium hydroxide or sodium methoxide [27].

Common alcohols used include methanol, ethanol, isopropanol, and butanol. Use of alcohols other than methanol or ethanol may impact fuel conformance to certain specifications. A key quality factor for the alcohol used is the water content. High water content can result in poor yield and high levels of soap, FFAs, and triglycerides in the final product.

Other issues such as the cost of the alcohol, fuel tax credits, and sustainability issues influence the choice of alcohol. Unused alcohol is recovered and recycled back into the process to minimize operating costs and environmental impacts. Although methanol is more toxic than ethanol, it is considerably easier to recover and, thus, less expensive to recover. Unlike ethanol, methanol does not form an azeotrope with water, so it vaporizes at a different temperature than water, making it more simple to recover and reuse [27].

Using bioethanol is more renewable than using fossil-based methanol, which is the common practice. Using bioethanol for production of fatty acid ethyl esters (FAEE) instead of using fossil-based methanol also can support farmers [28]. Because undenatured and anhydrous ethanol must be used, there can be benefits to co-locating biodiesel production with ethanol production facilities [29] although it is not currently common practice. Using renewable methanol when it becomes more available and affordable could mitigate some of these criticisms [30].

The industrial scale production of ultra-low carbon intensity renewable methanol is already underway in Iceland, Netherlands, and Canada. For example, in Iceland, CO₂ from geothermal power generation is

captured and reacted with renewable hydrogen produced via electrolysis into renewable methanol. In the Netherlands, biogas is being converted into advanced second generation bio-methanol. In Canada, bio-methanol is being produced from municipal solid waste (MSW) feedstocks [30].



The end products of transesterification are “raw” biodiesel and glycerol (also called glycerin). These “raw” products undergo additional cleaning.

The purified glycerol can then be used in the food and cosmetic industries, as well as in the oleochemical industry. Glycerol can also be used as a substrate for anaerobic digestion. Alcohol is used to remove glycerin in triglycerides because it is undesirable in diesel fuel.

In addition, triglycerides, monoglycerides and diglycerides can also exist. These are intermediates formed during the transesterification reaction which may contaminate the final product in addition to residual alcohol, glycerol, and catalyst [27], thus, they must be washed out to produce the final product.

Biodiesel Reaction



Reacting:

**100 Lbs.
Vegetable Oil
or
Animal Fat**

+

**10 Lbs.
Alcohol**

Methanol
or Ethanol

In the Presence of a Catalyst

Sodium Hydroxide or
Potassium Hydroxide



Yields:

**100 Lbs.
Biodiesel**

+

**10 Lbs.
Glycerine**

**Transesterification process produces mono-alkyl esters –
chemically similar to diesel fuel**

10

Figure 5: Diagram of Transesterification Process [190]

b) Innovations and Improvements to Basic Transesterification

Over the years biodiesel production has become commercialized and industrialized with continuous quality improvements, improvements of process, and resource use.

For example, acid/base technology, an evolution of the conventional transesterification process, includes a re-esterification step to remove FFA from feedstock. This approach can process waste feedstocks with high FFA levels but requires expensive pretreatment.

Biodiesel may also be made with solid state or enzymatic catalysts. Only a few small plants using this technology are in operation. They can accept various feedstocks, but the high cost of the enzymes or the difficulty of purifying the product downstream present challenges [31,103].

Here are brief descriptions of some other examples of developing innovations in biodiesel production:

- Use of multiple feedstocks, especially wastes [31]
- Advanced catalyst reduction and economization (ACRE) that adds reactors, reduces catalyst and acid usage.

- Use of decanters instead of centrifuges for separation
- Liquid phase plasma discharge technology as part of the transesterification step which makes the reactor create an excited molecular state for the mixture resulting in improved conductivity between the elements.
- Co-location with corn ethanol production. The carotenoid-rich FFA stream stripped from the distillers corn oil feedstock can be added to the distillers grains for a nutrient-rich, higher-priced animal feed [29].
- Additives, antioxidants and stabilizers are tailored to address issues related to biodiesel storage and differences related to the wide variety of feedstocks and developing technologies [29].

3. Making Biodiesel Fuel: Pre-Commercialized Conversion Technologies

a) Lipases as Enzymatic Catalysts

There is a continuing interest in using lipases as enzymatic catalysts; however, commercial use is limited since costs are high, rate of reaction is slow and yields are low [32,122].

b) Supercritical Fluid Processes

Supercritical fluid (SCF) technologies have been explored as an alternative to conventional processes for preparing biodiesel.

A supercritical fluid (SCF) is a compound, mixture, or element above its critical pressure (P_c) and critical temperature (T_c), but below the pressure required to condense into a solid; something between a gas and a liquid. The unique characteristics of supercritical fluids enhance extraction, reaction, fractionation and analysis processes. Another benefit is that they can be fully recovered and reused.



Challenges with using SCFs include cost, energy consumption, and safety issues in the high pressure/high temperature operation process. The SCF technology requires expensive equipment, such as strong durable reactors, high pressure pumps, efficient control devices, etc., and the costs involved in operation and maintenance are also higher than those of conventional processes. The SCF technology for the industrial production of biodiesel could be improved by the design of small reactors with enhanced catalytic efficiency, which, in combination with continuous operation approaches, may help offset the draw-backs [33].

c) *Liquid Plasma Discharge*

Not requiring catalysts or high temperatures, this high voltage AC-powered process is able to break down the chemical bonds of oil and alcohol so that the generated liquid plasma can induce transesterification. This technology boasts an extremely rapid reaction time, high conversion rate, and enhanced feedstock selectivity [34].

C. Properties of Biodiesel Fuel

Biodiesel contains oxygen atoms; however, petroleum diesel has only trace amounts of oxygen or none. This leads to different physical properties for biodiesel.

There is a noticeable difference in energy content between diesel and neat biodiesel (B100) [35]. Differences in energy content are proportionally significant. Power, torque, and fuel economy for B20 are about 1-2% lower than with petroleum diesel fuel. With lower blends such as B5, there is no noticeable performance difference [25].

Biodiesel's lack of aromatic compounds is often cited as an advantage because many aromatic compounds have low cetane numbers [27], and aromatics are also in a class of compounds which result in harmful emissions.

Biodiesel, even in very low concentrations, improves fuel lubricity and increases the cetane number of the fuel. Biodiesel can impart adequate lubricity to diesel fuels with poor natural lubricity, such as ultra low

sulfur diesel (ULSD), at blend levels as low as 1% [36].



When both petroleum diesel and biodiesel are sufficiently chilled, wax (paraffin) tends to separate and form a gel that reduces fuel performance. The temperature at which this separation begins is referred to as the cloud point. Winter temperatures are often below the cloud point of diesel and because the cloud point of biodiesel can be significantly higher than that of diesel, cold weather performance of biodiesel is a concern. Blending diesel with biodiesel results in an intermediate cloud point that depends on the characteristics of the fuel components.

A blend of renewable diesel and biodiesel that combines the increased cetane and lower cloud point of renewable diesel with the increased lubricity of biodiesel is promoted as offering improved combustion quality, reduced engine wear,

and more reliable year-round operation compared to conventional diesel [37].

To summarize, biodiesel is chemically different from petroleum diesel and renewable diesel (see page 18) and, as a

result, has different chemical and physical properties. Below is a comparison among petroleum diesel, biodiesel and renewable diesel of some of the properties most commonly used to describe a fuel that can be used in CI engines. See appendix for definitions.

Table 3: Comparison of Fossil-Based, Bio- and Renewable Diesel Fuel Properties [6,9,25,57,89]

Properties	Petroleum-Based Diesel	Biodiesel (B100)	Renewable Diesel
Cetane #	40-55	50-65	75-90
Energy Density, MJ/kg	43	38	44
Density, g/ml	0.83-0.85	0.88	0.78
Energy Content, BTU/gal	129 K	118 K	123 K
Sulfur	<10 ppm	<5 ppm	<10 ppm
NOx Emission	Baseline	+10	-10 to 0
Cloud Point, C	-5	20 ^a	-9 ^b
Oxidative Stability	Baseline	Poor ^c	Excellent
Cold Flow Properties	Baseline	Poor	Excellent ^d
Lubricity	Baseline	Excellent	Poor ^e

^a Depends on feedstock. The cloud point of B100 starts around -1°C to 0°C (30°F to 32°F) and can go as high as 20°C (68°F) or higher for biodiesel from highly saturated feedstocks [25].

^b Cloud point can vary widely. Depends on ratio of n- to iso-paraffins in fuel. In the US, range is -35°C (-31°F) to -9°C (16°F) [57].

^c Antioxidants, whether natural or incorporated as additives, can significantly increase the storage life or stability of B100 [25].

^d Only with sufficient isomerization [89].

^e Requires additives to meet specifications [89].

D. Biodiesel Fuel Specifications

B5 specifications are defined internationally by ASTM D975 which allows for biodiesel concentrations of up to B5 to be sold with no separate labeling required at the pump [38]. This differs from the EN 590 voluntary standard in Europe which allows blends of up to 7 percent FAME [9]. B6-B20 is specified internationally by the ASTM D7467 standard. B100 is specified by ASTM D6751.

The ASTM D6751 definition of biodiesel states that biodiesel is composed of “mono-alkyl esters of long-chain fatty acids derived from plant oils or animal fats.” The term mono-alkyl esters indicates that biodiesel contains only one ester linkage in each molecule. Raw or refined plant oils, straight vegetable oil, animal fats, and greases contain three ester linkages and are, therefore, not biodiesel [25].

For the EU, EN 14214 establishes specifications for fatty acid methyl esters for diesel engines. In contrast to ASTM D6751, B100 that meets this standard could be used unblended in a diesel engine (if the engine is supported to operate on B100) or blended with diesel fuel to produce a blend in accordance with EN 590 or other applicable standards. EN 14214: 2012 introduced a number of changes including an expansion of the scope to cover heating oil applications and updates to cover blends up to B10. An additional set of climatic classes based on monoglycerides content was also established [39]. Other countries may have developed their own specification. For example, India's BIS 15607: 2016 [40].

The National Biodiesel Board (NBB) states that individual engine manufacturers may support use of higher levels of biodiesel, more than B5, on a case-by-case basis. Most experience thus far has been with B20 blends [41].

In addition, the NBB has formed the National Biodiesel Accreditation Commission (NBAC) to issue a 'Certified Biodiesel Marketer' seal of approval for biodiesel marketers that have met all requirements of fuel accreditation audits. This accreditation is designed to provide added assurance to customers as well as engine manufacturers that the biodiesel marketed by these companies meets the ASTM standards for biodiesel and that the fuel supplier will stand behind its products [41,188].



In some cases, B5 is initially used by fleets considering transitioning to higher blends such as B20 because B5 is still classified as ASTM D975 diesel fuel [42] and its use approved for all diesel fuel uses. B20 is recognized as equivalent to regular diesel fuel for the purpose of complying with underground storage tanks in California and the rest of the country [43].

New blend “standards” are being tested at levels such as B15 [44], B30 [45,46] and B35

[13]. Indonesia plans to move to a 40 percent bio-content diesel policy that might be achieved by mixing 30% fatty acid methyl (FAME) with 10% renewable diesel and 60% petroleum diesel, although they refer to it as B40 [99,100].

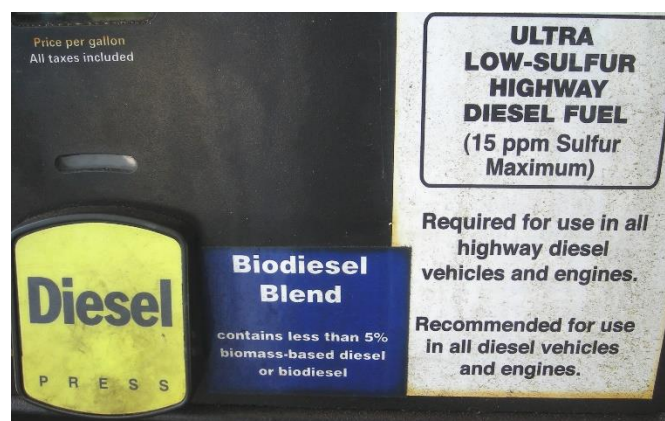
In its neat form (B100) biodiesel can only be used if proper precautions are taken. For example, one company has developed a two-tank biodiesel conversion vector system. The engine runs on B100 between starts and stops powered by #2 diesel [14]. Thus, it operates even in cold temperatures [47].

Some users claim that B100 can be used without any modifications. India's Synergy Teletech Private Limited produces Synergy Green Diesel, highly distilled biodiesel from a variety of feedstocks that has successfully completed test-piloting at B100 in stationary engines and may be used as a blend for transportation [48,49].

E. Biodiesel's Environmental Impact

Biodiesel significantly reduces life-cycle greenhouse gas (GHG) emissions. Life cycle analysis using Argonne National Laboratory's GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model) analysis found that greenhouse gas emissions for B100 are 74% lower than those from petroleum diesel. The California Air Resources Board (CARB) reported similar values for its life-cycle analysis of biodiesel from various sources using CA-GREET 2.0 [25,50].

The U.S. Department of Energy (DOE) reported that testing done up to 2016 shows that biodiesel is fully compatible with the emission control catalysts and filters that dramatically reduce nitrogen oxides (NO_x) and particulate matter (PM) emissions from new technology diesel engines (sometimes called NTDEs) and that these effects are feedstock neutral for biodiesel. Research is on-going to determine whether the current biodiesel specification contains adequate protection for NTDE emission control catalysts and filters [25].



According to DOE, when biodiesel is used in boilers or home heating oil applications, NO_x tends to decrease because the combustion process is different (open flame for boilers, enclosed cylinder with high-pressure spray combustion for engines) [25].

Concerns about particulate matter and hydrocarbon emissions from diesel engines which may be toxic and/or carcinogenic are mitigated by use of biodiesel [51,101,102].

Other environmental impacts vary depending on the feedstock. For example,

some in the European Union (EU) criticize the regulatory advantage given to UCO because it may contain palm oil, which the European Union (EU) decided to phase out due to concerns about indirect land use change (ILUC) or unintended and significant environmental consequences when harvested in places like Indonesia or Malaysia [52,53].

The European Waste-to-Advanced Biofuels Association (EWABA) represents EU UCO collectors and waste biodiesel producers using used cooking oil (UCO) and animal fats. EWABA is encouraging improved sustainability certification and promotes the establishment of a physical testing method differentiating UCO from virgin vegetable oils to address these criticisms [54].



5. Renewable Diesel

A. Overview of Renewable Diesel Fuel

Renewable diesel, often called green diesel, hydrotreated vegetable oil (HVO), second generation diesel, hydrogenation-derived renewable diesel (HDRD), "bio-hydrogenated diesel," paraffinic diesel and a variety of other names, refers to petrodiesel-like fuels derived from biological or renewable sources that are chemically not esters and thus distinct from biodiesel [55].

Renewable diesel can be produced from the same feedstocks as biodiesel and from many other feedstocks such as crop residues, grasses, woody biomass, municipal solid waste (MSW), plastics, and

dedicated energy crops, depending on the feedstock and conversion technology used [55,56].

The definition of renewable diesel is not as straightforward as that of biodiesel. In the U.S., the term "renewable diesel" has been defined differently by DOE, the Internal Revenue Service (IRS) and the Environmental Protection Agency (EPA). The specifics of the definitions can be found in the appendix [57,58,59].

In addition, the terms for renewable diesel and green diesel have been further distinguished based on the processing method to create fuel with petrodiesel-like chemical composition. For the purpose of this discussion, the term "renewable diesel" will refer to diesel fuels derived from biomass or other renewable feedstock, including waste materials, that meet the

standards of ASTM D975 and are not mono-alkyl esters. Renewable diesel is also distinct from synthetic paraffin fuel made from fossil carbon such as coal.

Generally, renewable diesel differs from biodiesel in its chemical properties, conversion processes, and applications despite being made from the same feedstocks. Due to the more complex conversion technologies, renewable diesel can also be made from many feedstocks, including wastes, that are not bio-based. And, it is known for performing as a renewable “drop-in” one-on-one replacement for fossil-based diesel.



The term “drop-in” indicates that the fuel can be integrated into existing transportation and engine infrastructure without any modification. With regard to renewable diesel, 100% substitution is possible.

The term is also used when a significant percentage of the fuel can be substituted. For example, several industries and engine manufacturers have imposed limits on the amount of renewable diesel that they support. The railroad industry and locomotive manufacturers such as General Electric limit the amount of renewable diesel to 30% due to performance issues [191]. Most currently available renewable jet fuel (often referred to as sustainable aviation fuels or SAF) is considered “drop-in” although it may be limited to use in a 50/50 mixture or less due to the need for some of the properties of petroleum jetfuel that are lacking in SAF [63].

B. Production of Renewable Diesel Fuel

There are many ways to produce renewable diesel from a wide variety of feedstocks. A brief description of a wide sample of these follows.

1. Feedstocks Used to Make Renewable Diesel Fuel

One of the benefits from the development of renewable diesel is the ability to convert into useful fuel, in addition to all the feedstocks that can be used to make biodiesel, waste materials characteristic of different parts of the world. From forest and agricultural residues and waste to industrial and municipal waste streams, a variety of processes have been developed to convert to the building blocks of renewable fuel everything from plastics and tires to anything made from cellulosic fiber, such as sawmill waste, railroad ties, power poles, paper and cardboard [60].

2. Making Renewable Diesel Fuel: Commercialized and Advanced Technology Readiness Level Conversion Technologies

There are a number of distinct methods to obtain ASTM D975 fuel. They include a variety of biochemical, thermochemical, hybrid, and depolymerization technologies such as hydrotreating or hydroprocessing, thermal conversion (pyrolysis) and upgrading of bio-oil, biomass-to-liquid (BTL) thermochemical processes, catalytic upgrading of sugars, starches and alcohols (ethanol-to-hydrocarbon), and syngas fermentation.

The catalytic upgrading of sugars and alcohols involves liquid phase technologies such as aqueous phase reforming (APR). Thermal conversion involves the pyrolysis of biomass and the production of bio-oil which is then refined into green diesel. BTL processes involve the high temperature gasification of the biomass for the production of syngas which is rich in H_2 and CO and the subsequent chemical synthesis of liquid green diesel through the well-known Fischer-Tropsch (FT) process. The green diesel produced by the Fischer-Tropsch method is sometimes referred to as FT green diesel [61,62].

a) Biomass-to-Liquid (BTL) via Gasification and Fischer-Tropsch (FT)

The most common process for making renewable diesel fuel is to convert biomass by partial oxidation through high-temperature gasification into synthetic gas

or “syngas,” a gaseous mixture rich in hydrogen and carbon monoxide (gasification) and then refine it by using the Fischer-Tropsch (FT) process.

The first BTL step takes place by heating the material at temperatures above 700 °C with a controlled sub-stoichiometric amount of O_2 and/or steam and leads to the production of mixtures containing syngas (i.e., CO and H_2) and smaller amounts of CO_2 and methane (CH_4).



Compared to pyrolysis, described below, it provides higher yields of syngas without any significant co-product competition [74].

Gasification is also an established process for the production of syngas from coal, char, oil sands, biogas and natural gas [75].

When an organic material is combusted, it can be completely oxidized or gasified to carbon dioxide and water, or it can be partially oxidized to carbon monoxide and hydrogen. The partially oxidized gasification reaction is accomplished by restricting the amount of oxygen during the combustion process. The resulting

carbon monoxide and hydrogen mixture is the syngas, the starting material for the Fischer-Tropsch process, or a set of

chemical reactions that converts the syngas into liquid hydrocarbons. The overall process can be seen in Figure 4 [74].

1) Synthesis Gas Formation



2) Fischer-Tropsch Reaction



3) Refining



Figure 6: BTL & Fischer Tropsch Process (graphic from Syntroleum) [76]

Renewable diesel results from the sequence of processes.

Although syngas-to-Fischer-Tropsch is a common, long-established process, the syngas can also be converted to renewable diesel (or jet fuel or other chemicals) via fermentation in a modern, newly-developed biological process described below.

As with other processes, when renewable hydrogen can be used, carbon intensity can be significantly improved [77].

b) Hydrotreating/Hydroprocessing/Hydrodeoxygenation

Hydrotreating converts triglycerides of biomass oils and fats into saturated hydrocarbons through catalytic processing with hydrogen at high temperatures and pressures. Also known as hydroprocessing or hydrodeoxygenation, the hydrotreating process is utilized by petroleum refineries to remove oxygen, sulfur, nitrogen, condensed ring aromatics or metals.

When used with renewable feedstock, this results in a “drop-in” diesel-like renewable substitute, which consists of highly paraffinic hydrocarbons.

When hydrotreating uses fossil-derived hydrogen (the current usual practice), this product is not 100% renewable [64]. This must be taken into account when calculating the energy return, greenhouse

gas emissions (GHG) and carbon life cycle. Should renewable hydrogen be used, the calculations can be adjusted, depending on how the hydrogen is derived [65,108,109].

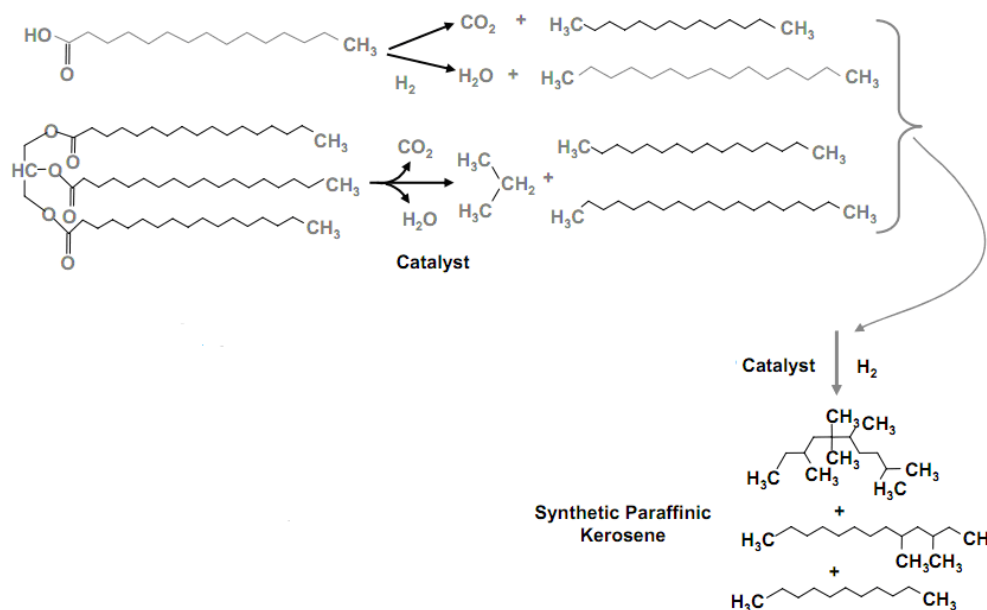


Figure 7: Hydrotreating Process [65]

This process is currently used by many petroleum refineries, and ASTM D975 diesel fuel with a renewable component may be produced at existing refineries by co-processing with petroleum feedstock, as discussed below [66].

c) Thermal Depolymerization/Pyrolysis/Thermal Processing/Cracking/Rapid Thermal Processing

Also known as hydrothermal processing, thermal conversion, cracking, pyrolysis and rapid thermal processing, thermal depolymerization is another process that

can convert biomass or other carbon-containing material into a “bio-oil” that is then refined into a petrodiesel-like fuel using the hydrotreatment processes described above.

Because this process converts the large polymers (cellulose, hemi-cellulose, lignin, and proteins) of biomass into smaller molecules, this process is used to convert different types of woods, forest residues and agricultural residues such as straw, willow, olive pits, and nut shells.

Pyrolysis is the endothermic reaction that takes place by heating lignocellulosic

biomass at 300–900 °C (572-1652 °F) with a pressure range of 100-170 atmospheres in absence of air. The pyrolysis co-products are biochar (a black solid residue), syngas (a mixture of H₂ and CO), and bio-oil (a brown liquid) [67,68]. The bio-oil can then be refined to fuels using hydrotreatment described above and the syngas can be further processed with a Fischer-Tropsch process described above or with a fermentation process (See page 24).

d) **Hydrothermal Liquefaction (HTL)**

Liquefaction is an alternative pathway for the production of bio-oils by the catalytic thermal decomposition of large molecules to unstable shorter species that polymerize again into a bio-oil.

Biomass is mixed with water and basic catalysts like sodium carbonate, and the process is carried out at lower temperatures than pyrolysis (252–452 °C) but higher pressures (5–20 atmospheres) and longer residence times. These factors combine to make liquefaction a more expensive process; however, the liquid product obtained contains less oxygen (12–14%) than the bio-oil produced by pyrolysis and typically requires less extensive processing [69,70].

Bio-oils, in general, have been successfully tested in engines, turbines and boilers, that required small modifications [72]. However, problems exist associated with the complexity of the bio-oil product, leading to unsuitability for long term storage [72].

As with other bio-oils, HTL products can be further refined into renewable diesel or other products. Bio-oil might be used in a blend with petroleum products for heating oil [119,120] and maritime shipping fuel [121].



e) **Thermal Catalytic Depolymerization**

Thermal Catalytic Depolymerization blends waste with a chemical catalyst and low heat to convert feedstock to renewable diesel, jet fuel, and naphtha fuel.

The process can use a wide variety of feedstocks, including all those previously listed along with all types of plastics. It blends them with used motor oil and a powdered chemical catalyst. The mixture is then heated to a temperature that breaks down the molecules and “cracks” the materials into a blend of distillate fuels. This converts the feedstock into gas which is then heated to 350 degrees Celsius and distilled into naphtha diesel and other products.

The developers of this process point out that the benefits include lower temperatures than pyrolysis, lower energy use, and the wide variety of feedstocks,

particularly plastics that are not used in other processes, which enable this system to contribute to improved waste management solutions [73].

f) Syngas Fermentation

Fermentation of reformed biogas, industrial off-gases, or syngas generated from any biomass resource (e.g. municipal solid waste (MSW), organic industrial waste, agricultural waste, biomass) essentially captures and recycles carbon.

Precursors and biointermediates are produced by biological conversion of syngas or flue gas and then further refined using the above described processes into finished renewable diesel.

The processes used to convert these gases into renewable diesel and chemicals are the same as those used for commercial gas-to-liquid (GTL) production of diesel fuels.

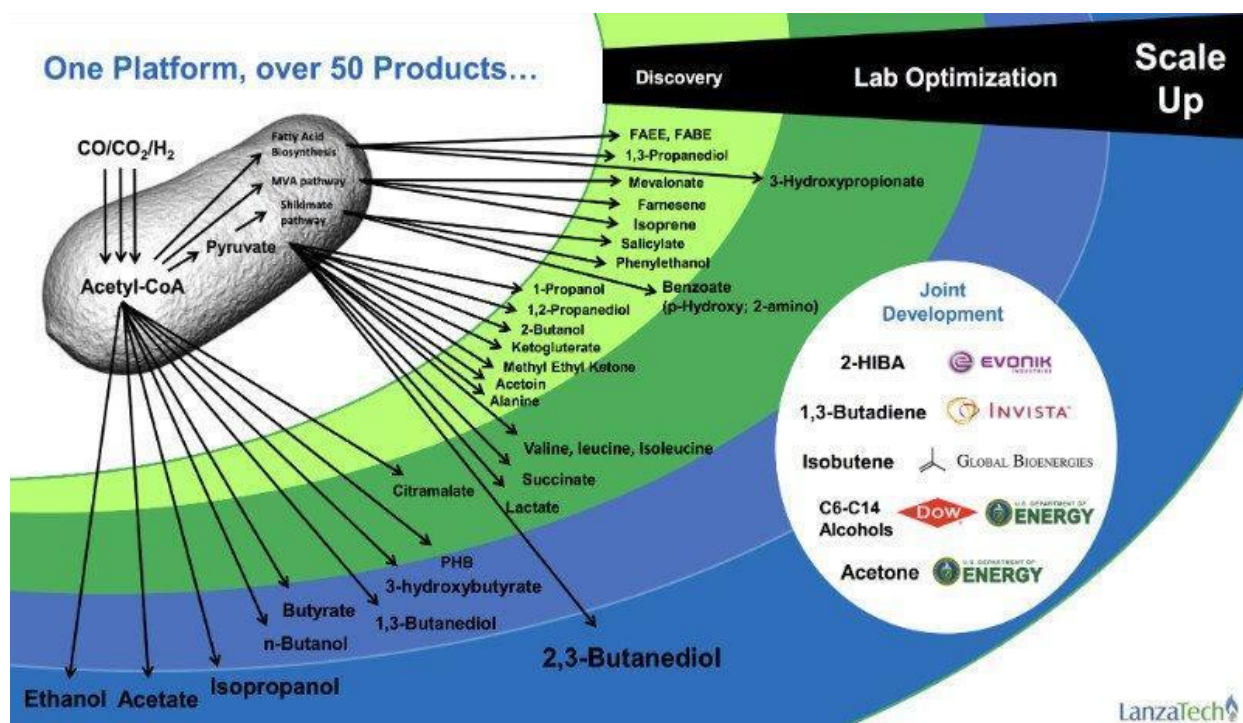


Figure 8: Example of Product Potential from Gas Fermentation (LanzaTech) [78]

Figure 7 illustrates the multiple precursors and biointermediates that might be produced by biological conversion of syngas, flue gas, etc [78].

Building on this, the U.S. Department of Energy has been funding a project, "Bio-

syngas to Fatty Alcohols (C6-14) as a Pathway to Fuels." The objective is to develop a new bio-syngas fermentation process using engineered bacteria for the production of intermediate (C6-C14) fatty alcohols leveraging robust chemical markets enabling scaling to biofuels production at < \$3/gge. They expect their

technology to function as a front-end upgrading process within an integrated biorefinery or to bolt-on within conventional conversion infrastructure such as an FT refinery [142].

g) Oil-splitting Pretreatment

A patented technology combines ultra-degumming and bleaching with oil splitting to remove glycerin before the hydrogenation reactor. This oil-splitting step translates to increased production capacity, no propane byproduct, and lower hydrogen and utilities consumption, which further reduces the carbon intensity of the fuel [31].

3. Making Renewable Diesel Fuel: Pre-Commercial and Low Technology Readiness Level Conversion Technologies

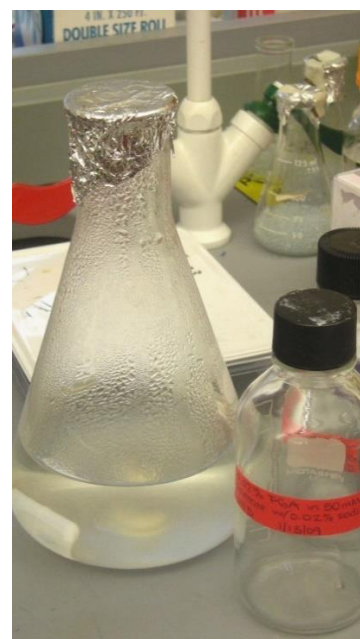
The following are technologies being developed to make renewable diesel that are at a lower Technology Readiness Level and are not close to commercialization. Aggressive climate change mitigation policies, a higher price of oil, or a tax on carbon could spur development of these and other technologies.

a) Catalytic Upgrading of Sugars, Starches, Alcohols

Catalytic upgrading of sugars involves liquid phase technologies such as hydrolysis, hydrogenation, hydrogenolysis, dehydration, isomerization, oxidation,

aqueous phase reforming (APR) and aldol condensation.

Biomass (lignocellulosic, sugars, starches) must initially receive pretreatment to break down the biomass for a subsequent enzymatic hydrolysis to convert polysaccharides into a hydrolysate slurry of monosaccharides such as xylose, fructose and glucose. The slurry is then purified and after possible hydrogenation or hydrogenolysis in pretreatment reactors it is routed to the aqueous phase reforming (APR) catalytic reactor. During APR the hydrolysate slurry reacts with water which converts the sugars and sugar alcohols into H_2 , CO_2 , lower saturated hydrocarbons, and condensable chemical intermediates at temperatures about 175–300 °C and pressures of 9.87–88.8 atmospheres over catalysts.



The specific mixture composition depends on the reactor design, process conditions, feed concentration, solution pH, catalyst support, and catalyst.

The effluent of the APR reactor contains oxygenated molecules such as alcohols, ketones, aldehydes, and organic acids

with less than six carbon atoms that can be converted into the desired liquid fuel in subsequent chemical processes.

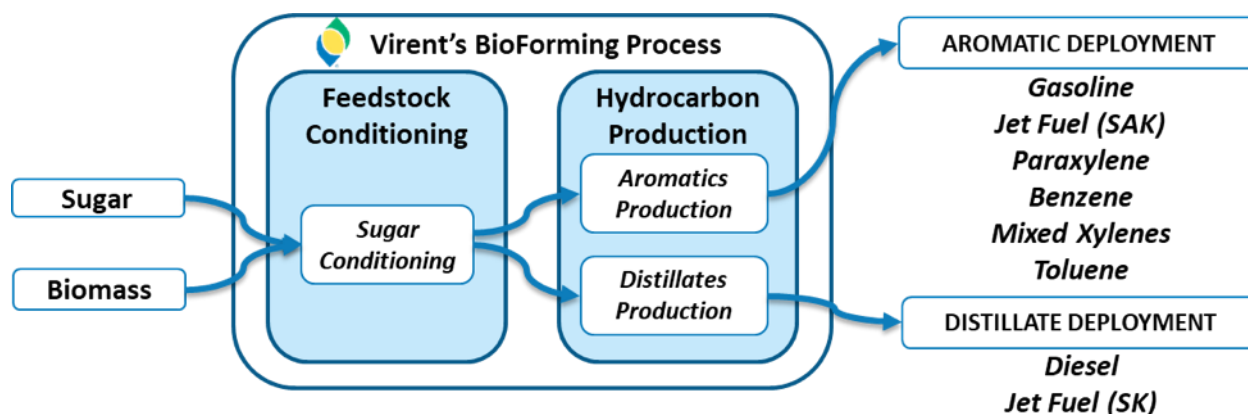


Figure 9: A diagram of the basics of catalytic upgrading of sugars [79].

Renewable gasoline and renewable jet fuel can be produced as well as renewable diesel through dehydration, alkene oligomerization, and alkene saturation. Alkene oligomerization describes the conversion of lower alkenes such as propylene, butylene, and pentene to heavier alkenes in the boiling range of gasoline and petroleum diesel [80,81,82,83,84,85,86,87,88].

b) Hydrodecarboxylation

An alternative method to deoxygenate biomass-derived oils is that of decarboxylation or decarbonylation, a process that requires hydrogen and a catalyst as illustrated in Figure 8.

Hydro-decarboxylation of the same feedstocks used for biodiesel produces oxygen and aromatic free hydrocarbons, i.e., renewable diesel.

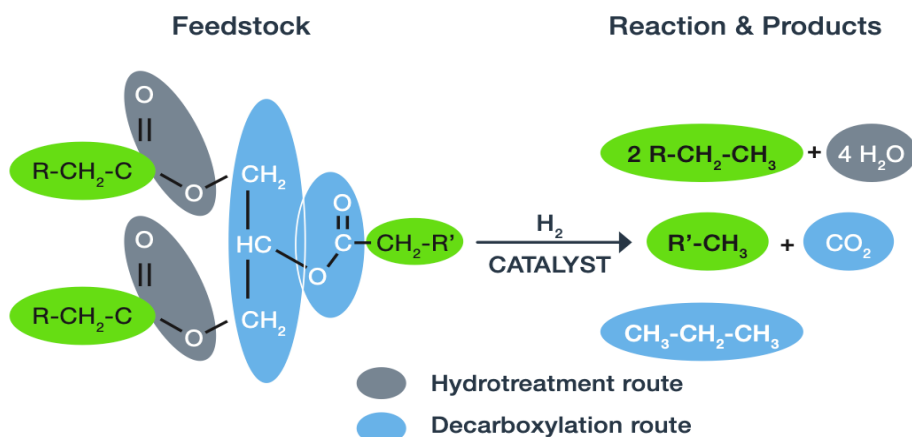


Figure 10: Hydrodecarboxylation process to prepare renewable diesel (Neste) [89]

A study published by India's TERI (The Energy and Resources Institute) found that the hydrodecarboxylation process of vegetable oil, used cooking oil, etc. can produce a biofuel with fewer tail-pipe emissions of air pollutants, particularly unhealthy nanoparticles.

However, because the process requires hydrogen and catalyst, the authors recommend additional research on the development of bio-hydrogen and suitable catalyst as well as a more detailed study following standardized protocol for tail-pipe emissions [90].

c) Ethanol-to-Hydrocarbon

Although conversion of sugar alcohols to renewable diesel is part of the sugar upgrading reaction described above, alcohol, such as ethanol from whatever

sugar source, converts to renewable diesel or other hydrocarbons using a new class of hetero-bimetallic catalysts as shown in Figure 9.

Under moderate atmospheric conditions, it is possible to convert ethanol into a blend-stock for diesel and jetfuel utilizing a zeolite catalyst to transform a mixture of C3 – C16 hydrocarbons. Operating at 310 °C, this direct conversion process is demonstrated to have the capability to convert about half of its feedstock into usable blend-stock.

Oak Ridge National Laboratory (ORNL) lab-scale tests indicate, however, that the catalyst can effectively operate at relatively low temperatures and pressures, whereby it can regenerate under these mild conditions and withstand long periods of use without significant degradation [91].

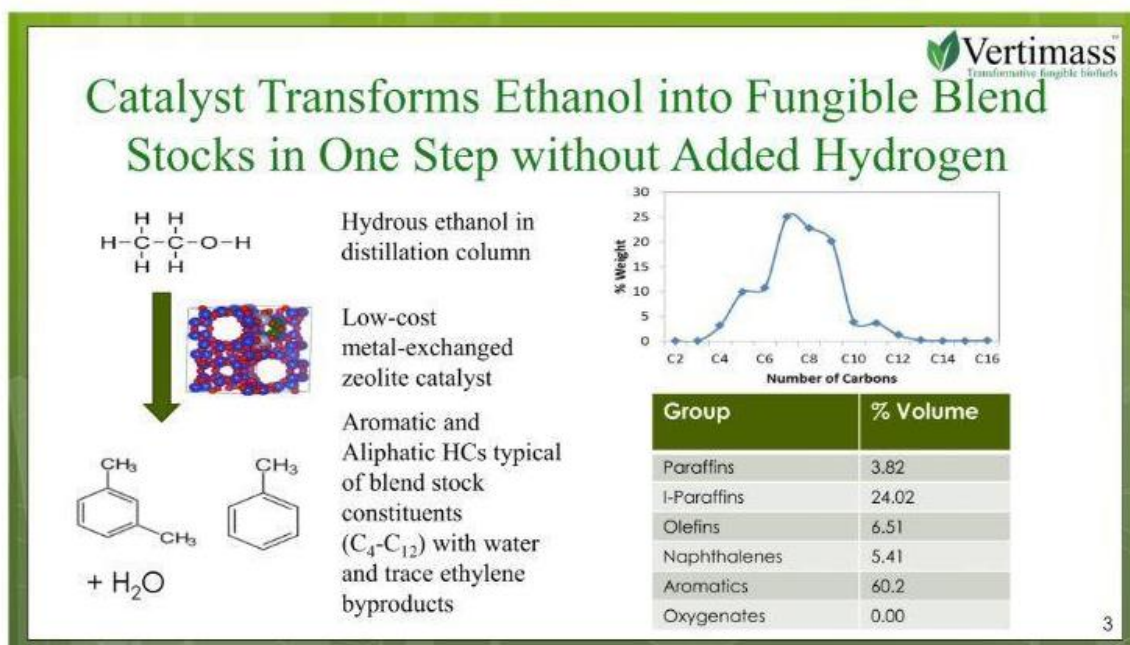


Figure 11: Vertimass' Diagram Illustrates Ethanol-to-Hydrocarbon Catalysis [92]

d) Conversion of cellulose via carboxylic acid

The **U.S Department of Energy** has been funding a Biological Upgrading of Sugars project that has worked on developing several routes to sugar upgrading to make fuel precursors. The project delivered an oleaginous yeast strain to an integration team for longer-term process development, and then the project turned their strain engineering attention to C2–C4 produced in anaerobic fermentation with both yeast and bacterial candidates considered for C2–C4 production. The focus shifted to anaerobic secreted products, short-chain carboxylic acids, due to significantly lower production costs, the ability to reach larger scale than aerobic processing, and the ability to convert these acids to jet and diesel fuels [93].

C. Renewable Diesel Fuel Properties

Renewable diesel is chemically similar to petrodiesel and meets the same ASTM specification [55]. Like biodiesel, renewable diesel has near-zero aromatic content and very low sulfur content; however, it does not have the enhanced lubricity of biodiesel. It typically has a very high cetane number and a cloud point more similar to conventional diesel fuels.

Renewable diesel blends follow the same nomenclature as biodiesel. Renewable diesel in its pure form is designated RD100 while a blend of 20% renewable diesel and 80% petrodiesel is called RD20.

Because renewable diesel is chemically similar to and possesses properties similar to petrodiesel, it can be used to displace petrodiesel in any quantity [94], although not all engine manufacturers approve of high blends.

Also as a result of their similarities, renewable diesel users must be aware that lubricity may be an issue and may require additives to address this issue. Users must make sure to use an additive that is compatible with renewable diesel in order to avoid engine damage [74].



Unlike biodiesel, renewable diesel does not contain oxygen and therefore it is more stable, non-corrosive and has a heating value similar to petroleum diesel. Renewable diesel also has superior cold weather behavior than biodiesel, it does not increase NO_x emissions, and it has a higher cetane number (CN) which translates to easier ignition in CI engines.

Also, renewable diesel produced by the hydro-processing of triglycerides has propane, a gaseous fuel of high market value, as a co-product. This could make renewable diesel production more attractive in economic terms when compared to the production of biodiesel [74,110,111].

This can vary depending on the feedstock and generally ranges from 50% to 85% lower than baseline diesel fuel [97].

As discussed in the biodiesel section above, environmental impacts also depend on the type of feedstock.

D. Renewable Diesel Fuel Specifications

Renewable diesel meets the ASTM D975 specification in the United States and EN 15940 in Europe [89].

E. Renewable Diesel Fuel Environmental Impacts

Renewable diesel has some of the largest lifecycle greenhouse gas reductions with a carbon intensity of about 30 compared to 102 for ultra low sulfur petroleum diesel [96].

In addition, renewable diesel can help improve air quality. Based on limited data, the California Air Resources Board (CARB) determined that RD100 can decrease NOx by roughly 10 percent when used in older heavy-duty engines that don't have state-of-the-art emission controls. Preliminary data also indicate renewable diesel can reduce particulates emitted from older diesel engines by about 30 percent. When used in newer engines or vehicles with diesel engines compliant with 2010 standards, the NOx and particulate reduction benefits are likely to be reduced significantly [98,104]

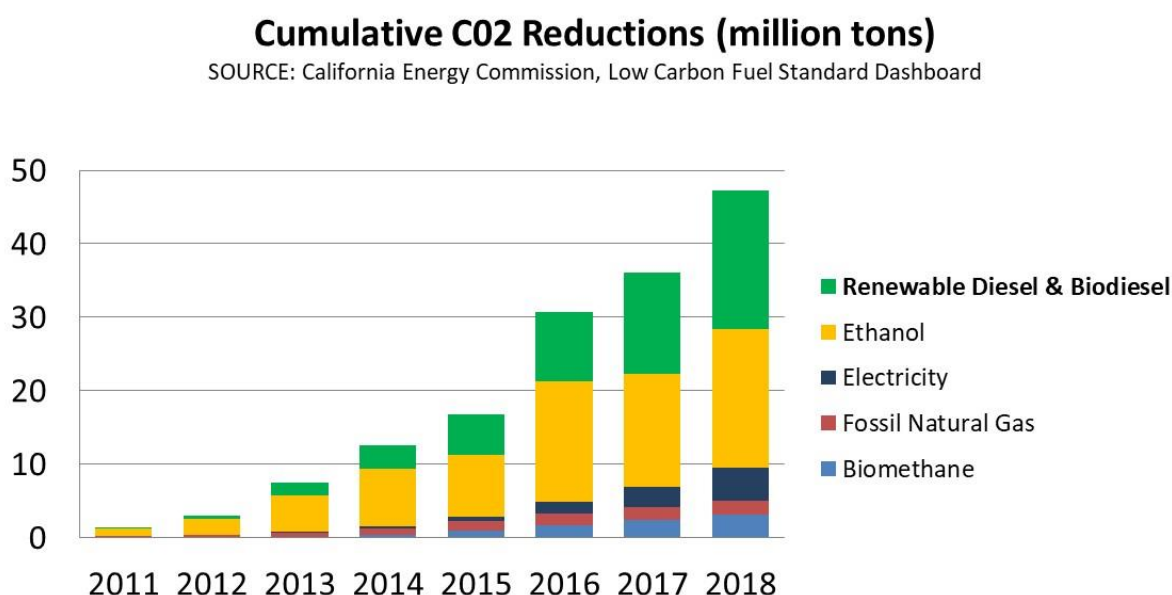


Figure 12: California Low Carbon Fuel Standard CO2 Reductions (Diesel Technology Forum)

6. Renewable Dimethyl Ether (rDME)

A. Overview of Renewable Dimethyl Ether

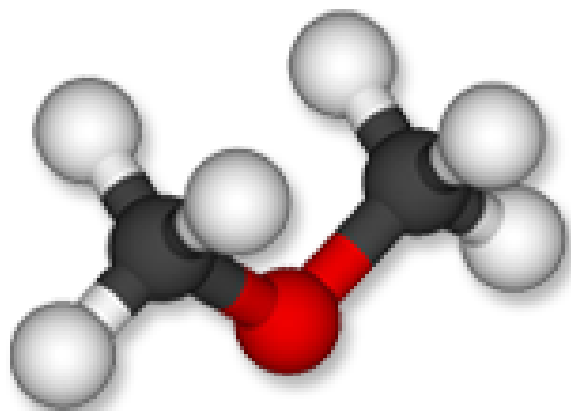
Renewable dimethyl ether (rDME), also known as bio-DME, is a synthetically produced fuel that is pressurized into liquid form for use in a CI engine. Dimethyl ether (DME) is the simplest ether, similar to methanol, consisting of two methyl groups bonded to a central oxygen atom, with a chemical formula $\text{CH}_3\text{-O-CH}_3$.

rDME is promoted as a cleaner alternative to fossil-based diesel as it does not even require a diesel particulate filter. It also has high diesel thermal efficiency, quiet combustion, low nitrogen oxide (NO_x) emissions, and it is also a way to use waste streams, such as biogas and landfill gas, for transportation fuel feedstock [192].

rDME is not a “drop-in” fuel like renewable diesel. Although rDME has a high cetane number (55) and does not require spark plugs, high pressure, or cryogenics like CNG and LNG, its differences in density, viscosity, lubricity, etc., require a DME fuel system (renewable or fossil-based) with different fuel injectors to allow higher flow. It also requires a fuel pump and fuel storage tank although it has fewer requirements for after-treatment equipment. To maintain a liquid state, DME requires around 73 psi or 5 bars of pressure, less pressure than required to liquefy propane such as that used in a barbecue grill [105].

DME is not commercially available in the United States, although it is used for heating and cooking in China, Japan, Egypt, Korea and Brazil [192].

Another potential fuel in the class of dimethyl ether (DME) derivatives is polyoxymethylene dimethyl ether commonly abbreviated to OME (also known as PODE or POMDME). Research, especially in German universities, suggests that OME may eventually be used as a diesel fuel replacement. Not enough is yet known about this to include a full evaluation of its production, use, or environmental impact [193].



B. Production of Renewable Dimethyl Ether

DME can be produced through three different production pathways: a two-step, a one-step, and a liquid-one-step process called bireforming. DME is typically produced through a two-step process using syngas as a feedstock. The syngas is converted to methanol, which is then converted to DME [106].

rDME is produced either from the direct synthesis gas produced by the gasification of biomass or indirectly by a catalytic dehydration reaction of methanol.

a) Feedstocks Used for Making Renewable Dimethyl Ether

rDME is typically produced from biomass and methanol unlike non-renewable DME which is produced from fossil fuels such as natural gas. DME can be produced from any methane-containing feedstock, including pipeline natural gas, biogas, landfill and waste water treatment gas, and stranded natural gas.

b) Making Renewable Dimethyl Ether: Commercialized Conversion Technologies

No renewable conversion technologies for DME have expanded beyond demonstration projects to achieve commercial scale.

c) Making Renewable Dimethyl Ether: Pre-Commercialized Conversion Technologies

(1) Indirect Liquefaction (IDL) Platform

In 2015, the National Renewable Energy Laboratory produced a report describing a potential conversion process for the production of high-octane gasoline blendstock via indirect liquefaction of biomass. The processing steps of this pathway included the conversion of biomass to synthesis gas or syngas via indirect gasification, gas cleanup, catalytic conversion of syngas to methanol intermediate, and methanol dehydration

to DME on the way to the production of a high octane gasoline-range blendstock via catalytic conversion of that DME to a hydrocarbon blendstock product.

The process configuration presented in that report described similarities to methanol-to-gasoline (MTG) technologies [107].



(2) California Funded Project

California is funding a project to assess the technical feasibility and economics of using a proprietary small-volume process to convert renewable methanol, a by-product of the paper industry's pulping process, into rDME and to develop an associated rDME fueling infrastructure. Uses may include blending with propane. The process consists of syngas production, methanol synthesis, and simultaneous DME synthesis and separation via catalytic distillation [106].

(3) U.S. Department of Energy Funded Project

The U.S. Department of Energy is funding research to develop a process for producing rDME using renewable electricity, air, and water. They anticipate that carbon dioxide would be captured from sustainable sources, such as biogas production, and fed into a reactor with hydrogen generated from high temperature water splitting. The CO₂ and hydrogen would react on a bifunctional catalyst to form methanol and, subsequently, rDME. To improve conversion to rDME, they will use a novel catalytic membrane reactor with a zeolite membrane. The final rDME product is separated, and the unreacted chemicals are recycled back to the catalytic reactor. Each component of the process is modular, compact, and requires no additional inputs aside from water, CO₂, and electricity. The system is also designed to be compatible with intermittent renewable energy sources [153].

C. Renewable Dimethyl Ether Fuel Properties

Although rDME has a slightly higher cetane number over diesel fuel, rDME has about half of the energy density of diesel fuel [112]. Because rDME is a gas at ambient temperature and pressure, it must be stored under pressure as a liquid similar to LPG (liquefied petroleum gas).

D. Renewable Dimethyl Ether Fuel Specifications

ASTM specification D7901 covers dimethyl ether (DME) for use as a fuel in engines

specifically designed or modified for DME and for blending with liquefied petroleum gas [113].

Because DME is proposed as a new fuel for use in California, the California Air Resources Board (CARB) requires a “multimedia risk assessment” before adopting new fuel specifications [106].



E. Renewable Dimethyl Ether's Environmental Impact

When used as a diesel fuel, DME provides reduced PM and NO_x emissions, but increased CO and hydrocarbons. Preliminary studies in the 1990s concluded that it should be possible to achieve California ultra-low emission vehicle (ULEV) emissions in a passenger car using a properly designed DME fuel injection system with a high speed direct injection engine and an oxidation catalyst [114]. That is, it would emit 50% less polluting

emissions than the average for new cars released in that model year.

More recently, an SAE study compared well-to-wheels (WTW) energy use and emissions of five DME production pathways with those of petroleum gasoline and diesel using the GREET® model. The five DME pathways include:

- 1) fossil natural gas with large-scale DME plants,
- 2) methanol from fossil natural gas with large-scale plants for both methanol and DME (separately),
- 3) landfill gas with small-scale DME plants,
- 4) manure-based biogas with small-scale DME plants, and
- 5) methanol from black liquor gasification with small-scale DME plants.

The study also analyzed DME production and use in the U.S. and Europe as well as in

two vehicle classes (light and heavy duty vehicles).

The WTW results showed significant reductions in fossil fuel consumption and GHG emissions by DME compared to gasoline and diesel if DME was produced from landfill gas and manure-based biogas. When methanol from black liquor was used for DME production, there were reductions in GHG emissions, though smaller than DME produced from landfill gas or manure. No significant difference from petroleum diesel GHG emissions were found from fossil natural gas-based DME produced in large-scale DME plants or from natural gas-based methanol [115].

In general, DME is a zero-soot alternative and a potential carrier for hydrogen, making it easy to deliver renewable hydrogen for use in hydrogen fuel cell vehicles.



7. Co-Processed Diesel

A. Overview of Co-Processed Diesel

It is possible to mingle bio-based or renewable oil, often called green crude or biocrude, or other renewable liquid feedstocks such as triglycerides, with petroleum oil at a refinery. The diesel fuel product may include bio-based molecules or molecules from recycled carbon, but it is not considered different from petroleum diesel for current U.S. regulatory or performance/use purposes because, critics claim, it is too difficult to accurately determine the amount of renewables in co-processed fuel [116].

Co-processing and refinery integration strategies could potentially decrease capital cost by:

- Reducing the investment cost of stand-alone infrastructure (renewable feedstock-to-finished renewable fuel at one location)
- Co-location with hydrogen sources
- Repurposing existing infrastructure
- Co-processing biobased intermediates in existing refineries to produce fossil fuels with a higher renewable content
- Production of lower carbon intensive fuels
- Improved properties of final fuels e.g. lower sulfur [117]

However, where and how one inserts co-processing depends on the nature of the

feedstock i.e. chemical characteristics; the refinery configuration, i.e. where the catalytic cracker and hydrotreater are positioned; and the overall risk to the refinery, i.e. catalyst inhibition, unplanned shutdowns and increased maintenance, and reduced fuel quality.

In addition to potential risks, some potential impacts include changes in product yields, product characteristics like cetane properties, product quality of high specification fuels such as jet fuel, hydrogen consumption, and catalyst inhibition

Key challenges of co-processing overall include:

- Limited refinery level data on co-processing
- Understanding interactions of co-processing different feedstocks
- Understanding impacts on products and quality
- Ideal blend for different feedstocks
- Specific impact on refinery, cost and managing risk
- Defining standards for biobased intermediates
- Method for determining renewable content

Advantages of co-processing overall may include:

- Lower cost production of low carbon intensive fuels
- Faster expansion of production of fuels with renewable composition

- Creating a market for biobased intermediates such as bio-oils/biocrudes
- Petroleum refineries become key allies in biofuel production
- Improved fuel qualities possible – e.g. higher cetane diesel and lower sulfur content [117]

Indonesia is planning to develop a policy based on using “B40” made not by mixing 40% biodiesel with petroleum diesel, but with a combination of renewable diesel, FAME/biodiesel and petrodiesel. Another modification they plan to make is to co-

process the fossil crude oil and palm derivatives together [100].

The main ways to determine if diesel fuel has been co-processed with renewables are carbon dating or mass balance calculations [117].

Fuel properties and specifications would be consistent with petroleum diesel or renewable diesel, depending on the type of processing and amount of renewable feedstock used. Co-processing remains rare with little experience or study of any otherwise unique environmental impact.



8. Fuel Ethanol

A. Overview of Fuel Ethanol

Currently, and most commonly, ethanol serves as an oxygenate and to enhance octane in gasoline for spark ignition engines. Also, processes have been

developed to use ethanol as a feedstock for renewable diesel and jet fuel described in previous sections including syngas fermentation and catalytic upgrading of sugars and alcohols.

Attempts to concurrently use alcohols, including ethanol, in a CI engine with

diesel fuel include alcohol fumigation, dual injection, alcohol-diesel fuel emulsions, and alcohol-diesel fuel blends.

Among these approaches, only alcohol-diesel emulsions and blends (known as e-diesel) are at all compatible with most commercial diesel engines, although they do not meet any current ASTM fuel specifications. Efforts in the early 2000s to add ethanol to diesel emulsions, blends either as micro-emulsions or using co-solvents of up to 15% ethanol, revealed that emulsions are difficult to achieve and tend to be unstable [118].

B. Production of Fuel Ethanol

Numerous feedstocks are used to make ethanol. In the United States, most fuel ethanol is made from fermented corn starch. In Europe, sugar beets are commonly used; in Brazil, sugar cane; in Asia and Africa, cassava is also used.

Research on the use of other sugar and starch sources abounds, as well as efforts to use agricultural waste such as corn stover, rice, and wheat straw in addition to energy crops like energy beets and grasses.

Fermentation of sugars with yeast is the typical process for making ethanol. Enzymatic processes are being developed to convert other parts of biomass to ethanol [71,156]. Research is also being done on other conversion methods, such as using a copper-based catalyst to produce ethanol from carbon monoxide [123,157,158] or direct hydration of

alkenes, such as the hydration of ethene [124].



C. Fuel Ethanol Properties

Because ethanol is a molecule, regardless of its feedstock, it consists of the same chemical formula ($\text{CH}_3\text{CH}_2\text{OH}$).

E100 has a much higher octane rating (110 at the pump) than traditional gasoline [35].

In the US, “regular gasoline” with 87 octane meets standard octane rating requirements by combining ethanol with 84 octane blendstock, called E10 gasoline [125,159].

Octane rating or number refers to the measure of resistance to engine knocking in spark-ignition internal combustion engines that gasoline or other fuels can withstand [126]. A higher octane number means higher spark-ignition engine performance. Although ethanol has a higher octane number, it has less energy density than gasoline. Higher fuel concentrations of ethanol contain up to 30% less energy per gallon than gasoline [127]. Engine development that optimizes

other characteristics of ethanol enables greater efficiencies.

For example, higher levels of ethanol in engines also have higher compression ratios which allows for greater thermal efficiency, greater torque, and increased performance [127]. Compression ratio has to do with “the ratio between the volume of the cylinder when the intake valve closes at the bottom of the compression stroke and the volume when the piston reaches the top” [128].

High level ethanol blends containing 20% to 40% ethanol (High Octane Fuel (HOF)) are being studied as fuels that enable

design of more efficient engines which may have compression characteristics close to CI engines [125,129]. The importance of these characteristics to performance of spark ignition, compression ignition, and combination ignition engines can be seen in these videos [179,180].

When evaluating engine combustion, the latent heat of vaporization is an important characteristic to take into account. A high level of latent heat of vaporization allows for better removal of heat from the engine and helps increase the control of detonation [130,131]. Compared to pump gasoline, pure ethanol has a much higher latent heat of vaporization.

Table 4: Fuel properties comparison of Gasoline, Biodiesel, and Ethanol [35, 128].

Properties	Gasoline/E10	Biodiesel	Ethanol/E100
Pump Octane Number	84-93	N/a	110
Energy Content (lower heating value)	112,114-116,090 Btu/gal	B100: 119,550 Btu/gal	E100: 76,330 Btu/gal
Energy Content (higher heating value)	120,388-124,340 Btu/gal	B100: 127,960 Btu/gal	E100: 84,530 Btu/gal
Gasoline Gallon Energy Equivalent	97-100%	B100: 103% B20: 109%	E85: 73-83%
Compression Ratio	9:1 - 10:1	N/a	13:1+

1. Pre-Commercialized Compression Ignition Engine Technologies that Use Ethanol

Ethanol fuel blends described above are not used in CI engines using any commercialized technologies. The following describe efforts to use ethanol blends in CI engines.

a) High temperature combustion compression ignition engine

Alcohols such as ethanol usually do not ignite in CI engines. Recently, researchers are modifying a CI engine to make it more efficient by combining the best of three processes related to CI engines while eliminating their weaknesses. Their modifications maintain torque and

durability characteristic of a classic CI engine while making it more efficient and reducing soot.

The processes are three-way catalysis, mixing controlled compression ignition and using low carbon, low soot renewable fuel (high ethanol blends (85% (E85) to 98% (E98)). Adding insulation also increases efficiency and lowers fuel costs.

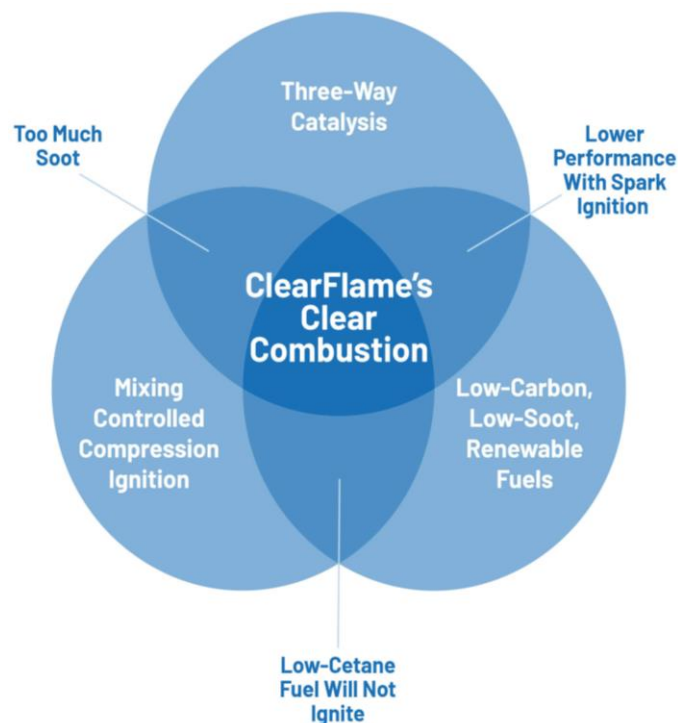


Figure 13: Three processes combination diagram [140].

Due to the lack of soot in the exhaust, the system eliminates the need for Selective Catalytic Reduction and Diesel Particulate Filter elements of the exhaust gas recirculation (EGR) which reduces NO_x. This means that the engine is no longer limited to lean operation and can instead use the chemically correct (i.e. stoichiometric) air-fuel ratio and maintain it under varying load conditions.

The researchers claim that this stoichiometric operation also substantially increases power density and that simplifying the aftertreatment system reduces its cost dramatically (~75%) and improves its NO_x reduction capability to near zero levels while eliminating the need for both a particulate trap and diesel emission fluid (DEF).

Researchers aim first to demonstrate the performance of this engine in power

generation then move to transportation applications [141].

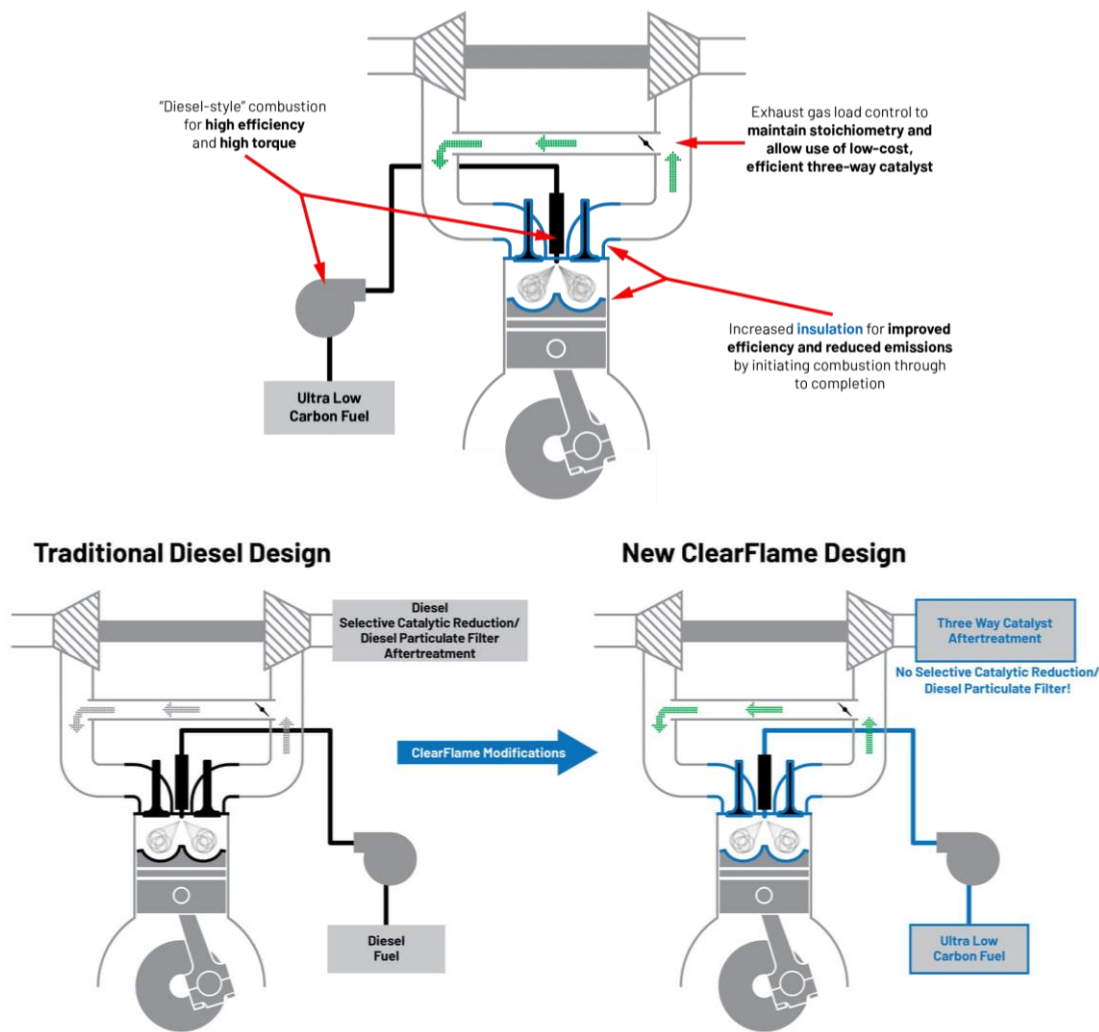


Figure 14: ClearFlame diesel engine modification compared to traditional diesel design [135].

b) Other Uses of Ethanol in CI Engines

(1) Blends with Ethanol

Blends of ethanol with diesel fuel are often referred to as "E-Diesel" or "eDiesel".

It was hoped that the use of e-diesel would reduce particulate emissions as well as NO_x, CO, and hydrocarbon emissions; however, research did not confirm

substantial results in those areas. Due to potentially significant operational and safety issues such as dangers from characteristics such as low flash points, research in that area has been largely abandoned [118].

A study by the National Renewable Energy Laboratory in 2001 concluded that ethanol-diesel blends have a number of potential advantages including: displacement of imported petroleum with a domestic and renewable resource, significant lowering of diesel particulate

matter emissions, possible improvement in cold flow properties, and possible improvement in fuel lubricity imparted by the emulsifier additives.

The study also explored technical barriers to commercializing e-diesel including the low flashpoint of this fuel which requires it to be handled like gasoline rather than like conventional diesel. This may necessitate some modifications to storage and handling equipment, as well as vehicle fuel systems. And, it may limit the use of e-diesel to centrally refueled fleets.

Another obstacle is obtaining OEM warranty acceptance. Engine manufacturers' warranties may be violated by use of e-diesel because of concerns about safety and liability, as well as materials and component compatibility.

In addition, in the U.S., as a non-baseline diesel fuel, e-diesel will be required to undergo Tier 1 and Tier 2 emission and health effects testing, a time consuming and expensive process, before it has EPA approval for use.

In addition to these major concerns there are issues related to quantifying the stability, water tolerance, and other fuel properties of e-diesel [146,167].

To address the instability with ethanol and other alcohol-based additives, a technology has been developed that uses renewable feedstocks to make an additive that meets ASTM D8181 specifications for microemulsion blendstock for middle distillate fuels. It is promoted particularly to

address phase separation issues with alcohols with biodiesel, renewable diesel, and petroleum diesel [143,144,145].

Ethanol fumigation into the engine intake port requires modifications to the engine. Aftermarket dual fuel kits were developed, some of which incorporated a heat exchanger to preheat the ethanol to a temperature to improve fuel vaporization. A 2015 study found that although soot decreased, other emission benefits did not materialize [118,147].

Other reviews also noted vehicle safety issues with ethanol/diesel blends and indicated using such blends may require fuel tank modifications [148].

(2) Lignin Ethanol Oil Maritime Fuel

For maritime shipping, Copenhagen University is conducting laboratory-scale development of a mixture of lignin and ethanol called lignin ethanol oil (LEO) The level of interest in using lignin, a low-value pulp/paper production co-product and ethanol to achieve environmental benefits is illustrated by the creation of a LEO Coalition of the university and major shipping companies. The project aims to move into phase II – testing the fuel on actual vessel engines – in the second quarter of 2020. Following a successful phase II, they anticipate phase III, scaling up of LEO fuel production [149].

D. Fuel Ethanol Specifications

Fuel specifications for ethanol use in CI engines do not exist. ASTM International

has developed standards for ethanol as a fuel for use in spark ignition engines.

- ASTM D4806, Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel: This covers fuel-grade ethanol that is suitable for blending with gasoline in levels up to 10 volume percent ethanol [194].
- ASTM D4814, Specification for Automotive Spark-Ignition Engine Fuel: The spark-ignition engine fuels covered here are gasoline and its blends with oxygenates, such as alcohols and ethers, and not fuels that contain an oxygenate as the primary component, such as fuel methanol (M85) [195].
- ASTM D5798, Specification for Ethanol Fuel Blends for Flexible-Fuel Automotive Spark-Ignition Engines: This entails a fuel blend, nominally 51 to 83 volume percent ethanol, for use in ground vehicles equipped with ethanol fuel blend flexible-fuel spark-ignition engines. Ethanol fuel blends, also referred to as “Ethanol Flex Fuel” shall conform to the performance requirements prescribed [196].
- ASTM Research Report D02:1347 — Research Report on Reformulated Spark-Ignition Engine Fuel: This provides information on the requirements of federal reformulated gasoline and EPA-approved state fuel requirements in the United States for ground vehicles equipped with spark-ignition engines [132].

The U.S. Environmental Protection Agency and states have additional requirements and regulations for ethanol blend fuels. Generally, in the US, regular 87 octane gasoline (E10) includes up to 10% ethanol and regular 88 octane gasoline (E15) includes up to 15% ethanol. The highest blend of ethanol is E85 which can only be used in flex fuel vehicles. It has 51-83

percent ethanol [160,161,162,163]. Other countries such as Brazil have different, sometimes higher, standard blends; most other countries typically use much lower percentages of ethanol in fuel [164].



E. Fuel Ethanol's Environmental Impact

Similar to biodiesel, renewable diesel and other transportation fuels, the environmental impact of ethanol varies with the feedstock used to make it and circumstances of production. When fuel is made from waste or residues, the GHG benefits increase. In addition, making fuel with ethanol replaces the need for carcinogenic components [133,134].

The new CI engine described below, using high ethanol blends, is expected to meet California regulations on reductions in nitrous oxide emissions and reduces emissions by 40 percent compared to petroleum diesel use. Compared to existing CI engines, promoters claim that this provides an effective alternative to diesel aftertreatment systems mandated by US federal regulations to lower particulate and NOx emissions [135].

In general, renewable ethanol has significantly less carbon intensity than the gasoline it replaces as calculated using the GREET model. This analysis takes into account not only feedstock, but inputs “from seed to wheel.” For example, the U.S. Department of Agriculture studies show GHG emissions associated with the

production and combustion of U.S. grown corn ethanol (which is currently most prevalent in US E10 gasoline) 39-43 percent lower than that of an energy equivalent quantity of gasoline [136,137]. California Air Resources Board numbers make clear that the carbon intensity of gasoline is getting worse as that of corn ethanol improves [138].

In addition, use of ethanol in CI engines significantly reduces soot (particulate pollution) [135,165,166].

In other applications, ethanol replaces carcinogenic and potential carcinogenic aromatics in fuel [139,134].



9. Straight Vegetable Oil (SVO)

A. Overview of Straight Vegetable Oil

Straight vegetable oil (SVO) is also referred to as pure plant oil (PPO) in Europe. Compression ignition engines will operate with it; however, that does not mean that its use would not violate warranties. It doesn't burn the same as biodiesel or renewable diesel in the engine -- many studies have found that it can damage engines.

Its use in a CI engine has been done in a number of ways: drop-in, diesel blend, organic solvent additive blend, and in a modified two- and single-tank system [150].

B. Production of Straight Vegetable Oil

There are no special production processes other than those used in general vegetable oil production.

C. Fuel Properties of Straight Vegetable Oil

Compared to diesel fuel, SVO is much more viscous, 11 to 17 times thicker than fossil-based diesel. It is much more reactive to oxygen, and has a higher cloud point and pour point temperature [151].

SVO's very different chemical properties and combustion characteristics mean that

it will not atomise properly when the fuel injectors spray it into the combustion chamber and it will not combust properly. Injectors get coked up. This leads to poor performance, higher exhaust emissions, and reduced engine life [150,168].

In an effort to reduce the viscosity of SVO, it is fairly essential to employ a preheating system.



According to DOE, research shows that plant oils, animal fats, and/or greases used in diesel engines, even at concentrations as low as 1%, can cause long-term engine deposits, ring sticking, lube oil gelling and other maintenance problems, and can reduce engine life. These problems are caused mostly by the much higher viscosity, or thickness, of the raw fats and/or oils compared to that of diesel fuel, for which the engines and injectors were designed.

DOE also points out that the significantly higher boiling point of raw fats and oils may also lead to failure of the fuel to fully evaporate, especially during cold starts. This can lead to harmful engine deposits and engine oil sludging [152,25].

Some research was done in Germany to explore straight rape/canola oil use in farm tractors. As a result, drop-in SVO was strongly discouraged and was found only suitable for short-term use [154].

1. Properties of Straight Vegetable Oil Blended with Diesel

People are known to use SVO/diesel mixes such as 50/50 in the winter and 70/30 or even 90/10 in the summer; although some enthusiasts don't recommend more than 20/80 ever.

Some reported problems are the same as using SVO straight with cold starts, deterioration, filters clogging, injectors getting coked up, rings sticking, glazing of the cylinder walls, increasing lube oil consumption, and eventual engine failure. In any case, mixing SVO and diesel isn't advisable without heating the fuel. See tank system below [150].

2. Properties of Straight Vegetable Oil with an Organic Solvent Additive Blend

Some use a variety of commercial products and "do it yourself" mixes of solvents such as turpentine or additives such as kerosene or unleaded gasoline; however there is a lack of studies about long-term durability or emissions information and safety could be a concern [150].

3. Two-Tank Systems for Using Straight Vegetable Oil

With two-tank SVO systems one tank holds SVO and the other petro-diesel (or equivalent).

Similar to the double-tank system described for B100 use, the engine is started on the petro-diesel tank and runs on petro-diesel for the first few minutes while the SVO is heated to lower the viscosity. Fuel heaters can be electrical or use the engine coolant as a heat source. When the fuel reaches the required temperature, the engine is switched over to the second tank and runs on SVO.

Before the engine is shut down, it must be switched back to petro-diesel and the fuel system "purged" of vegetable oil before switching off, so that there's no cold veg-oil left to coke up the injectors next time the engine starts [150].

Easier-to-use one-tank systems are available that include specialized injector nozzles and other system modifications and limitations on what kinds of SVO can be used in them or what kinds of vehicles are appropriate [150].

D. Fuel Specifications

In Europe, PPO comprised solely of rapeseed oil is standardized by the "Quality Standard for Rapeseed Oil as a Fuel" or the RK-Qualitätsstandard [155].

E. Environmental Impact

Little has been published about the environmental impacts of emissions, mileage, or other environmental impacts of SVO. Little is publicly available about use of SVO in general.

10. Conclusion

In 2011, the original publication of “What’s the Difference between Biodiesel and Renewable (Green) Diesel?” seemed to cover all the bases for renewable fuel used in compression ignition engines. Since then, extensive work has been done on varieties of feedstocks and development of other renewable fuels and engine modifications to expand the possibilities.

Some adjustments have also been made in regulations.

This paper should help the general public better understand the options that they have for diesel or compression ignition personal use vehicles and for fleets. Extensive references enable deeper dives into specifics.



11. Appendix

A. Warranties

All diesel engine companies warranty the engines they make for “materials and workmanship.” If there is a problem with an engine part or with engine operation due to an error in manufacturing or assembly within the prescribed warranty period, the problem will be covered by the engine company.

Typically, an engine company will define what fuel the engine was designed for and will recommend the use of that fuel to their customers in their owner's manuals. Because they do not manufacture fuel or fuel components, they do not provide warranties of any kind for fuel.

If engine problems are caused by a fuel these problems, not related to the materials or workmanship of the engine, they may be the responsibility of the fuel producer or supplier if there is a flaw in the fuel or in the way it is sold. Any reputable fuel supplier should stand behind its products and cover any fuel quality problems if they occur.

If a fuel is used that is not recommended by the engine manufacturer, resulting problems would not be covered by the engine manufacturer under the warranty [41].

B. U.S. Government Definitions

1. Internal Revenue Service

For tax credit purposes, the Department of Defense (DOE) and the IRS broadly define renewable diesel. A definition of and tax credit for renewable diesel were originally included in the Energy Policy Act (EPA) of 2005. Current tax credit definitions are found in 26 U.S.C. § 40A.

(d) Definitions and special rules. --For purposes of this section--

(1) Biodiesel. --The term “biodiesel” means the monoalkyl esters of long chain fatty acids derived from plant or animal matter which meet--

(A) the registration requirements for fuels and fuel additives established by the Environmental Protection Agency under section 211 of the Clean Air Act ([42 U.S.C. 7545](#)), and

(B) the requirements of the American Society of Testing and Materials D6751.

Such term shall not include any liquid with respect to which a credit may be determined under [section 40](#) .

(2) Agri-biodiesel. --The term "agri-biodiesel" means biodiesel derived solely from virgin oils, including esters derived from virgin vegetable oils from corn, soybeans, sunflower seeds, cottonseeds, canola, crambe, rapeseeds, safflowers, flaxseeds, rice bran, mustard seeds, and camelina and from animal fats.

(f) Renewable diesel. --For purposes of this title--

(1) Treatment in the same manner as biodiesel. --Except as provided in paragraph (2), renewable diesel shall be treated in the same manner as biodiesel.

(2) Exception. --Subsection (b)(4) shall not apply with respect to renewable diesel.

(3) Renewable diesel defined. --The term "renewable diesel" means liquid fuel derived from biomass which meets--

(A) the registration requirements for fuels and fuel additives established by the Environmental Protection Agency under section 211 of the Clean Air Act ([42 U.S.C. 7545](#)), and

(B) the requirements of the American Society of Testing and Materials D975 or D396, or other equivalent standard approved by the Secretary.

Such term shall not include any liquid with respect to which a credit may be determined under [section 40](#). Such term does not include any fuel derived from coprocessing biomass with a feedstock which is not biomass. For purposes of this paragraph, the term "biomass" has the meaning given such term by [section 45K\(c\)\(3\)](#) [169].

The IRS includes the following in its notice regarding tax credits:

(2) Thermal depolymerization is a process for the reduction of complex organic materials through the use of pressure and heat to decompose long-chain polymers or hydrogen, oxygen, and carbon into short-chain hydrocarbons with a maximum length of around 18 carbon atoms. A process may qualify as thermal depolymerization even if catalysts are used in the process [170].

2. Environmental Protection Agency

The Environmental Protection Agency (EPA), in regulations implementing the Renewable Fuel Standard uses the following definitions:

Advanced biofuel means renewable fuel, other than ethanol derived from cornstarch, that has lifecycle greenhouse gas emissions that are at least 50 percent less than baseline lifecycle greenhouse gas emissions.

Biodiesel means a mono-alkyl ester that meets ASTM D 6751 (incorporated by reference, see §80.1468).

Biomass-based diesel means a renewable fuel that has lifecycle greenhouse gas emissions that are at least 50 percent less than baseline lifecycle greenhouse gas emissions and meets all of the requirements of paragraph (1) of this definition:

(1)(i) Is a transportation fuel, transportation fuel additive, heating oil, or jet fuel.

(ii) Meets the definition of either biodiesel or non-ester renewable diesel.

(iii) Is registered as a motor vehicle fuel or fuel additive under 40 CFR part 79, if the fuel or fuel additive is intended for use in a motor vehicle.

(2) Renewable fuel that is co-processed with petroleum is not biomass-based diesel.

Cellulosic biofuel means renewable fuel derived from any cellulose, hemi-cellulose, or lignin that has lifecycle greenhouse gas emissions that are at least 60 percent less than the baseline lifecycle greenhouse gas emissions.

Cellulosic diesel is any renewable fuel which meets both the definitions of cellulosic biofuel and biomass-based diesel, as defined in this section 80.1401. Cellulosic diesel includes heating oil and jet fuel made from cellulosic feedstocks.

Co-processed means that renewable biomass was simultaneously processed with fossil fuels or other non-renewable feedstock in the same unit or units to produce a fuel that is partially derived from renewable biomass.

Neat renewable fuel is a renewable fuel to which 1% or less of gasoline (as defined in this section) or diesel fuel has been added.

Non-ester renewable diesel, also known as renewable diesel, means renewable fuel that is not a mono-alkyl ester and that is either:

(1) A fuel or fuel additive that meets the ASTM D 975-13a (incorporated by reference, see §80.1468) Grade No. 1-D or No. 2-D specifications and can be used in an engine designed to operate on conventional diesel fuel; or

(2) A fuel or fuel additive that is registered under 40 CFR part 79 and can be used in an engine designed to operate using conventional diesel fuel [171].

C. Terms and Definitions [25,172,173]

Ash – Ash is a measure of the amount of metals contained in the fuel. Ash forming materials may be present in three forms: (i) abrasive solids, (ii) soluble metallic soaps, and (iii) residual biodiesel catalyst. Abrasive solids and biodiesel catalyst materials result in wear of fuel system and internal engine components exposed to fuel after injection. Metallic soaps can contribute to deposits in the fuel system. All ash forming compounds can contribute to the accumulation of materials on diesel particulate filters, requiring filter maintenance.

Cetane Number – Cetane number is a measure of the fuel's ignition and combustion quality characteristics. Biodiesel blend stock typically has a higher minimum cetane level than that of petroleum diesel. Fuels with low cetane numbers will cause hard starting, rough operation, noise and increased smoke opacity.

Cloud Point – Cloud point is a test used to characterize the low temperature operability of diesel fuel. It defines the temperature at which a cloud or haze appears in the fuel under prescribed test conditions. The cloud point for biodiesel blends is generally higher than it is for petroleum diesel fuel. To avoid component precipitation in vehicle fuel tanks and blockage of fuel filters, the traditional blending practices for D1 and D2 for a given ambient temperature should be modified prior to blending with biodiesel. Alternative low temperature operability test methods such as Cold Filter Plugging Point (CFPP) and Low Temperature Flow Test may be agreed to between the supplier and the purchaser of the fuel.

Compression Ratio – The ratio between the volume of the cylinder when the intake valve closes at the bottom of the compression stroke and the volume when the piston reaches the top [128].

Copper Strip Corrosion – The copper strip corrosion test indicates potential compatibility problems with fuel system components made of copper alloys such as brass and bronze.

Flash Point – The flash point temperature is the minimum temperature at which the fuel will ignite (flash) on application of an ignition source under specified conditions. Flash point varies inversely with the fuel's volatility. Flash point minimum temperatures are required for proper safety and handling of fuels. Note that the biodiesel component must meet a flash point criteria, prior to blending, for the purpose of assuring that the biodiesel component does not contain methanol. It is not possible, however, to rely on the flash point of the blend for the same purpose inasmuch as the flash point of the petroleum component is much lower.

Kinematic Viscosity – Kinematic viscosity is the measure of momentum per volume that fuel can transfer. The higher it is, the more momentum the fuel can transport. For excellent results, the fuel would have to have high viscosity and low density [197].

Lubricity – Lubricity is a measure of the fuel's ability to provide adequate lubrication of the components of the fuel system, including fuel pumps and injectors. The precision required in the manufacturing of these components and the significant influence of abnormal wear require that they be adequately protected from scuffing, scratching, wearing, etc. that may affect their fuel delivery characteristics.

Octane Rating – The octane rating is a measure of the resistance of gasoline and other fuels to detonation (engine knocking) in spark-ignition internal combustion engines. High-performance engines typically have higher compression ratios and are therefore more prone to detonation, so they require higher octane fuel since the compression ratio is fixed by the engine design [126].

Oxidative Stability – measures the ability of fuel to resist oxidation during storage and use. Fuels with a lower oxidative stability are more likely to form peroxides, acids, and deposits that adversely affect engine performance. Because it generally has lower oxidative stability, petroleum diesel can be stored longer than biodiesel feedstocks such as white grease and tallow. Biodiesel producers may use additives to extend the storage and usage timelines of biodiesel [16].

Physical Distillation – Distillation provides a measure of the temperature range over which a fuel volatilizes or turns to a vapor. D1 typically has a greater volatility than D2; however, the inclusion of biodiesel at B20 blend levels results in comparable T90 temperature characteristics. Volatility directly affects the engine's ability to operate as intended. Biodiesel does not have a traditional petroleum distillation characteristic; however, the addition of biodiesel to petroleum diesel in a blend can result in an increase in T90 distillation temperature. Higher volatility, as represented by a lower T90 temperature, generally provides better engine performance, while lower volatility generally provides better fuel economy.

Rams bottom Carbon Residue – The Rams bottom Carbon residue test is intended to provide some indication of the extent of carbon residue that results from the combustion of a fuel.

Sulfur – Sulfur levels in fuel are regulated by various governmental agencies to assure compatibility with emission standard requirements. In the United States there are currently three sulfur grades: S5000, S500, and S15, for both D1 and D2 petroleum diesel fuel. Biodiesel blends may not exceed the applicable maximum sulfur levels as defined for petroleum diesel.

Water and Sediment – Fuel should be clear in appearance and free of water and sediment. The presence of these materials generally indicates poor fuel handling practices. Water and sediment can shorten filter life or plug fuel filters, which can lead to engine fuel starvation. In addition, water can promote fuel corrosion and microbial growth. The level of water specified is within the solubility level of water in fuel and, as such, does not represent free water. Limits are established to allow measured results to be compared to a maximum level acceptable for proper engine operation.

D. Resources

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