Neste Renewable Diesel Handbook

NESTE

The only way is forward

Foreword

This booklet provides information on Neste Renewable Diesel, in Europe classified as a Hydrotreated Vegetable Oil (HVO), and its use in diesel engines. Its potential readership consists of, e.g., fuel and exhaust emission professionals in oil companies, automotive industry representatives, fuel blenders, research facilities, and people preparing fuel standards and regulation.

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This booklet will be updated periodically when enough new or additional information has become available.

Possible questions are welcome to NEXBTL.support@neste.com, as well as proposals for issues to be taken into account in the next update.

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Neste Corporation

Disclaimer

Contents

General

The common acronym ”HVO” comes from ”Hydrotreated Vegetable Oil” or ”Hydrogenated Vegetable Oil”. They originate from last decade when only vegetable oils were used as feedstocks. Today more and more of HVO is produced from waste and residue fat fractions coming from food, fish and slaughterhouse industries, as well as from non-food grade vegetable oil fractions. Thus ”HVO” and ”Hydrotreated Vegetable Oil” are no longer accurate terms describing the origin of the fuel. However, those terms cannot be changed easily since they are common in the European regulation, fuel standards, and biofuel quality recommendations set by automotive companies. According to several chemistry experts ”Hydrotreated” referring to fuel processing should be preferred instead of ”Hydrogenated” as the latter is commonly linked to manufacturing of margarine.

Neste Corporation calls its own product “Neste Renewable Diesel”. ”Renewable Paraffinic Diesel” has also been commonly used as it is chemically a proper definition for product quality. However, this term covers also pilot scale BTL fuels made by Fischer-Tropsch synthesis and, therefore, does not define feedstock and process used to produce ”HVO”. Also terms “HDRD” i.e. “Hydrogenation Derived Renewable Diesel”, “Non Ester Renewable Diesel”, “Renewable Hydrocarbon Diesel”, and “HBD” i.e. “Hydro-generated Biodiesel” have been used especially in North America and Far East. The European EN 15940 standard uses a definition ”Paraffinic Diesel Fuel from Hydrotreatment”. This document refers to isomerized high cetane number (above 70) products meeting EN 15940 Class A requirements. In this document “HVO”, “Neste Renewable Diesel” and “renewable diesel” are used to refer to such product.

The hydrotreating of vegetable oils as well as suitable waste and residue fat fractions to produce HVO is a quite new but already mature commercial scale manufacturing process. It is based on oil refining know-how and is used for the production of biofuels for diesel engines. In the process, hydrogen is used to remove oxygen from the triglyceride vegetable oil molecules and to split the triglyceride into three separate chains, thus creating hydrocarbons which are similar to existing diesel fuel components. This allows blending in any desired ratio without any concerns regarding fuel quality.

Traditionally, diesel components produced from vegetable oils are made by an esterification process. The products are called “Fatty Acid Methyl Esters” i.e. “FAME” or “biodiesel”. Other acronyms are also used, such as Rape Seed Methyl Ester” i.e. “RME”, “Soybean Methyl Ester” i.e. “SME”, “Palm Oil Methyl Ester” i.e. “PME”, or “Used Cooking Oils Methyl Ester” i.e. “UCOME”.

A very simplified scheme regarding the inputs and outputs of esterification and hydrotreating processes is shown in the Figure 1 below. More detailed descriptions about all feedstock and energy streams, as well as products, side products and emissions from the production plan can be generally found from the case-by-case Life Cycle Assessments. Both the FAME and HVO processes are similar in that they use intermediates produced from natural gas. In the future, both hydrogen and methanol could be produced from biomass or biogas. The need for natural gas is about the same in both FAME and HVO processes and is confirmed by figures published by the Renewable Energy Directive 2009/28/EC (“RED”) which show that life cycle greenhouse gas emissions of HVO are slightly lower than those of FAME if both are made from the same feedstock.

Neste spends 70% of all its R&D investments on the development of new raw materials, especially waste and residues. With year-on-year increases, the supply of Neste Renewable Diesel from waste and residue material reached 68% in 2015; thus the use of such raw materials by Neste is very remarkable already today. Aim of the company’s current efforts are focused on the utilization of ever lower quality waste and residue materials, as well as on the development of promising new materials, such as algae and microbial oils.

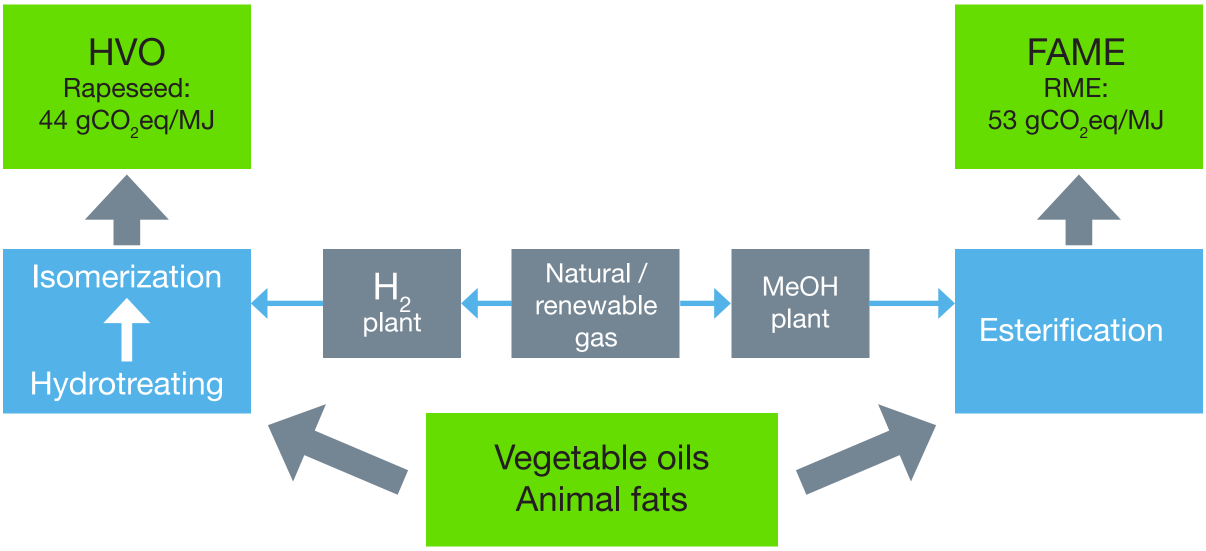


Figure 1. Simplified scheme showing inputs and outputs of esterification and hydrotreating processes for biofuel production. Default well-to-tank GHG values are according to RED Annex V D with a rape seed feedstock.

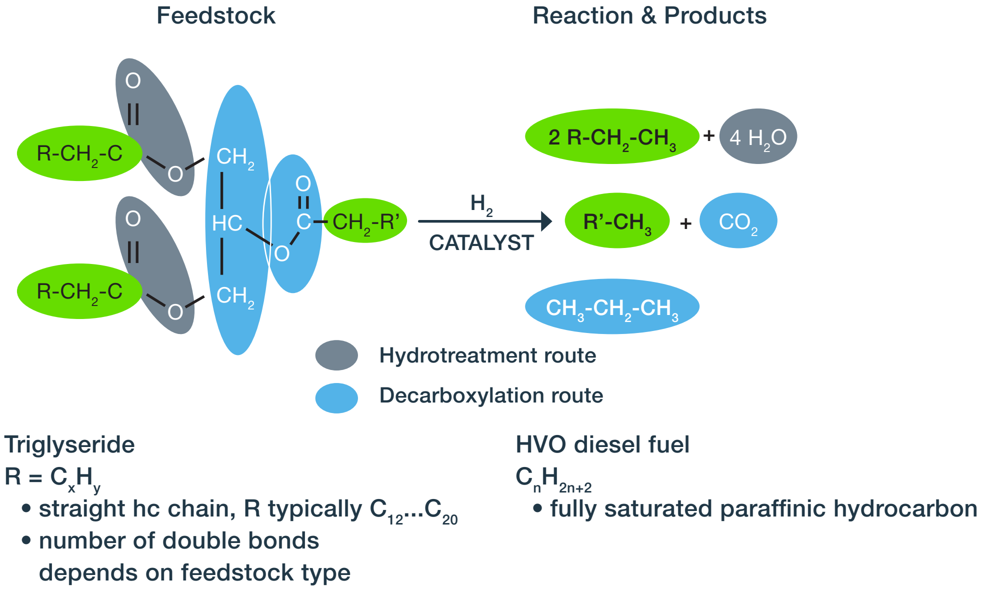


Figure 2. HVO chemistry.

HVO is a mixture of straight chain and branched paraffins – the simplest type of hydrocarbon HVO is a mixture of straight chain and branched paraffins – the simplest type of hydrocarbon molecules from the point of view of clean and complete combustion. Typical carbon numbers are C_{15} ... C_{18}. Paraffins exist also in fossil diesel fuels which additionally contain significant amounts of aromatics and naphthenics. Aromatics are not favorable for clean combustion. HVO is practically free of aromatics and its composition is quite similar to GTL and BTL diesel fuels made by Fischer Tropsch synthesis from natural gas and gasified biomass.

At least the following companies have developed stand-alone HVO production processes and products:

- Axens IFP: Vegan
- Honeywell UOP: Green Diesel
- Neste: NEXBTL™, Neste Renewable Diesel
- Haldor Topsoe: Hydroflex
- ENI: Ecofining

The following description provides an overview of the NEXBTL™ HVO production process and products of NEXBTL™ process. The current sites are optimized for diesel fuel yields. In addition to diesel fuel, small amounts of renewable gasoline components, propane and isoalkane are formed as side products. Renewable gasoline components can be blended into gasoline where they provide a high bioenergy value but suffer from low octane numbers compared to, for example, ethanol. Biopropane can be used in cars and other applications using LPG; it can also be used as renewable process energy at the production site reducing the carbon footprint of products from NEXBTL™ process. Isoalkane provides possibility to usage in a wide range of chemical applications e.g. paints and coatings. The NEXBTL™ process includes also an isomerization unit for improving cold properties even down to arctic diesel fuel grades. NEXBTL™ process also enables production of renewable jet fuel.

Fuel specifications

EN 15940:2016

Neste Renewable Diesel meets EN 15940:2016 for paraffinic diesel fuels. This standard covers also synthetic Fischer-Tropsch products GTL, BTL and CTL. Before that, paraffinic diesel fuel was specified by CEN Technical Specification TS 15940:2012 and CEN Workshop Agreement CWA 15940:2009. Since there are no practical methods for measuring paraffinic content, the paraffinic nature is proven by limiting aromatic content to practically zero. Usually Neste Renewable Diesel is delivered without any FAME, although 7 vol-% FAME is allowed as a blending component by EN 15940. However, originally CWA 15940 did not allow FAME.

In many cases, an abbreviation “XTL/HVO” is used for paraffinic fuels. XTL is a term used to describe synthetic GTL, BTL, and CTL Fischer-Tropsch production paths.

The common ester type biodiesel (FAME) specification EN 14214 is not valid for Neste Renewable Diesel since Neste Renewable Diesel consists of hydrocarbons only. Neste Renewable Diesel as such meets the European diesel fuel standard EN 590 in all respects except density, which is below the lower limit. The American diesel fuel standard ASTM D975 and Canadian CGSB-3.517 are met as such.

CEN TC441 is preparing a standard for fuel labeling at retail points according to the Directive 2014/94 article 7. This new labeling will be based on fuels’ technical compatibility with vehicles and not on biocontent as itself. Labeling is planned to come into force in late 2016 using 24 months implementing time.

Table 1. Typical properties of pure Neste Renewable Diesel and how it relates to EN 15940, EN 590 and ASTM D975 standards.

Property		Neste Renewable Diesel	EN 15940:2016 Class A	EN 590:2013	ASTM D975:15b
Appearance at +25 °C		Clear & Bright			
Cetane number		> 70.0	≥ 70.0	≥ 51.0	≥ 40
Density at +15 °C	kg/m³	770.0…790.0	765.0…800.0	820.0…845.0 ≥ 800.0 *	
Total aromatics	% (m/m)	< 1.0	≤ 1.1		≤ 35
Polyaromatics	% (m/m)	< 0.1		≤ 8.0	
Sulfur	mg/kg	< 5.0	≤ 5.0	≤ 10.0	≤ 15
FAME-content	% (V/V)	0	≤ 7.0	≤ 7.0	
Flash point	°C	> 61	> 55	> 55	> 52
Carbon residue on 10 % distillation	% (m/m)	< 0.10	≤ 0.30	≤ 0.30	≤ 0.35
Ash	% (m/m)	< 0.001	≤ 0.010	≤ 0.010	≤ 0.01
Water	mg/kg	< 200	≤ 200	≤ 200	
Total contamination	mg/kg	< 10	≤ 24	≤ 24	
Water and sediment	% (V/V)	≤ 0.02			≤0.05
Copper corrosion		Class 1	Class 1	Class 1	Class 3
Oxidation stability	g/m³ h	< 25	≤ 25 ≥ 20 **	≤ 25 ≥ 20 **	
Lubricity HFRR at +60 °C	µm	≤ 460 *** ≈ 650 ****	≤ 460	≤ 460	≤ 520
Viscosity at +40 °C	mm²/s	2.00 … 4.00	2.000 … 4.500	2.000 … 4.500 ≥ 1.200 *	1.9…4.1
Distillation 95% (V/V) 90% (V/V)	°C °C	< 320 282 … 338	≤ 360	≤ 360	 282…338
Final boiling point	°C	< 330			
Cloud point and CFPP *****	°C	As needed -5…-34	As in EN 590	Down to -34	
Antistatic additive		Added			
Conductivity	pS/m	≥ 50			≥ 25

*) Winter grades

**) Additional requirement if contains above 2 vol-% FAME

***) Including lubricity additive when delivered to be used as such in vehicles which are validated for EN 15940 fuel

****) If delivered without lubricity additive to be used as a blending component, preference is to add lubricity additive into the final blend

*****) If delivered as such, CFPP will be near the cloud point

EN 590:2013 diesel fuel standard

EN 590

- defines properties of ”B7” diesel fuel sold at retail
- does not take any position on how and from what feedstock fuel is processed
- limits the use of FAME to max. 7 vol-%
- allows HVO without any limit
  - HVO can be blended as such or in addition to max 7 vol-% FAME
- allows HVO without pump labeling

Fuel standard EN 590 is a voluntary fuel quality agreement to be used for fuel manufacturing and commerce. It defines properties that are important for operability, durability, and tailpipe emissions of diesel vehicles. In principle, such properties must be satisfied at retail points where vehicles are refueled, but in practice they are controlled at the level of fuel blending and bulk sales. EN 590 does not take into consideration whether the fuel's origin is fossil or renewable. It also does not specify on the production processes used.

This standard is developed, updated, and approved by CEN bodies which consist of fuel and automotive experts nominated by the national member bodies of CEN. This drafting exercise takes place outside any political setting and is carried out by experts with no direct legislative mandate. In addition, the CEN includes members from non-EU countries.

The fuel properties laid down in Annex II of the Fuel Quality Directive 2009/30/EC ("FQD") are copied into EN 590 as such. Fuel which does not meet the specifications contained in EN 590, but satisfies the requirements laid down in the FQD, can be put on the market, but may not be labeled as EN 590. For example, B10 (maximum 10.0 vol-% FAME) can be sold on the condition that the appropriate fuel quality information is provided to consumers, it is compliant with the vehicle manufacturer's requirements, and a national waiver according to FQD has been given for >B7. If a vehicle's owner decides to use a fuel not compliant with the car manufacturers' recommendations, it is then at his/her own responsibility. This is confirmed by Article 4(1) of the FQD.

EN 590 does not require any labeling of bio content at retail points provided that the fuel meets the EN 590 specifications (maximum 7.0 vol-% FAME). This means there is no need to label HVO at retail points at any blending ratio. The common abbreviations B7 or B10 define only the maximum allowed FAME-content in vol-%. HVO can be used as such or in addition to FAME regardless of B7, B10, B20 or B30 definitions.

CEN is preparing a standard for fuel labeling according to the Directive 2014/94 article 7 which comes into force in late 2016 using 24 months implementation period. Labeling will be based on the technical compatibility of fuels with vehicles and not on the biocontent itself. This labeling will not require any additional labeling for HVO when it is blended into diesel fuel since HVO consists of hydrocarbons.

HVO's position in EN 590:2013

EN 590 does not take any position on the type of feedstock used to produce fuel components or on the way such components are processed and blended. The only requirement is that the final fuel meets the defined technical requirements. All suitable hydrocarbon-type blending components such as straight run gas oils or kerosenes, various types of cracked gas oils or kerosenes, gas-to-liquid diesel fuels (GTL), hydrotreated vegetable oils and animal fats (HVO), as well as bio-to-liquids fuels (BTL) can be used. It does not matter whether the components to be blended are handled only inside a specific refinery site or whether they are traded as bulk batches between fuel suppliers before the final blending. The allowance of HVO is especially mentioned in EN 590 paragraph 5.4 "Other (bio)components".

HVO belongs to the group of hydrocarbons which are miscible with a hydrocarbon matrix of a fuel blend. Therefore, the use of HVO as a blending component does not need to be regulated further through technical standards.

The maximum amount and quality of FAME (EN 14214) are defined by EN 590 since FAME has different chemistry, properties, and levels of impurities compared to hydrocarbons. These requirements in EN 590 are not applicable to any other biocomponents than FAME. In the same vein, Annex II of the FQD requires FAME to comply with EN 14214. For example, the presence of phosphorous, which may be harmful to vehicles' exhaust after-treatment systems, can only originate from FAME. It is more convenient to control phosphorous content at a robust level from neat FAME before blending than to measure phosphorous from all diesel fuels using accurate analytical methods after FAME has been diluted by 93% of phosphorous-free hydrocarbon fuel. The same applies for aging and decomposition during storage, which is different for hydrocarbons and esters. As a consequence, different requirements apply to neat FAME (EN 14214), fuels containing 2 to 7 vol-% FAME, and pure hydrocarbons.

In addition, the analytical method EN 14078 for measuring the biofuel content of diesel fuel is valid only for FAME. This means that the amount of HVO in diesel fuel has to be shown by audit trail and mass balance from the fuel blending. If an audit trail is contested, a radioisotope carbon ^{14}C method can be used for estimating the biofuel content. This method has already been referred to in EN 228:2012 for proving the bio-origin of ethanol in gasoline, but this test is too laborious for routine fuel quality control.

prEN 16734 ”B10” diesel fuel standard draft

prEN 16734:2015 standard draft for diesel fuels containing maximum 10.0 vol-% FAME is comparable to EN 590; i.e. the use of HVO is allowed without any limits and without specific labeling for HVO, provided that the final blend complies with prEN 16734.

EN 16709:2015 ”B20” and ”B30” diesel fuel standard

EN 16709:2015 standard defines requirements for diesel fuels containing 14.0…20.0 vol-% (B20) or 24.0…30.0 vol-% (B30) FAME. B20 and B30 can be used only in dedicated fleets since they do not meet density requirement maximum 845 kg/m^3 set by Fuel Quality Directive 2009/30/EC (“FQD”) Annex II for market fuels. HVO is not separately mentioned in EN 16709. However, B20 and B30 should be manufactured by adding FAME into EN 590 diesel fuel. Since HVO is already allowed in EN 590 diesel fuel, B20 and B30 are also allowed to contain HVO without any specified limit or labeling at retail points.

ASTM D975

Fuel standard ASTM D975 is a standard for diesel fuel oils suitable for various types of diesel engines. There are seven different grades in this standard and renewable hydrocarbon diesel fulfill No 2-D Grade, its purpose being to use this kind of diesel in engine applications requiring a fuel with 15 ppm sulfur (maximum). It is especially suitable for use in applications with conditions of varying speed and load.

HVO and EN 14214 FAME standard

HVO

- due to different chemical composition and properties, cannot meet any FAME standards
- paraffinic fuels have an own specification: EN 15940

Since HVO consists of paraffinic hydrocarbons, it cannot meet the requirements set by EN 14214 which is a standard developed and valid only for methyl ester chemistry type biodiesel, namely FAME. As a matter of fact, HVO meets EN 590 except the requirement for minimum density. Because of this, attempts to require that all biocomponents meet EN 14214 are technically impossible and discriminatory.

HVO, as well as BTL and GTL meet the specifications contained in EN 15940 for paraffinic diesel fuels. The purpose of the EN 15940 is to define properties of paraffinic diesel fuel when it is used as such in vehicles which are validated for this fuel by the engine or vehicle supplier.

For example, EN 15940 specifies a certain density range which is considerably lower than FAME’s density range defined by EN 14214. This shows that properties of HVO and FAME are so far from each other that they cannot be covered by the same standard.

When HVO is used as a blending component in EN 590 diesel fuel, HVO does not need to meet EN 15940 requirements because HVO is fully miscible with diesel fuel. EN 590 requires only that the final fuel blend meets limits set by the EN 590.

Worldwide Fuel Charter (WWFC)

The Worldwide Fuel Charter (WWFC) is a recommendation published by automotive companies for fuel qualities to be used with different vehicle emission requirements. WWFC also includes justifications for each parameter required. The fifth edition (2013) of WWFC pays attention to challenges related to the use of FAME, and recommends using HVO as a biocomponent.

WWFC can be downloaded from

http://www.acea.be/uploads/publications/Worldwide_Fuel_Charter_5ed_2013.pdf

and justifications for biofuels can be found from

- page 53 … 54 for FAME
- page 55 … 56 for HVO

Legislative fuel composition requirements in Europe

HVO

- by definition is not biodiesel (only FAME is biodiesel)
- meets compositional requirements set by FQD Annex II for diesel fuels
- may be blended into diesel fuel without any limit or labeling at retail pumps because of its hydrocarbon nature according to FQD recital 33
- originally RED required the labeling of any biocomponent that was used over 10 %, but that requirement was deleted in 2015
- energy content is defined in RED Annex III
- typical and default greenhouse gas values are defined in RED Annex V and FQD Annex IV
- the original FQD (98/70/EC) requires compliance to the directive on free circulation of fuels: a member state may not discourage HVO use
- RED and FQD define feedstock issues and properties of final fuels but not production processes: a manufacturer or fuel supplier is free to choose between HVO and FAME

The following paragraphs present a detailed account of how HVO has been treated in European Union directives. It is important to note that directives do not set any limits on how fuels or fuel components are processed, which means that a fuel company is free to choose between HVO, FAME, co-processing, GTL, or any other technically suitable production process. The regulation only sets limits regarding sustainability issues of feedstock, amount of bioenergy, greenhouse gas emissions, and quality of the final fuel when it is related to tailpipe emissions or technical compatibility with vehicles.

Directives of the European Union

The fuel quality Directive 98/70/EC (“FQD”) with remarkable amendments by Directive 2009/30/EC lays down fuel requirements which are related to health, environment and engine technology (Article 1 (a)), and determines targets for the reduction of greenhouse gas emissions (Article 1(b)).

The regulatory technical requirements for diesel fuel are related to the minimum cetane number and the maximum density, 95 % distillation point, polyaromatics, sulfur and FAME. When FAME is used, it must comply with the EN 14214 standard (FQD Annex II).

The use of biocomponents in diesel fuel was not limited by legislation until the latest amendment brought by Directive 2009/30/EC which limited the use of FAME to maximum 7 vol-%. This limitation is justified by the technical properties of FAME (Recital 33), mainly with respect to engine and vehicle operability and durability (Recital 31).

According to Article 1(9) of the FQD, this Directive applies to biofuels within the meaning of Directive 2009/28/EC ("RED"). Article 2(e) and (i) of the RED define biofuels on the basis of their feedstock path without any requirements as to how the final fuel has been produced or as to their chemical composition. Furthermore, according to Article 3(4)(b) of the RED, all types of energy from renewable sources must be taken into account in the calculation of the share of energy from renewable sources used in each Member State. It follows from these provisions that biofuel process paths and compositions are allowed without any limitations, in accordance with the principles of technical and commercial neutrality.

In this respect, the FQD specifically provides that the use of biofuels other than FAME in diesel fuel is not limited. Hydrotreated vegetable oil is explicitly mentioned as one of the unlimited diesel-like hydrocarbon biofuels (Recital 33). As a matter of fact, even in its pure state, hydrotreated vegetable oil (HVO) meets all the diesel fuel specifications set forth in Annex II of the FQD.

It follows from footnote 3 of Annex II of the FQD that the requirements set out in EN 14214 only apply to FAME. Also, the analytical method contained in EN 14078 (Annex II) for measuring the biofuel content of diesel fuel is valid only for FAME. This means that the amount of HVO used in diesel fuel has to be shown by audit trail and mass balance from fuel blending which is defined both in the RED (Article 18 (1)) and in the FQD (Article 7c (1)). If an audit trail is contested, the biofuel content can be estimated by the radioisotope carbon ^{14}C method.

Article 21(1) the RED previously required that information had to be provided to the public when a fuel contained more than 10 vol-% of biofuel. However, this article was deleted by Directive 2015/1513 meaning that there are no longer any legal requirements to label any HVO content of diesel fuel at retail points any more.

Greenhouse gas emission values are defined by the FQD (Annex IV) and the RED (Annex V). Hydrotreated vegetable oil (HVO) from several production pathways is mentioned besides biodiesel (FAME) in both directives. The same applies to energy content which is determined in Annex III of the RED as regards hydrotreated vegetable oil. HVO is also considered to be fully from renewable sources.

As a result, HVO is explicitly mentioned by both the RED and the FQD, which allow for HVO to be marketed in exactly the same way as FAME, provided that such biofuels meet the sustainability and greenhouse gas emission requirements. It is only FAME that has a technical based blending limit of 7 vol-% and that is subject to the quality requirements contained in EN 14214.

Legislative requirements for free markets

Neste Renewable Diesel

- directive 98/70/EC (original FQD) requires free circulation of fuels:
  - Neste Renewable Diesel or any fuel shall not be discouraged if it complies with specification

Article 34 TFEU ("Treaty on the Functioning of the European Union") and the free movement clause contained in Article 5 of Directive 98/70/EC preclude Member States from prohibiting, restricting or preventing the placing on the market of fuels which comply with the requirements of that Directive (as amended). This means that a Member State may not limit the use of Neste Renewable Diesel as a biocomponent in diesel fuel provided that such Neste Renewable Diesel satisfies the greenhouse gas and sustainability requirements set forth in the RED and the FQD, and provided that the final diesel fuel complies with the limits imposed by Annex II of the FQD as regards cetane, density, distillation, polyaromatics, sulfur and FAME.

In this respect, the European Court of Justice has consistently held that Member States are not allowed to impose additional requirements on products the specifications of which have been fully harmonized at EU level.

The RED and the FQD do not require diesel fuel to meet the EN 590 specifications. The FQD only refers to EN 590 in relation to the test methods in order to ensure that fuel producers and regulators use the same laboratory methods for demonstrating and monitoring compliance with its requirements (Article 8(1) and Annex II of the Directive). As a result, Member States cannot make the marketing of Neste Renewable Diesel or of any other diesel fuel conditional upon it satisfying EN 590 specifications.

In any event, it should be noted that technical standards such as EN 590 are not compulsory, as explicitly stated in Article 1(4) of Directive 98/34/EC laying down a procedure for the provision of information in the field of technical standards and regulations.

This is further confirmed in the Commission's Guide to the implementation of directives based on the New Global Approaches, according to which "the application of harmonized standards, which give a presumption of conformity, remains voluntary […]. Thus, the product may be manufactured directly on the basis of the essential requirements [contained in the relevant Directive]".

Case: Fuel taxation in Finland

Fuel taxation in Finland

- based on energy content (MJ/l), well-to-wheels CO_2 and locally harmful tailpipe emissions
- promotes
  - paraffinic diesel fuels (HVO, GTL, BTL) because of their lower tailpipe emissions
  - biofuels
  - biofuels made from waste or cellulosic feedstock (double counting)

Fuel taxation in Finland (act 1399/2010 with its amendments e.g. 1184/2014) promotes the use of renewable and clean combusting fuels. Taxes are based on energy content, greenhouse gas emissions, and tailpipe emissions. In addition to those, a security of supply levy is charged.

The energy tax on diesel fuels is 0.88 euro cents per megajoule (MJ). For practical reasons, energy tax is converted to cents per liter of fuel to be paid.

CO_2 tax is 58 euros per ton of CO_2. Here CO_2 is the CO_2 formed in the final combustion using the well-to-wheels approach which is common for biofuels. Again, this tax is calculated to cents per liter of fuel to be charged. Renewable fuels which meet sustainability and GHG-criteria of directive 2009/28/EC ("RED") are entitled to 50% reduction in CO_2 tax. Fuels which meet the double counting criteria of waste or cellulosic based feedstock are free of CO_2 tax. Renewable fuels which do not meet criteria set by RED are taxed like fossil fuels.

Locally harmful tailpipe emissions are taken into account by monetizing NO_x, HC and particulate emissions by using principles presented in directive 2009/33/EC which promotes clean and energy-efficient road vehicles. The directive gives the following external cost effects for emissions: NO_x 0.44 cents/g, HC 0.1 cents/g and particulate matter 8.7 cents/g, which can be doubled according to a local consideration.

The use of paraffinic diesel fuels instead of standard fuels reduces emissions which have been monetized by using doubled values since it is a question of urban air quality. The result is calculated to cents per liter of fuel and taken off from the energy tax (Table 2). A corresponding benefit is given in the vehicle tax of methane vehicles because the fuel tax of methane is so low that there is no room for reduction. Biodiesel does not qualify for any air quality benefit due to its higher NO_x, but tax per liter is slightly lower because the energy tax per megajoule is the same, but the heating value per liter is lower than that of fossil diesel fuel. The same applies for ethanol diesel fuel (ED95) which has quite a low energy content.

Paraffinic diesel fuel is defined in the Finnish act 181/2016 by parameters set by directive 2009/30/EC ("FQD") by choosing limit values which make a clear difference between paraffinic and common diesel fuel: cetane number min 51, density 765...810 g/l, total aromatics 1,1 wt-%, sulfur max 5 mg/kg and 95 % distillation max 360 °C.

Table 2. Diesel fuel taxes in Finland from January 2016, euro cents per liter without value added tax (act 1184/2014). Taxes of ethanol diesel fuel (ED95) for dedicated engines are also presented for reference.

	Energy tax (c/l)	CO_2 tax (c/l)	Security of supply levy (c/l)	Total (c/l)	Difference to diesel fuel (c/l)
Diesel fuel	31.65	18.61	0.35	50.61	
Paraffinic diesel (e.g. GTL, CTL)	24.89	17.58	0.35	42.82	- 7.79
Renewable paraffinic diesel (e.g. HVO)	24.89	8.79	0.35	34.03	- 16.58
Double counted paraffinic diesel (e.g. HVO from waste, BTL)	24.89	0.00	0.35	25.24	- 25.37
Biodiesel (e.g. FAME)	29.01	8.53	0.35	37.89	- 12.72
Double counted biodiesel (e.g. FAME from waste)	29.01	0.00	0.35	29.36	- 21.25
Renewable ethanol diesel (e.g. ED95)	14.53	5.99	0.35	20.87	
Double counted ethanol diesel (e.g. ED95)	14.53	1.07	0.35	15.95	

Tax benefit can be utilized when paraffinic diesel fuel is used as such, for example, in city bus fleets. When paraffinic fuel is blended into diesel fuel, tax is based on a blending ratio only if the base fuel meets requirements set by FQD before adding the paraffinic component. In other words, the base fuel has to meet FQD, and the blended one has to be a premium grade producing fewer emissions as a function of the paraffin blending. If blending of paraffinic fuel to meet FQD is used for upgrading gas oils not yet meeting FQD, the energy tax benefit is lost but the reduced CO_2 tax is valid according to the renewability.

Fuel properties

Neste Renewable Diesel

- highest heating value among current biofuels
- severe winter and arctic grades available due to the isomerization process
- benefits for blending diesel fuels at refineries or terminals:
- very high cetane number (>70)
  - low density (~780 kg/m^3)
  - sulfur-free (<5 mg/kg)
  - very low aromatics (<1 wt-%)
  - reasonable distillation range, not limiting 90% and 95% distillation points
- effect of cetane number, density, sulfur, and aromatics practically linear in blending
- behaves in logistics like fossil diesel fuel, i.e. no issues with:
  - stability: no need for "use before" date
  - water separation
  - microbiological growth
  - impurities causing precipitation above cloud point
- practically free of metals and ash-forming elements
- lubricity additive needed like in all sulfur-free diesel fuels

Properties of Neste Renewable Diesel have much more similarities with high quality sulfur free fossil diesel fuel than with FAME. As a matter of fact, the properties of renewable diesel are very similar to the synthetic GTL diesel fuel which was earlier considered to be the best diesel fuel for engines and regarding tailpipe emissions. Now renewable diesel offers the same compositional benefits as GTL, and in addition to that is also from a renewable origin. Also, the same analytical methods as used with fossil fuels are valid for renewable diesel.

Familiarizing oneself with the properties of Neste Renewable Diesel and analytical methods to be used is valuable since they differ from FAME, which is a more familiar biocomponent to oil companies. These differences remain relevant regardless of whether renewable diesel is used as a blending component in diesel fuel, or as such in vehicles which have been validated for XTL/HVO.

Density and energy content

HVO

- lower density (780 kg/m^3) compared to common European diesel fuels (800...845 kg/m^3)
- higher energy content compared to FAME, both in MJ/kg and MJ/l
  - less HVO in mass and volume needed to fulfill a given biomandate

Due to the paraffinic nature and the low final boiling point, the density of renewable diesel is lower than that of fossil diesel fuels. Fuel density has traditionally been an important factor as it has a positive effect on maximum power output of engines and their volumetric fuel consumption. This is due to the heating value of diesel fuels being quite constant per mass for various fossil diesel fuel grades when they are inside a certain range of aromatic content. If density is reduced, heating value per volume is decreased as a function of density. With a lower volumetric heating value, engine gets less energy in with full throttle and needs more fuel volume in order to provide the same energy output at part loads.

With Neste Renewable Diesel, the case is different since energy content is higher per mass compensating part of the effect of lower density (Table 3). The higher heating value of Neste Renewable Diesel per mass is based on the fact that hydrogen content of Neste Renewable Diesel is about 15.2 wt-% compared to about 13.5 wt-% of standard diesel fuel.

A slightly smaller Neste Renewable Diesel blending ratio is needed compared to FAME for meeting the same bioenergy mandate because HVO's energy content is higher than that of FAME, both per liter and per kg. Compared to ethanol, HVO's volumetric benefit is large since the heating value of ethanol is only 21 MJ/l.

The low density often offers benefits when Neste Renewable Diesel is used as a blending component in diesel fuel production because it may allow the use of heavier fractions that would in other cases have to be used for lower profit products like heating gas oil. In blending recipes density behaves linearly.

Table 3. Typical densities and lower calorimetric heating values.

		Diesel fuel (typical summer grade without biocomponent)	Neste Renewable Diesel	FAME
Density	kg/m^3	835	~780	~880
Heating value	MJ/kg	43.1	44.1	37.2
Heating value	MJ/l	36.0	34.4	32.7
• difference to diesel fuel			-5 %	-9 %
Heating value, 10 vol-% blend	MJ/l		35.8	35.7
Heating value, 30 vol-% blend	MJ/l		35.5	35.0

Distillation

Neste Renewable Diesel
- lower final boiling point than with FAME

Distillation curves give the amount of a fuel sample that is evaporated in atmospheric pressure at each temperature when the temperature is increased gradually. Distillation characteristics illustrate how fuel is evaporated when it is sprayed into the combustion chamber of a diesel engine. Some fractions boiling at low temperatures are needed for engine start-up, while fractions boiling at too high temperatures may not combust completely forming engine deposits and increasing tailpipe emissions. A typical boiling range of a European summer grade diesel fuel is from about 180 °C (356 °F) to about 360 °C (680 °F). Neste Renewable Diesel's distillation range is within that of fossil diesel, but FAME contains significantly heavier compounds (Figure 3).

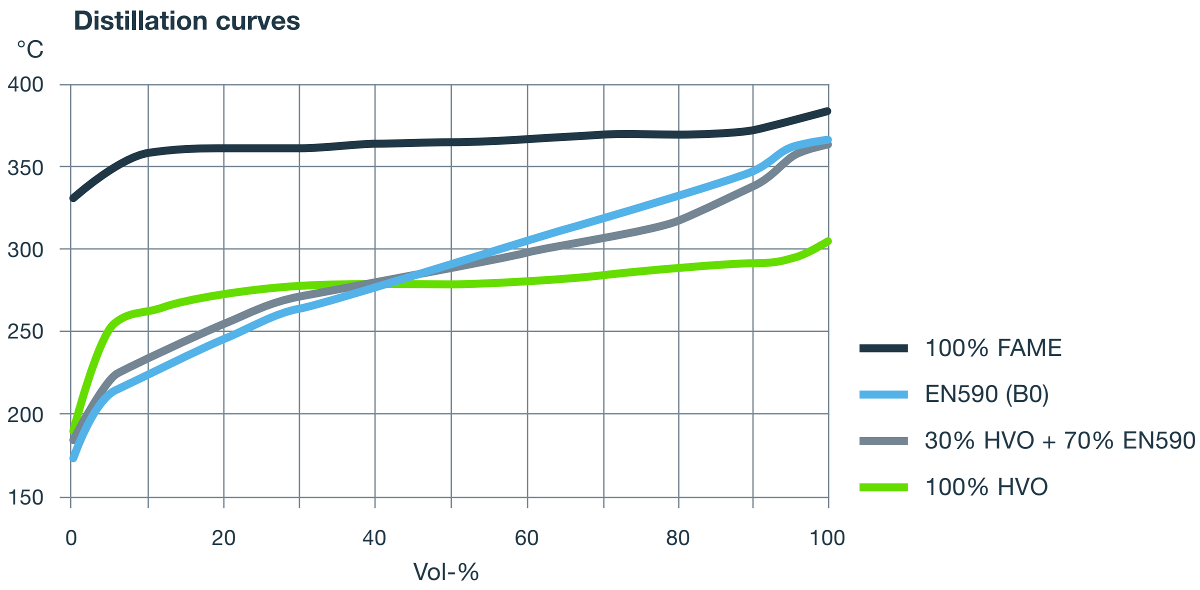


Figure 3. Distillation curves of a typical diesel fuel without any biocomponents (fuel meets EN 590), FAME, HVO, and diesel fuel containing 30 vol-% HVO.

Cold properties

Neste Renewable Diesel
- excellent cold properties: cloud points down to -40 °C (-40 °F) can be reached
  - high biomandate blending ratios possible all year round
- CFPP practically the same as cloud point: cold operability characteristics made mainly by adjusting cloud point
- no risk for impurity precipitation temperatures above cloud point
- density is the same regardless the cloud point

Fit-for-purpose at all times of the year is an essential requirement for diesel fuels. In the case of Neste Renewable Diesel, cold properties can be improved to satisfy severe and arctic climate grades down to -40 °C (-40 °F). Cold properties can be adjusted in the isomerization unit with all feedstocks. In the FAME process, feedstock limits the cold properties. This means that a high biomandate content can be met by using Neste Renewable Diesel all year round without risking cold operability of vehicles or having trouble with fuel logistics.

Only minor improvements with cold flow additives can be achieved due to Neste Renewable Diesel's narrow distillation range and narrow carbon chain distribution (C_{15}...C_{18}) of paraffinic hydrocarbons. This means that with Neste Renewable Diesel, the cold filter plugging point (CFPP) may be only a few degrees better than cloud point. It is safe to say that CFPP value is the same as cloud point. Pour point can be a couple of degrees better than cloud point, but due to the inaccuracy of pour point measurements, it is safe to guarantee only that pour point is better than cloud point. Similar attention is needed when Neste Renewable Diesel is blended with diesel components; it is recommended to confirm cold flow properties of the final blend.

In conventional oil refining, the required cold properties are obtained by distilling fuels to lighter and narrower fractions in order to achieve the desired cloud point. Additional help is obtained from cold flow additives which reduce CFPP and pour point. Density and viscosity will be lower, which cause reduced engine performance and higher volumetric fuel consumption. Isomerization of Neste Renewable Diesel has a negligible effect on density since the process changes the structure of the molecules keeping the distillation curve practically the same. As a side effect, the reduction of cetane number by some units takes place when cold properties are enhanced, but the cetane number of winter grade Neste Renewable Diesel is also very high, usually above 70. However, due to economic and yield challenges excellent cold properties should be produced only when needed.

Viscosity may also have an effect on cold operability in some applications. Viscosity of Neste Renewable Diesel at -15 °C (5 °F) is about 15 mm^2/s. That is around the same as of fossil diesel fuels, and only half of FAME's viscosity.

During long time storage, neat Neste Renewable Diesel as well as blends containing Neste Renewable Diesel behave like fossil diesel fuels. Neste Renewable Diesel does not contain any harmful impurities, e.g. saturated monoglycerides, like FAME. With Neste Renewable Diesel there is no risk for precipitation at temperatures above cloud point causing cold operability problems. Below cloud point, Neste Renewable Diesel blends behave like fossil diesel. As with traditional diesel fuels, some precipitation of paraffins originating either from the fossil part or Neste Renewable Diesel may take place if the temperature is below cloud point for a long period. It is recommended to store all diesel fuels above cloud point.

Additionally, Neste Renewable Diesel and EN 590 (B0) blends containing 10, 30 and 50% of Neste Renewable Diesel have been tested by running diesel cars in a climate chamber and by using a cold test rig consisting of a complete fuel system of a passenger car built in a deep-freezer. The tested fuels, Neste Renewable Diesel and blends, operates as expected in severe winter conditions [Nylund et al. 2011].

Figure 4. Testing of cold properties with diesel cars in a climate chamber.

Cetane number

Neste Renewable Diesel

- very high cetane number: 70 ... 95
- when blending Neste Renewable Diesel, cetane number increases linearly according to blending ratio

The cetane number of most paraffinic diesel fuels is very high, from 70 to 95, because of their nature as a mixture of n- and isoparaffins.

Cetane number of Neste Renewable Diesel can be measured with two different methods, as described in EN 15940: cetane engine and derived cetane number (DCN, EN 15195). When determining precision data for cetane number, it was noted that DCN is the most precise method for paraffinic diesels. Cetane number precision data for high cetane paraffinic diesel, as Neste Renewable Diesel, is explained separately in EN 15940 Annex B. The formula of the cetane index is designed only for conventional diesel fuels, which means that the cetane index is not applicable for neat Neste Renewable Diesel.

When Neste Renewable Diesel is used as a blending component, the cetane number increases somewhat linearly (Figure 5). A well-known possibility is to use 2-ethyl hexyl nitrate additive for improving the cetane number, but the effect is limited. Automotive companies claim that a cetane number enhanced by additives is not as beneficial for real engine performance as an increased natural cetane number which can be made by blending Neste Renewable Diesel. So, the use of Neste Renewable Diesel as a blending component is a good way to increase cetane number either for getting the blend to meet the regulated cetane number or for producing premium diesel fuel grades.

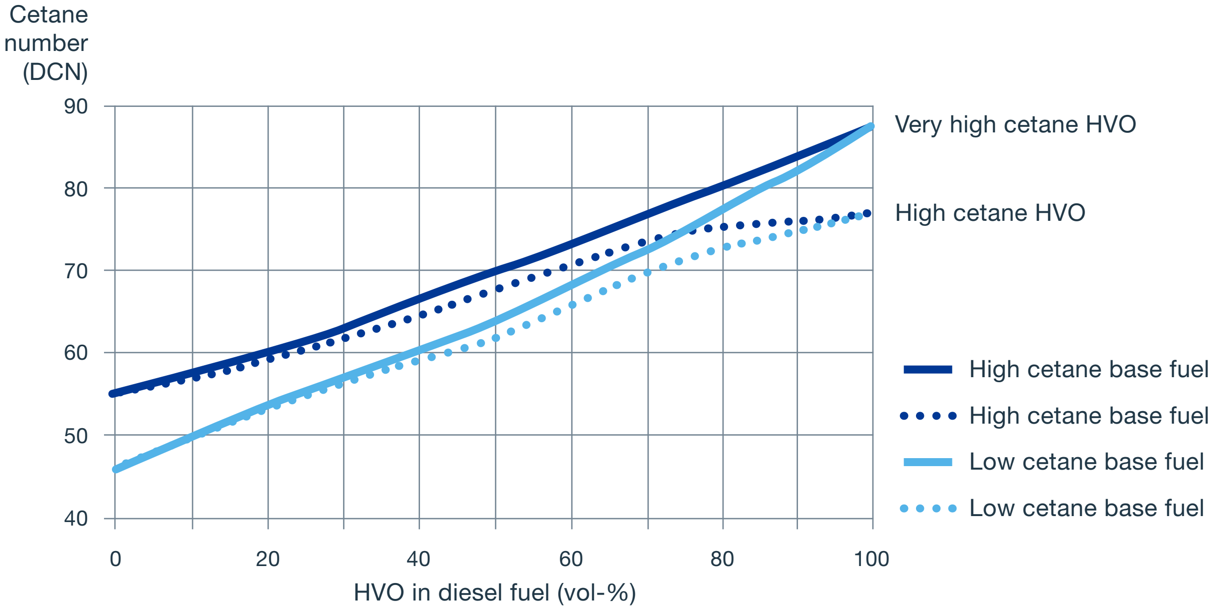


Figure 5. Cetane number of two different Neste renewable fuels (HVO: high and very high cetane) with two different diesel fuels (low and high cetane).

Stability

Neste Renewable Diesel

- stability is good
  - comparable to fossil diesel
  - challenges related to FAME are not a concern with Neste Renewable Diesel
  - no need for “best before” date

Since Neste Renewable Diesel consists of only hydrocarbons, the traditional stability methods used for fossil diesel fuel are applicable. Because of this, the methods developed for FAME do not apply for Neste Renewable Diesel. In particular, it should be noted that the “Rancimat” method EN 15751 designed for neat FAME and diesel fuel containing more than 2 vol-% FAME is not valid for Neste Renewable Diesel or diesel fuel containing only Neste Renewable Diesel as a biocomponent.

Neste Renewable Diesel’s stability is at the same level of conventional fossil diesel, which means that there is no need to apply a “use before” date [Hartikka et al, 2013]. There is no risk of problems if vehicles or stationary engines are out of use for extended periods. This may take place with, e.g., mobile homes used seasonally, vehicles parked in dealers’ yards, seasonal agricultural machinery, boats, and emergency generator sets.

Fuel stability is today an even more important factor than before. A fuel efficient diesel family car may be refueled once per month or even only once per two months, especially if it is the family's second car. Refueling may take place even more seldom with plug-in hybrid cars which may emerge on the market in the future. New sophisticated fuel injection systems may also be even more sensitive for impurities than older ones.

Sulfur content

The sulfur content of Neste Renewable Diesel coming out from the production process is < 1 mg/kg. Due to possible contaminants within normal diesel fuel logistics, sulfur content within Neste Renewable Diesel fuel specification is set to ≤ 5.0 mg/kg. This meets requirements set by the most modern exhaust aftertreatment systems, especially because most of the sulfur entering into the exhaust originates today from engine oil.

If the sulfur content of the base diesel fuel or blending component is slightly above the legal specification, blending of Neste Renewable Diesel can bring the blend to meet the specification.

Ash and metals content

Ash content of Neste Renewable Diesel is very low, < 0.001%.

The amount of vegetable oil feedstock originated compounds like P, Ca and Mg are well below practical detection limits of analytical methods (<1 mg/kg) since contaminants have to be removed within the feedstock pretreatment unit in order to guarantee a long lifetime for the Neste Renewable Diesel production plant catalysts.

Because of its ash-free combustion, Neste Renewable Diesel offers at least as long lifetime as high quality fossil diesel fuel for exhaust aftertreatment systems which are used in current and future vehicles.

Filterability

A lot of fuel filter blocking issues have occurred in Europe over the last few years due to poor diesel fuel quality. This is not the case with Neste Renewable Diesel. There has been discussion for the need for more suitable method for measuring filterability than total contamination (EN 12662). Total contamination is intended to analyze solid particulates, but not other contaminants causing filter blocking. Filter blocking tendency (FBT) IP 387 is one option for measuring filterability and, for example, UK has launched a limit of 2.52 for diesel fuels. FBT of Neste Renewable Diesel is usually around 1.0-1.1, so there is no risk of filter blocking when using neat Neste Renewable Diesel.

Water content

Water is polar, and Neste Renewable Diesel, like fossil hydrocarbons, is non-polar. Due to this, the solubility of water into Neste Renewable Diesel is similar to fossil diesel fuels, or even lower. This means that water issues do not require any additional measures in fuel logistics compared to fossil diesel fuels.

Microbial growth

Microbial growth is an issue which has created a lot of debate recently. It has been mainly related to special applications like marine fuels and extended parking periods, but cases have happened also with automotive vehicles. It is well known that ester type biodiesel (FAME) used in diesel fuel may promote microbial growth. This is due to the chemical composition of FAME, and its tendency to increase the water content of diesel fuel.

Test results show that Neste Renewable Diesel as such or used as a blending component in diesel fuels does not require any additional precautions compared to fully fossil diesel fuels. However, good housekeeping is needed in any case since microbes may grow even in pure fossil fuels during long time storage in the presence of water and favorable conditions. High temperatures (~+30°C) may strongly enhance the microbiological growth in fossil diesel and HVO especially when mineral salts are present in the water phase. At low temperatures (< +10 °C), no microbiological growth was observed.

Appearance and odor

In temperatures above the cloud point, Neste Renewable Diesel is clear and bright, its color is almost water-like (Figure 6). Neste Renewable Diesel does not have an unpleasant diesel fuel type odor. There are no impurities that precipitate in temperatures above the cloud point in neat Neste Renewable Diesel and FAME-free diesel fuel blends. Below cloud point, paraffins make Neste Renewable Diesel cloudy and crystallized paraffins may settle during an extended storage, which is a known phenomenon also for fossil fuels.

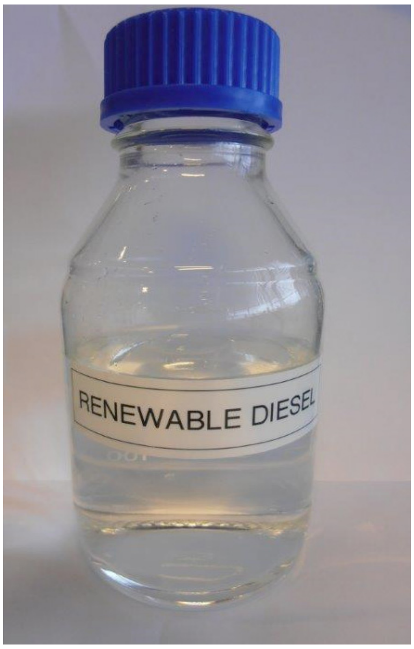


Figure 6. Appearance of Neste Renewable Diesel.

Lubricity

Neste Renewable Diesel

- requires a lubricity additive in the same way as sulfur free diesel fuels and GTL
- generally similar types of lubricity additives can be used in fossil diesel fuel and Neste Renewable Diesel

The lubricity of neat Neste Renewable Diesel corresponds to that of sulfur-free fossil diesel and GTL diesel fuels. It is essential that all of these types of fuels contain lubricity additives in order to meet the HFRR specification <460 µm for protecting fuel injection equipment against wear. Lubricity additives generally used in fossil diesel fuels operate also in Neste Renewable Diesel. Additives representing neutral chemistry are recommended, because they do not affect the acid number of the diesel fuel. If Neste Renewable Diesel is used neat, additive dosing rate is typically about the same as in arctic grade diesel fuels. Neste Renewable Diesel can be delivered with or without lubricity additive. When used either neat or blended with other diesel fuels, the lubricity of fuel has to be always checked. In commercial fuels, HFRR is typically clearly better than <460 µm.

In addition to the specified HFRR tests, lubricity has been evaluated with two 1,000 hour test runs with fuel lubricated distributor type fuel injection pumps. This test is based on a CEC/Bosch procedure which runs a distributor type VE-type pump with injectors using an electric motor at varying loads at +60 °C (140 °F) fuel temperature. For the tests, two Neste Renewable Diesel batches were treated with a minimum dosing rate of lubricity additives to be at a borderline acceptance, i.e. as near the <460 µm HFRR limit as possible. After 1,000 hours tests, all inside parts of the pumps were in good condition, and the overall rating of the both pumps was pass. Distributor pumps are no longer used in new engines, but since they were known to be sensitive to fuel lubricity, pass in the pump test gives additional confidence over HFRR on lubricity of Neste Renewable Diesel treated with lubricity additive. Standardized pump tests with more modern designs like Common Rail systems are not yet available. However, some in-house Common Rail tests are already ongoing in order to guarantee operability of both EN 590(B0) diesel fuels, as well as Neste Renewable Diesel. No issues have been reported when using Neste Renewable Diesel fulfilling HFRR according to EN 15940 specification.

Fuel injection system suppliers have indicated that for a paraffinic diesel fuel some extra lubricity evaluation methods are needed to secure lubricity to a sufficient level, even though there has been successful usage of paraffinic diesel fuels without lubricity issues for well over 12 years in captive fleets (EN 15940 Annex A). Fuel injection system suppliers are suggesting the SLBOCLE method with a minimum limit of 3500 g. There have been studies concerning lubricity of paraffinic fuels with both methods: HFRR and SLBOCLE. The main conclusion of the publications [Lehto et al. 2014; Kuronen et al. 2015] has been that the SLBOCLE method is so inaccurate that it cannot be taken on as a part of a specification. CEN has decided to study this phenomenon, and this work is ongoing.

Production and logistics

Neste Renewable Diesel

- to be used for
  - meeting biomandate without 7% blending wall set today for FAME by EN 590
  - upgrading gasoils to meet retail diesel fuel requirements producing premium diesel fuels
  - dedicated vehicles like city bus fleets for reducing locally harmful tailpipe emissions and greenhouse gases
  - can replace ASTM D975 diesel as such
- fully fungible with current logistical systems: stability, water, and microbiological issues similar to fossil diesel fuel
- reporting of bioenergy content shall be based on bookkeeping of mass balance
- after blending biocontent can be determined only by ^{14}C isotope method if audit trail is contested
- if blended with FAME, special attention is needed in order to avoid precipitation of FAME -originated impurities, especially in cold conditions

Ways to use Neste Renewable Diesel

There are five principal ways to use renewable diesel fuel:

- By adding a few percent into diesel fuel in order to meet bioenergy mandates. For this purpose renewable diesel can be used in addition to the max 7% FAME in EN 590, or as such without a blending wall. Renewable diesel can be used alone to fulfill biomandate all year round without the challenges related to cold operability, engine oil dilution or storage stability.
- By adding tens of percents into diesel fuel in order to upgrade the final fuel to meet EN 590 or ASTM D975. When renewable diesel is blended, the original fossil fuel or fuel component does not need to meet standard requirements since renewable diesel has a remarkable beneficial blending value for diluting aromatics, reducing density, and increasing the cetane number. Renewable diesel can also be added without any detrimental effects on the final boiling area. Since target needs to be that only the final blend meets, e.g., FQD and EN 590 specification or ASTM D975, the fossil part can be out of specification and renewable diesel fixes it. So renewable diesel as a blending component offers new economic benefits for refineries and fuel blenders.
- By adding tens of percents into diesel fuel in order to prepare a premium diesel fuel. Renewable diesel increases cetane number and decreases aromatic content resulting in reduced exhaust emissions and better overall performance. Cold properties can be enhanced with renewable diesel due to its superior cold properties. These blends meet diesel fuel standards like EN 590 and ASTM D975 without any technical blending wall for the biofuel part. For retail marketing, fuel can be produced to meet, e.g., the highest Worldwide Fuel Charter (WWFC) requirements which are the toughest ones set by the automotive industry for premium fuels [Hartikka et al, 2013].
- Renewable diesel can be used in order to reach a high biocontent level within EN 590 or ASTM D975 and without separate engine validation. A fleet operator may decide to use, e.g., 30% biocontent. For these applications, fuel containing 30% renewable diesel can be produced while simultaneously meeting FQD and EN 590. If the same biocontent is made by FAME, engines have to be validated and accepted separately for EN 16709 B30 fuel.
- Renewable diesel can be used as neat, for example, in city buses, delivery vans and trucks, taxis and non-road machinery, in order to improve local air quality. This will reduce the emissions of all the vehicles concerned, including old high-emitters. Also, the exhaust aftertreatment device will function better when engine-out particulate and NOx emissions are lower and the ash content of the fuel is negligible. This is also a convenient way to use 100% biofuel in cases where it is required by local policy makers or company profiles. ASTM D975 diesel can be directly replaced by renewable diesel. Extra benefits of the Neste Renewable Diesel can be achieved by optimizing calibration of engine's fuel injection system.

- Using renewable diesel as such in fleets and non-road machinery operating in areas where local air quality is of a special interest and correspondingly less biofuel or even fully fossil fuel on road traffic has double benefits: less harmful tailpipe emissions in critical areas, excellent storage stability, and meeting bioenergy or GHG-reduction mandate in a country or a quota area. Renewable diesel's capability for reducing harmful tailpipe emissions is mainly lost if it is mixed using small blending ratio into all diesel fuel only for meeting bio- or GHG-mandates.

Blending properties with diesel fuel

Neste Renewable Diesel in blend

- preserves high quality properties of diesel fuel, and even improves some properties
- effects depend on blending ratio
- minimum limit of diesel density defines maximum amount to be used in EN 590 fuel
- can be blended in all ratios with ASTM D975

Neste Renewable Diesel can be blended into diesel fuels as "drop in fuel" without "blending wall" set by vehicle technology or limitations by fuel logistics. Fuel Quality Directive 2009/30/EC i.e. "FQD" (recital 33) states that the limit is not required for diesel-like hydrocarbon biofuels and hydrotreated vegetable oil. In practice, the maximum amount of Neste Renewable Diesel to be blended is limited by the lower density limit in EN 590, which often limits blending to approximately 35% Neste Renewable Diesel. Even more could be added if the density of the base diesel fuel is over the 845 kg/m³ limit defined by FQD, since only the value of the final blend needs to be taken into account in order to meet EN 590 and legislative requirements. In the American ASTM D975, there is no limit for density – so there are no limits for adding Neste Renewable Diesel from that point of view.

Due to its lack of aromatics, reasonable distillation range, low density and high cetane number, Neste Renewable Diesel is a superior blending component. It is fully fungible with current logistics systems and practices since its tendency to pick up and dissolve water is even lower than that of fossil diesel fuels. Storage stability of Neste Renewable Diesel is good without any need for a "use before" date. Neste Renewable Diesel is a valuable component for oil refineries since it enhances practically all the properties of base diesel fuel (Table 4).

Table 4. Example of blending properties. The referred base fuel is free of biocomponents and represents very good fossil quality due to its very low polyaromatics.

		Required by regulation (FQD) and markets	Base fuel sample (B0)	Neste Renewable Diesel	30% Neste Renewable Diesel + 70% base fuel	Effect of Neste Renewable Diesel in blending
Density	kg/m³	820* … 845	837	780	820	Benefit
Cetane number		≥ 51.0	55	88	65	Benefit
Polyarom.	%	≤ 8.0	1.1	< 0.1	≈ 1	Benefit
Sulfur	mg/kg	≤ 10.0	3.6	≈ 1	≈ 3	Benefit
Ox. stability	g/m³	≤ 25	≤ 25	≤ 25	≤ 25	No effect
Viscosity	mm²/s	2.0 … 4.5	3.6	3.0	3.4	No effect
Water	mg/kg	≤ 200	20	20	20	No effect
Ash	%	≤ 0.01	0.001	0.001	0.001	No effect
Metals	mg/kg	-	~ 0	~ 0	~ 0	No effect
Dist. 95%	°C	≤ 360	360	298	355	Benefit
Cloud point	°C	As needed	-1	-11	-3	Benefit, even -34 possible

*) For winter ≥ 800 kg/m³

If the base fuel does not meet regulative requirements, for example, density being above 845 kg/m^3, cetane number below 51 or polyaromatics above 8% as set by the FQD, the effect of adding Neste Renewable Diesel is practically linear on the values to be corrected by blending.

Storage and blending of Neste Renewable Diesel with FAME

Neste Renewable Diesel

- is not a good solvent for impurities that may exist in FAME
- some care needed if FAME and renewable diesel blended together as such

Since Neste Renewable Diesel is fully paraffinic, it does not have such good solvency characteristics as fossil diesel fuels which in almost all cases contain 15...30% total aromatics; lower aromatic content diesel fuels are used, for example, in Sweden and in California. Less severe solvency may have benefits regarding material compatibility, but on the other hand, possible impurities existing in fuels may precipitate easier.

A maximum 7% of high quality FAME (total monoglycerides max 0.3 wt-%) can be mixed with Neste Renewable Diesel as defined by EN 15940. Precipitation risk of FAME's impurities increases if more or low quality FAME is used. CONCAWE has given a recommendation for EN 590 diesel SMG (saturated monoglyceride) content [Engelen et al, 2009] as well as Annex C in the FAME standard EN 14214. These recommendations can be used also when blending FAME with Neste Renewable Diesel. Swedish class 1 and renewable diesel behave similarly when blending with FAME, so the same SMG levels in the final blend can be required also for renewable diesel. The max level of SMG coming from FAME can be 20 mg/l in final blend.

Aromatic content of diesel fuel has an effect on the precipitation risk of FAME's impurities. The better the diesel fuel is (lower aromatics), the higher is the risk for precipitation; thus quality of FAME becomes even more important for avoiding problems in fuel filters.

It is not recommended to store more than 7% blend of FAME in renewable diesel. There is a risk for precipitation of impurities if FAME is mixed with low aromatic or aromatic-free fuel. Precipitation may take place even at temperatures higher than cloud point of the blend. Due to limited tank capacity, the same tank might be used for FAME and renewable diesel. If the same tank is used either for FAME or renewable diesel, the normal procedure with quality change should be performed. For example, the level of FAME should be as low as possible in the storage tank before changing to renewable diesel. Blending temperatures should be well above the cloud points of both fuels. Then when changing back to FAME, the renewable diesel level in the storage tank should be as low level as possible. There is also a remarkable difference in densities between FAME and Neste Renewable Diesel which need to be taken into account when blending.

Blending of GTL and Neste Renewable Diesel

In some urban areas, the use of neat GTL diesel fuel has been considered in order to reduce locally harmful tailpipe emissions and dependence on crude oil. If the addition of a biocomponent is also required, Renewable Diesel fits perfectly to be blended into GTL.

Logistics

Neste Renewable Diesel and blends
- behave like traditional fossil diesel fuel
- no additional issues related to storage stability, water separation and microbiological growth
- no additional material compatibility issues
- small cross-contamination does not risk aviation jet fuel quality

Neste Renewable Diesel can be handled similarly to fossil diesel fuel. It can be mixed with diesel in any ratio, and there is no risk of precipitation or phase separation. Well-known practices used for fossil diesel fuels apply also for blends containing renewable diesel, and for renewable diesel as such. Because of these similarities, the same equipment can also be used for leak detection as for fossil diesel [Gordji, 2014].

Water solubility and storage stability properties of renewable diesel are so similar to fossil diesel fuels that no extra precautions are needed in pipelines, tank farms, tanker trucks or service stations. In addition, no need for extra precautions regarding microbiological growth or storage stability has been observed.

Water separation is fast from renewable diesel; usually it contains less than 100 mg/kg water, typically below 50 mg/kg. For a real-life long-term storage test, neat renewable diesel was left for 8 months in the refueling storage tank of a bus operator after a large field test of several years was completed. The fuel was clear and free from microbiological growth after the additional storage time [Nylund et al. 2011]. However, general good storage tank maintenance and housekeeping is recommended. Storage tanks should be kept free of water, and tanks should have provisions for water draining on a scheduled basis. There are two reasons for this: water promotes corrosion and microbiological growth can occur at the fuel-water interface.

The flash point of HVO is regulated to above +55 °C (131 °F) in paraffinic diesel standard EN 15940 meaning that it can be stored and transported like standard diesel fuel. The electrical conductivity of HVO is low and comparable to sulfur-free diesel fuels. Antistatic additive is used in Neste Renewable Diesel in order to allow high pumping velocities in pipelines and loading racks. Neste Renewable Diesel can be transported in multiproduct pipeline systems as it is essentially similar to diesel fuel.

As a neat 100% component, Neste Renewable Diesel is shipped with the proper shipping name: ”Alkanes (C_{10} — C_{26}), linear and branched” under MARPOL Annex II, Category Y and Ship Type 3. This means that cargo shall be carried on chemical tankers with prewash requirements.

Neste Renewable Diesel (HVO) is included in the IMO Biofuel category. When containing 75% or more of petroleum oil, the biofuel blend is subject to Annex I of Marpol.

A biofuel blend containing more than 1% but less than 75% of petroleum oil is carried under Marpol Annex II, Pollution Category X and Ship Type 2. The proper shipping name is: “Biofuel blends of Diesel/gas oil and Alkanes (C_{10}-C_{26}), linear and branched with a flashpoint > 60 °C (> 25 % but < 99 % by volume)”. For more details see MEPC.1/Circ.761/Rev.1.

Custom codes

In general, Directive 98/70/EC article 2 with its amendments (i.e. ”FQD”) defines that diesel fuel and gas oil (non-road diesel fuel) fall within CN codes 2710… Further CN nomenclature defines that 2710… “contains 70 wt-% or more petroleum oils” which can be interpreted so that the maximum amount of biocomponents is limited to max. 30 wt-%. However, CN nomenclature chapter 27 note 2 defines “2710 petroleum oils include not only petroleum oils… but also similar… as well as consisting of unsaturated hydrocarbons… provided that non-aromatic constituents exceeds aromatic constituents”. Based on this, HVO belongs to the 2710… CN group of diesel fuels, although HVO’s origin is renewable.

There are Binding Tariff Information for HVO shown in the table. In practice codes for the sulfur ≤ 0.001 wt-% (≤ 10 mg/kg) grades are used for the current diesel fuels.

Table 5. CN codes.

Gas oils, containing non-fossil origin	CN-code	Taric-code (import)
HVO with sulfur ≤ 0.001 wt-%		
- pure (more than 20 %)*	2710 19 43	2710 19 43 29
- blends (20 % or less)**	2710 19 43	2710 19 43 30

*) Paraffinic gasoil obtained from synthesis and/or hydro-treatment, of non-fossil origin, in pure form; blends containing more than 20 wt-% of paraffinic gasoil obtained from synthesis and/or hydro-treatment, of non fossil origin.

**) Blends containing 20 wt-% or less of paraffinic gasoil obtained from synthesis and/or hydro-treatment, of non-fossil origin.

Compatibility with materials

Neste Renewable Diesel may be considered as having the same compatibility regarding parts and materials as conventional diesel, for example, with seals, hoses, diaphragms, dry couplers, and base swivel joints. Construction materials may include carbon and stainless steel which are suitable for conventionaldiesel fuel. The use of both welded and riveted tanks is acceptable. Tanks may have internal floating roofs made of aluminum. Nitrogen blanketing can be used.

Neste Renewable Diesel is compatible with nitriles (NBR), fluoroelastomer (FKM), PTFE, vinyl ester resins, and epoxy resins. In principle, the lack of aromatic compounds may shrink elastomers that have already been swollen when used with aromatic or FAME containing fuels, but no fuel leakages have been observed during several large field tests with renewable diesel. Generally speaking, large changes of the liquid composition are able to cause changes in elastomer's volume i.e. swelling or shrinking especially regarding very old seals. Especially if the NBR seals have been in contact with high FAME blend, and after there is no contact with FAME diesel, leaking is probable. Mechanical seals of pumps can be considered to be compatible with Neste Renewable Diesel if they are compatible with fossil diesel fuel.

Measurement of Neste Renewable Diesel content in diesel fuel

Neste Renewable Diesel

- reporting of bioenergy content shall be based on bookkeeping of mass balance
- cannot be detected by mature routine analytical methods used for FAME
- can be detected by ^{14}C isotope methods but they are quite laborious

Neste Renewable Diesel consists of paraffinic hydrocarbons that exist naturally also in fossil diesel fuels. Therefore, the amount of renewable diesel in a blend cannot be analyzed afterwards with similar mature analytical methods as FAME content of diesel fuel or ethanol in gasoline. Due to this analytical challenge, renewable diesel content of a blend shall be based on the seller's declaration and bookkeeping of the blending procedures. If analyses of both the pure blending components are known, for example, the density of the blend indicates how much renewable diesel has been added.

If required, Neste Renewable Diesel content in a diesel blend can be determined by ^{14}C isotope methods. CO_2 in the atmosphere contains unstable ^{14}C and stable ^{12}C carbon isotopes in a fixed ratio. The same ratio can be found in living plants and animals. When these organisms stop their growth ^{14}C begins to decline gradually. The half-life of ^{14}C is 5730 years and as a consequence, fossil carbon does not contain ^{14}C isotope. Therefore, it is possible to estimate the time when the plant stopped growing naturally or was harvested, and thus a clear distinction can be made between fossil and renewable carbon. Principles can be found from the standard ASTM D6866. ^{14}C dating methods have been used, for example, for archeological studies.

The bio content of a fuel can be determined by two methods based on ^{14}C dating: Liquid Scintillation Counting (LSC) and Accelerated Mass Spectrometry (AMS). These methods are available in some commercial laboratories in case of a dispute. But due to the time needed for analysis and the limited availability of services, the use of these methods is not practical for everyday use. Some Custom's laboratories use ^{14}C dating methods. Preliminary results show that more than 2% renewable diesel in a fuel blend can be determined by AMS, and more than 5% by LSC. If, for example, 10% of renewable has been blended, analyzes are able to confirm that there is about 8…12% renewable diesel. AMS seems to be more accurate, but it is more laborious because the fuel sample has to be combusted before analyzing. A liquid fuel sample is suitable for LSC. Both LSC and AMS are also able to confirm that paraffins are bio-based (renewable diesel or BTL), and not fossil (GTL or CTL).

There is a DIN standard (DIN 51637) published for measuring ^{14}C content in diesel fuels and middle distillates by using liquid scintillation. This method is successfully being used at Neste.

These methods introduced above measure all renewable carbon. If a sample contains both FAME and renewable diesel, the amount of FAME needs to be measured with traditional methods and subtracted from the total biocontent in order to find out renewable diesel content. Some further calculations may be needed in order to change the ^{14}C results to vol-%, wt-% or bioenergy-% depending on what is needed in each case.

Since ^{14}C methods do not belong to everyday laboratory practices at oil companies or for the authorities, they should only be used in cases where the audit trail approach is contested. This approach is already mentioned in the EN 228:2012 standard in order to make a difference between fossil and renewable ethanol in gasoline. The European Custom Administration has noticed this challenge, and Round Robin tests with the methods are already proceeding.

Environmental properties

Renewable energy and greenhouse gas savings

EU

The European directive promoting the use of renewable energy ("RED", directive 2009/28/EC) requires that at least 10% by energy used in the transport sector has to be from renewable sources by 2020. In addition, the directive regulating fuel quality and overall greenhouse gas emissions ("FQD", directive 2009/30/EC) demands a 6% reduction of fuels' greenhouse gases by 2020. Individual member states may have even more challenging requirements. Energy contents to be used in reporting for authorities are defined by RED Annex III (Table 6).

Table 6. Energy contents (heating values, lower calorific values) of diesel fuel and some neat biofuels defined by RED.

	By weight (MJ/kg)	Compared to diesel fuel by MJ/kg	Compared to FAME by MJ/kg	By volume (MJ/l)	Compared to diesel fuel by MJ/l	Compared to FAME by MJ/l
Diesel fuel	43			36		
HVO	44	+2.2%	+19%	34	-5.6%	+3%
BTL	44	+2.2%	+19%	34	-5.6%	+3%
FAME	37	-14%		33	-8.3%	
Ethanol	27	-37%	-27%	21	-42%	-36%

These figures, where also ethanol is presented for comparison, show that renewable diesel (HVO) is the best existing biofuel in terms of energy content. This means that less renewable diesel is needed for meeting a given legislated biomandate compared to FAME, and significantly less compared to ethanol.

Both RED Annex V and FQD Annex IV define default greenhouse gas emission savings if case by case calculated actual values are not available. Figures listed in the table 7 show that renewable diesel's (HVO) performance is better than that of FAME; provided that both products are made in typical processes from the same feedstock.

Table 7. Greenhouse gas savings defined by RED and FQD.

	Typical savings	Default savings
FAME from rape seed oil	45%	38%
HVO from rape seed oil	51%	47%
FAME from sunflower	58%	51%
HVO from sunflower	65%	62%
FAME from palm oil, process not specified	36%	19%
HVO from palm oil, process not specified	40%	26%
FAME from palm oil, methane capture at oil mill	62%	56%
HVO from palm oil, methane capture at oil mill	68%	65%

The greenhouse gas calculation methodology established in both directives, RED and FQD, does not consider the differences in useful work. This means that the differences in engine efficiency between the various biofuels are not reflected in the final results. Total environmental benefit could be assessed with a well-to-wheels approach taking into account the total efficiency of the engine and fuel type combination. In this case, the comparisons would be made in terms of grams CO_2eq/passenger-km or grams CO_2eq/ton-km for trucks rather than grams CO_2eq/MJ fuel used, as currently is done in the directives.

Diesel engines are clearly more efficient than spark ignited engines which means clearly lower fuel consumption for diesel. Although well-to-tank greenhouse gas values of, for example, sugar cane ethanol are low per MJ of ethanol's calorific value, even a current HVO can be better on a well-to-wheels basis because of the diesel engine's better efficiency (Figure 7).

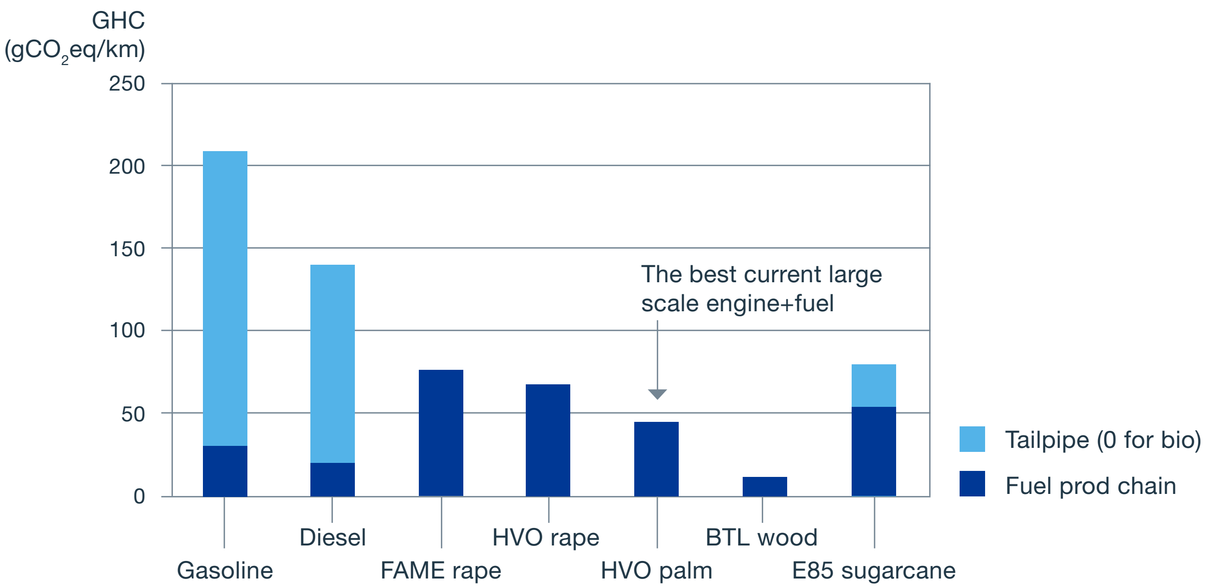


Figure 7. Well-to-wheels greenhouse gas emissions of a typical mid size class car. Well-to-tank part (fuel production chain) is based on RED and FQD values.

North America

Unites States

RFS (Renewable Fuel Standard) program in the United States requires obligated parties to use a certain volume of renewable fuel. The obligated parties are refiners or importers of gasoline and/or diesel fuel and compliance is achieved either by blending renewable fuels into transportation fuel or by obtaining credits, named Renewable Identification Numbers (RINs) to meet an EPA-specified Renewable Volume Obligation (RVO).

Under the RFS, each fuel type is assigned a "D-code" that identifies the renewable fuel type based on the feedstock, fuel type, energy inputs, and GHG reduction thresholds.

The four renewable fuel categories and their corresponding D-codes under the RFS are:

- Cellulosic biofuel, D3 or D7 for cellulosic diesel
- Biomass-based diesel, D4
- Advanced biofuel, D5
- Renewable fuel, D6

Standard renewable fuel must meet 20% GHG reduction and biomass-based diesel 50% reduction against a 2005 conventional baseline. Depending on the current feedstock, Neste Renewable Diesel qualifies as renewable fuel or biomass-based diesel. Biomass-based diesel can also be used to fulfill the advanced biofuel volume obligation.

In California, there is a separate Low Carbon Fuel Standard (LCFS) regulation in addition to the RFS. The LCFS standard is designed to reduce greenhouse gas emissions associated with all transportation fuels used in California.

Under the LCFS, each fuel is assigned a CI score based on the life cycle greenhouse gas balance. Fuel providers are required to ensure that the overall CI score for its entire fuel pool meets the annual carbon intensity target. Depending on the feedstock, CI scores for Neste Renewable Diesel are roughly between 16 and 50 gCO_2eq/MJ. This corresponds to a GHG savings of 50-80% against the diesel baseline CI in 2015.

Canada

Canada has had a federal mandate requiring 5% of the national gasoline pool to be renewable since December 15, 2010. The federal mandate was extended on July 1, 2011 to include a 2% blending requirement for renewable or biodiesel.

In Canada, the provincial policies are also significant as they have often been the forerunners of what has eventually been developed at the federal level. The western provinces, in addition to Ontario, have the following blending mandates for both gasoline and diesel.

Province	Gasoline Blend Mandate	Diesel Blend Mandate
British Columbia	5%	4%
Alberta	5%	2%
Saskatchewan	8.5%	2%
Manitoba	5%	2%
Ontario	5%	2–4%

The provinces of British Columbia and Alberta have sustainability requirements attached to their blend mandates. In British Columbia, there is also a separate low carbon fuel requirement that calls for a 10% reduction in the carbon intensity of transportation fuels by 2020 – this is comparable to the LCFS in CA.

In Ontario, the final blending requirement for diesel depends on the average GHG intensity of the diesel pool. In 2015, fuel suppliers were required to blend an average of 2% of renewable or biodiesel on an annual basis, with a GHG emissions 30% smaller than conventional diesel. For the calendar year 2016, fuel suppliers will be required to blend an average of 3% of renewable or biodiesel on an annual basis, with a GHG emissions of 50% smaller than conventional diesel. Beginning in 2017, fuel suppliers will be required to blend an average of 4% of renewable or biodiesel on an annual basis, with a GHG performance of 70% better than conventional diesel.

Renewable diesel offers an alternative to fulfill the different blend mandates. GHG emissions depend on feedstock and provincial sustainability requirements.

Case: Greenhouse gas balance of renewable diesel

When reporting to authorities, fuel suppliers are allowed to use default greenhouse gas savings as listed in the directives (Table 7) or individually calculated actual values. Greenhouse gas savings of commercially produced HVO, e.g., Neste Renewable Diesel, have been estimated for several feedstocks. Calculations with actual values show that compared to conventional diesel, Neste Renewable Diesel reduces greenhouse gas emissions by 40–90%. Further details can be found here:

https://www.neste.com/en/corporate-info/sustainability/cleaner-solutions/products-carbon-footprint

Tailpipe emissions

HVO

- reduces NO_x and particulate emissions of combustion remarkably
  - tailpipe emissions depend also on EGR and exhaust aftertreatment strategy
- reduces CO, HC, PAH, aldehyde and mutagenic emissions
- reduces particulate emissions of all size classes including nanoparticulates
- reduces cold start smoke and emissions in winter conditions
- effects seen already at 10 ... 30% blending ratios
- ash-free combustion offers a long life-time for particulate filters

Comprehensive exhaust emission tests have been performed with over 36 trucks and buses or their engines, and several passenger cars in vehicle and engine test beds. These tests consist of transient tests simulating real driving conditions and artificial driving cycles. Both of them include also acceleration phases. A summary of the results is shown in Figure 8, which highlights significant reduction of particulate mass, carbon monoxide (CO) and hydrocarbon (HC). It is also important to note that nitrogen oxides (NO_x) decrease or remain unchanged while the use of FAME typically increases NO_x emissions.

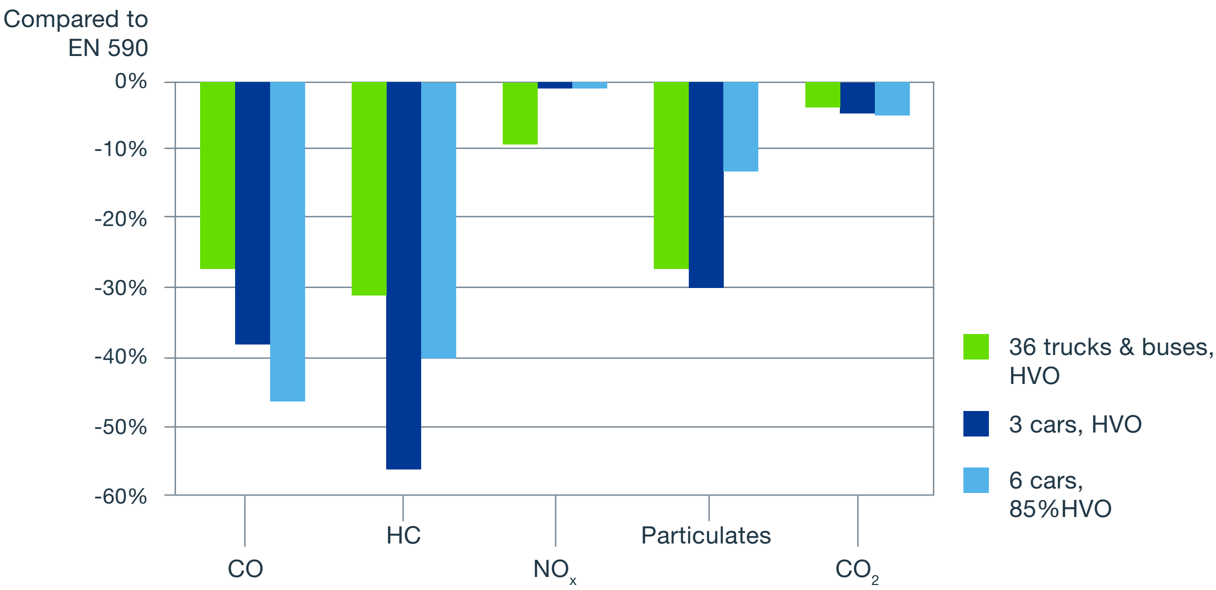


Figure 8. Average effect of neat and almost neat (85%) Neste Renewable Diesel (HVO) on tailpipe emissions in EURO II to EURO VI vehicles compared to a sulfur-free EN 590 diesel fuel.

CO_2 of all these vehicle and engine measurements is based on the measured tailpipe values without distinguishing the origin of the carbon, be it renewable or fossil. So, this CO_2 corresponds only to the tank-to-wheels part of a life cycle assessment without assuming renewable CO_2 to be absorbed back by growing plants. The reduced CO_2 from the tailpipe is caused by the higher hydrogen to carbon ratio of Neste Renewable Diesel compared to common fossil diesel fuel. Many studies have also shown slightly better (~ +1%) engine efficiency with Neste Renewable Diesel, but due to the measurement accuracy these results are only indicative.

Several unregulated exhaust emissions have been measured showing that the use of Neste Renewable Diesel reduces:

- polyaromatic hydrocarbons (PAH)
- aldehydes
- mutagenicity
- particulate number ($PM_{2.5}$, PM_{10})

Many stakeholders have been worried about nanoparticles. Test results have shown that Neste Renewable Diesel reduces number of particulates in all size classes (Figure 9).

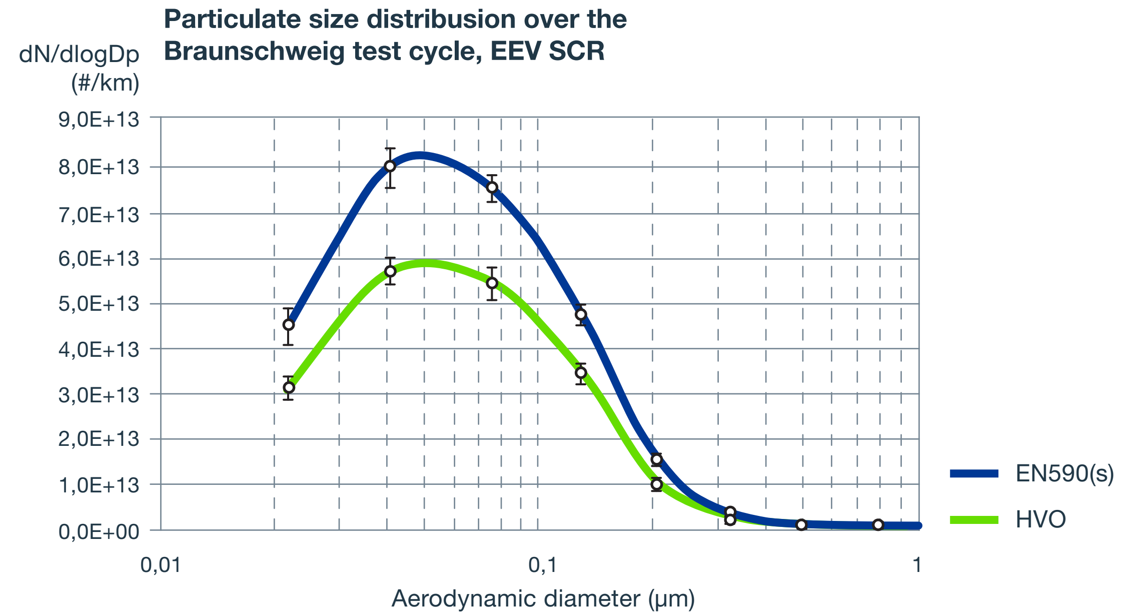


Figure 9. Example of particulate size distribution with summer-grade EN 590 fossil diesel fuel and neat Neste Renewable Diesel (HVO) in a Euro V/EEV city bus [Nylund et al. 2011].

However, the differences between individual engines have been so great that some truck or bus types have preferred a reduction of particulate mass of up to 47% together with a negligible or even slightly increasing effect on NO_x. On the other hand, in some engines NO_x is reduced more, up to 14%, and particulate emissions less. In any case, Neste Renewable Diesel moves the well-known NO_x particulate emission trade-off-curve of the base engine towards the origin, which is a desired effect for every engine designer. The total effect of Neste Renewable Diesel depends then on the engine's fuel injection and EGR control strategy (Figure 10).

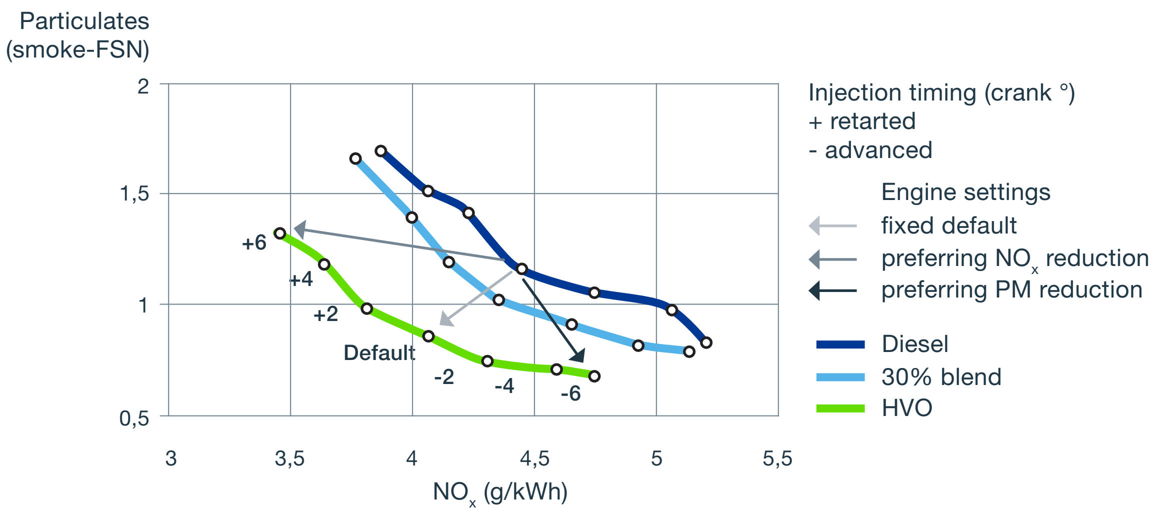


Figure 10. NO_x particulate emission trade-off curves of diesel fuel, diesel fuel with 30% Neste Renewable Diesel (HVO) and neat Neste Renewable Diesel (HVO). A modern direct injection heavy-duty engine, common rail fuel injection with different fuel injection advance settings [Aatola et al. 2008].

When Neste Renewable Diesel is used as a blending component, particulate and NO_x emissions are reduced quite linearly according to the blending ratio. Typically, already quite a small blending percentages of Neste Renewable Diesel reduce regulated emissions, especially HC and CO (Figure 11). However, HC, and CO emissions of diesel vehicles are low in grams per kilometer in any case. The key benefit resulting from the use of Neste Renewable Diesel is that the fuel significantly reduces NO_x and particulate emissions which are the Achilles heels of diesel vehicles, and also to the unregulated emissions mentioned above.

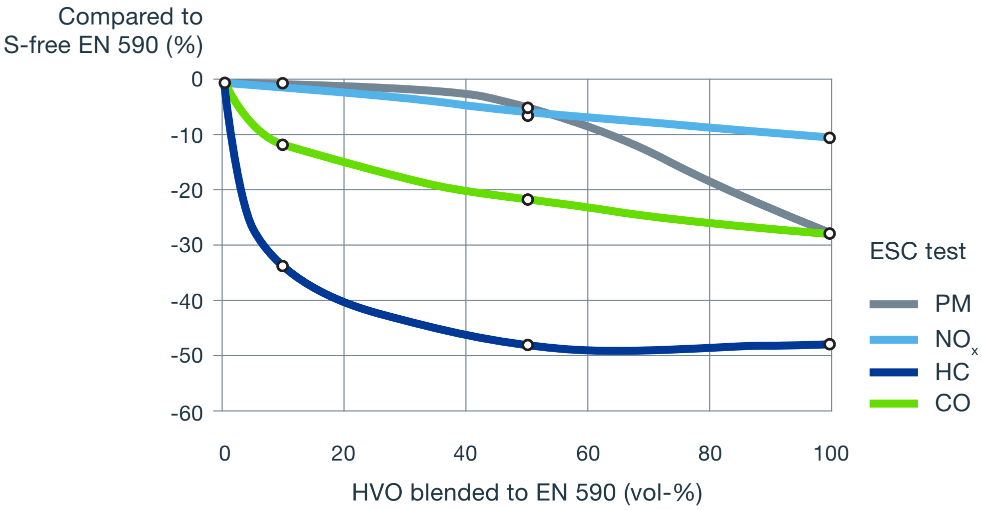


Figure 11. Effect of Neste Renewable Diesel (HVO) blending ratio on emissions of a Euro 4 truck engine with EGR but without any aftertreatment [Kuronen et al. 2007].

When Neste Renewable Diesel was blended with standard diesel fuel to produce a premium EN 590 diesel fuel, Neste Renewable Diesel representing some tens of percents of the blend offered the following benefits regarding exhaust emissions of passenger cars:

- particulate mass 0 …-10%
- nitrogen oxides (NO_x) 0 …-10%
- hydrocarbons (HC) -10 …-30%
- carbon monoxide (CO) -20…-40%
- less polyaromatic hydrocarbons (PAH)
- less aldehydes, benzene and 1,3-butadiene
- less mutagenic activity
- faster and easier cold start, less cold start smoke
- less engine noise after a cold start

An example of a passenger car with common rail fuel injection, EGR, and oxidation catalyst but without a particulate filter is presented in Figure 12. It shows a case with high NO_x reduction and no influence on particulate emissions.

In cold conditions (-7 °C, -20 °C), the effect of neat Neste Renewable Diesel and 30% blends on reducing CO, HC, and particulate emissions of cars was remarkable, up to -70...-90%. As a matter of fact, emissions of HVO at -20 °C (-4 °F) were about the same as those of standard diesel fuel at +23 °C (73.4 °F) [Nylund et al. 2011]. Reductions of this magnitude can have an immediate effect on ambient air quality in downtown areas during cold seasons.

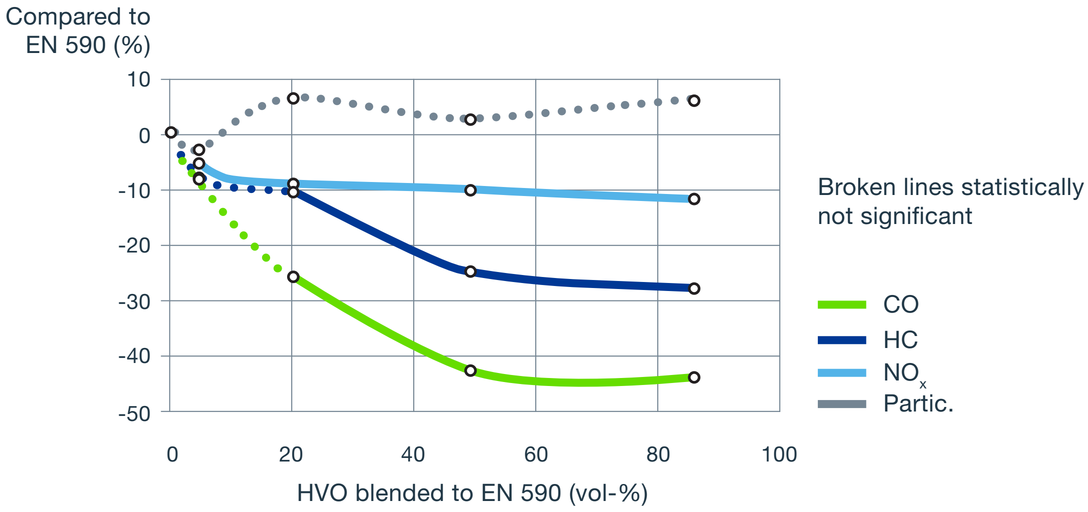


Figure 12. Effect of Neste Renewable Diesel (HVO) blending ratio on emissions of a car in which reduction of NO_x was clear but particulate emissions were practically unchanged.

Spread in emissions of passenger cars seems to depend highly on the type of fuel injection system, engine calibration and exhaust aftertreatment system. The strategy for controlling exhaust gas recirculation (EGR) is assumed to have a remarkable effect on NO_x emissions. In the tests, these factors were not taken into account since tests were made using factory engine mappings. As a result, the biggest benefits of paraffinic fuels used as such or in high concentrations can be achieved if cars can be designed in the future to detect fuel quality or combustion and then optimize engine parameters on-line. This could be a “Diesel-Flex-Fuel-Vehicle” (Diesel-FFV) -approach mirroring the development that has already taken place for spark ignition FFV-cars which adjust engines automatically to ethanol content from 0 to 85%.

Reduced exhaust emissions lead to better local air quality. This is important in many downtown areas where air quality is still a significant challenge, even though standard fuels and vehicle technologies have developed over the last few decades. Some special working environments, such as mines or construction sites of tunnels, may be challenging with regards to tailpipe emissions; Neste Renewable Diesel offers remarkable benefits over standard diesel fuels or non-road fuels within these environments.

Practically all new diesel cars and heavy duty vehicles today are equipped with a particulate filter (DPF, diesel particulate filter) which reduces emissions effectively. The lower engine-out particulate emissions resulting from Neste Renewable Diesel use offer benefits also to the users of these vehicles since exhaust back-pressure is lower and there is no need to clean the filter as often when using the so-called regeneration phase [Kopperoinen et al, 2008]. This can lead to slightly lower fuel consumption with Neste Renewable Diesel compared to other fuels if the control system of the particulate filter could be able to detect actual soot build up according to the fuel quality used. The life-time of filters is long because Neste Renewable Diesel is practically free of ash-forming components.

Excellence of Neste Renewable Diesel is based on it being practically free of aromatics, polyaromatics, olefins, sulfur, and high boiling fractions. Also its cetane number is very high. In addition to Neste Renewable Diesel, also the EN 590 fuel which was used as a reference in the tests described above scores high with regards to environmental quality. In many areas of the world, standard diesel fuel may contain more sulfur and aromatics, and so compared to those lower-quality fuels, the benefits resulting from Neste Renewable Diesel use are even more remarkable.

Most of the reports listed in “Public reports and articles” deal with detailed exhaust emission test results.

Other health and environmental properties

Neste Renewable Diesel
- accepted by REACH regulation
- well-known practices for handling and safety precautions of diesel fuels apply

Neste Renewable Diesel's health and environmental properties have been subject to a thorough testing program in order to comply with the EU REACH regulation. Neste Renewable Diesel as such is biodegradable according to OECD test guideline 301 B. Under the EU's and globally harmonized hazard classification system, Neste Renewable Diesel as such is not classified as hazardous for any other endpoint than aspiration hazard. Aspiration hazard is a characteristic for all low viscosity hydrocarbons, both fossil and renewable. Neste Renewable Diesel as such is practically insoluble in water.

The odor of Neste Renewable Diesel is very weak and of a paraffinic nature without the typical odor of diesel fuel. When handling 100% HVO, such as Neste Renewable Diesel as such, the precautions for personal safety described in the Safety Data Sheet of the product must be followed. The Safety Data Sheet is available upon request.

When Neste Renewable Diesel is blended into diesel fuel, well-known practices used for diesel fuel apply.

Fuel properties

Neste Renewable Diesel

- reasonable distillation range without high boiling fractions
- hydrocarbon, very high cetane number, free of aromatics
- no ash forming components reducing life-time of exhaust aftertreatment systems
- highest heating value of existing biofuels
- no engine oil dilution issues
- no chemical incompatibilities with engine oil
- good oxidation stability
- low tendency to form deposits in fuel injection system and fuel injectors
- the same torque and maximum power that with fossil diesel fuel in modern engines
- if used as such, higher volumetric fuel consumption than with fossil diesel fuel due to low density, but lower than with FAME
- no cold operability issues with severe winter grades
- possibility to design more fuel-efficient low-emission diesel engines ("diesel-FFV-vehicles")
- supported by automotive industry association ACEA
- supported by Worldwide Fuel Charter published by automotive and engine manufacturers

Some decades ago, diesel engines were used mainly in robust commercial applications like trucks and buses. Today, diesel engines are common also in passenger cars where requirements of customers for convenience are high. More stringent emission legislation has led to sophisticated engine, fuel injection system, and exhaust aftertreatment designs in both on-road and non-road applications.

Fuel properties and quality are integral parts of a proper operation and durability of engines and exhaust systems. From this point of view, adding biocomponents shall lead to an enhanced fuel quality rather than deteriorated properties.

Hydrocarbon type fuels

Fuel quality

- most fossil fuels have been of high quality
- adding of biocomponents shall not cause quality drawbacks
- new emission control systems require even higher quality fuels
- Neste Renewable Diesel is a high quality hydrocarbon enhancing quality of a fuel blend

Vehicle owners are used to high-quality ultra-low sulfur or sulfur-free hydrocarbon-type diesel fuels which are practically free of ash, heavy hydrocarbon fractions, and unstable components. For engines and emission control systems this has enabled longer lifetimes, less maintenance, and extended oil-change intervals compared to the situation a decade or more ago.

In addition to the requirements set by legislation and fuel standards for operability at +20 °C (68 °F) in a test chamber, "fit for purpose" has risen as an essential requirement for fuels. Thus the addition of biofuels should not cause fuel quality problems from the point of view of cold operability, engine cleanliness or durability of emission control systems. Fuel requirements are in fact becoming more stringent due to the extending mileage durability requirements for emission control systems and more stringent requirements for exhaust emissions, fuel economy and on-board diagnostics (Table 8).

Table 8. Fuel effects on operation, reliability, and need for maintenance of vehicles.

	Sulfur free fossil diesel fuel	Neste Renewable Diesel in a blend or as neat	Importance for vehicle technology and vehicle owner
Distillation range	Reasonable	Better than in fossil fuels due to lower FBP	Lower engine oil dilution Lower risk for degraded lubrication Long engine oil drain periods
Cetane number	Reasonable	Excellent	Rapid cold start Lower exhaust emissions Less noise
Chemical composition	Hydrocarbon	Hydrocarbon	Low engine oil aging Low engine oil thickening Low material compatibility issues
Carbon/hydrogen -ratio	Traditional	Better than in fossil fuels	Enhanced combustion Lower engine out CO_2 Lower well-to-wheels CO_2
Oxidation stability	Good	Good	Low deposit formation in fuel system Low fuel injector fouling No acid formation in fuel
Ash, S, P, metals	Practically zero	Practically zero	High exhaust catalyst performance Long lifetime for particulate filter
Cold properties	As needed 0 … -40 °C	As needed 0 … -40 °C	Fit for purpose even in arctic winters
Solubility of water	Low	Very low	Low risk for water pick up from logistics
Corrosion protection	Good with performance additive package	Good with performance additive package	Low risk for troubles if some water condensates and precipitates in fuel tanks

Fuel consumption

Volumetric fuel consumption

- vehicle results practically in line with measured calorific heating values (MJ/l)
- Neste Renewable Diesel's heating value higher than that of FAME
  - smaller amount of Neste Renewable Diesel than FAME needed for meeting a fixed bioenergy mandate
  - fuel consumption slightly lower with Neste Renewable Diesel blends compared to FAME-blends at the same bioenergy level
- with neat Neste Renewable Diesel, fuel consumption about 3% higher than with summer grade fuel
- with neat Neste Renewable Diesel, fuel consumption about 5% lower than with neat FAME

The fuel property having the largest effect on volumetric fuel consumption is the heating value which is normally expressed in MJ/liter. The fuel's heating value can be measured more accurately than what fuel consumption measurements made in test bed engines, vehicles in dynamometer or vehicles in real traffic can ever be.

Traditionally, fuel density has been the factor having the greatest effect on volumetric fuel consumption since the heating value per mass (MJ/kg) is practically the same for diesel fuels within a reasonable range of aromatic contents. So, for a fuel with a lower density, the heating value per volume is lower. This means that more fuel volume is needed in order to provide the same energy output. Neste Renewable Diesel's density is clearly lower than that of standard diesel fuels due to the paraffinic nature and reasonable distillation range.

Neste Renewable Diesel does not behave in exactly the same way as traditional fuels. Neste Renewable Diesel's heating value per mass (MJ/kg) is higher because of its paraffinic nature, which can be explained also by hydrogen content which is 15.2 wt-% for Neste Renewable Diesel compared to about 13.5 wt-% of standard diesel fuel. So, the higher heating value per mass of HVO partly compensates for the effect of lower density on heating value per volume (Table 9).

Neste Renewable Diesel's heating value is clearly higher than that of FAME per mass since it does not contain oxygen like FAME. The high density of FAME partly compensates the difference, but even after compensation Neste Renewable Diesel's heating value per volume is better.

Table 9. Typical densities and lower calorimetric heating values

	Unit	Diesel fuel (typical summer grade without biocomponent)	Neste Renewable Diesel	FAME
Density	kg/m^3	835	780	880
Heating value	MJ/kg	43.1	44.1	37.2
Heating value	MJ/l	36.0	34.4	32.7
• difference to diesel fuel	%		-5	-9
Heating value, 7 vol-% blend	MJ/l		35.9	35.8
Heating value, 10 vol-% blend	MJ/l		35.8	35.7
Heating value, 30 vol.% blend	MJ/l		35.5	35.0

Slightly less Neste Renewable Diesel compared to FAME is needed in a diesel fuel for meeting the same bioenergy mandate because energy content of Neste Renewable Diesel is higher than that of FAME (Table 10). Compared to ethanol, the benefit is large since the heating value of ethanol is only 21 MJ/l.

Because of the differences in heating values, fuel consumption of a diesel fuel containing Neste Renewable Diesel instead of FAME at 6% bioenergy level should be about 0.4% lower. However, no vehicle driver is able to identify this size of difference, but in any case heating value shows the trend that Neste Renewable Diesel is better. In this comparison, analytically measured heating values have been used instead of the rounded ones used by FQD for reporting bioenergy for authorities since engines run according to precise actual heating values.

Table 10. Energy contents of neat fuels and blends containing 6.0% bioenergy as an example (6% energy is the biomandate in Finland from 2011 to 2014).

	Bioenergy (%)	Heating value (MJ/l)
Fossil diesel fuel, summer grade	0	36.0
100% HVO	100	34.4
100% FAME	100	32.7
Diesel incl. 6.3 vol-% HVO	6.0	35.9
Diesel incl. 6.6 vol-% FAME	6.0	35.8

Heavy duty vehicle tests showed an average increase of about 3% in volumetric fuel consumption with neat Neste Renewable Diesel compared to ultra-low sulfur diesel fuel [Karavalakis et al. 2015]. Earlier studies have shown also different results. Fuel consumption results depend on test cycles, on test vehicles and on the reference fuel. One of these earlier studies discovered a slight tendency (0.5%) towards a lower energy consumption in MJ/km and better engine efficiency with neat HVO [Nylund et al. 2011].

Passenger car tests with neat Neste Renewable Diesel also show an average increase of about 3% in volumetric fuel consumption compared to fossil summer grade diesel fuel. Fuel consumption difference depends on the drive cycle used, on the test vehicle, and on the reference fuel.

However, the reference fuel used both in car and heavy duty tests was without any biocomponents ("B0"), meaning that these results show the maximum possible difference in fuel consumption. Today, a relevant reference in most of the cases would be B7, theoretically reducing the effect of HVO even further. If fuel consumption of neat FAME and neat Neste Renewable Diesel are compared, volumetric consumption of FAME would be about 5% higher based on the differences in heating values.

Engine power and torque

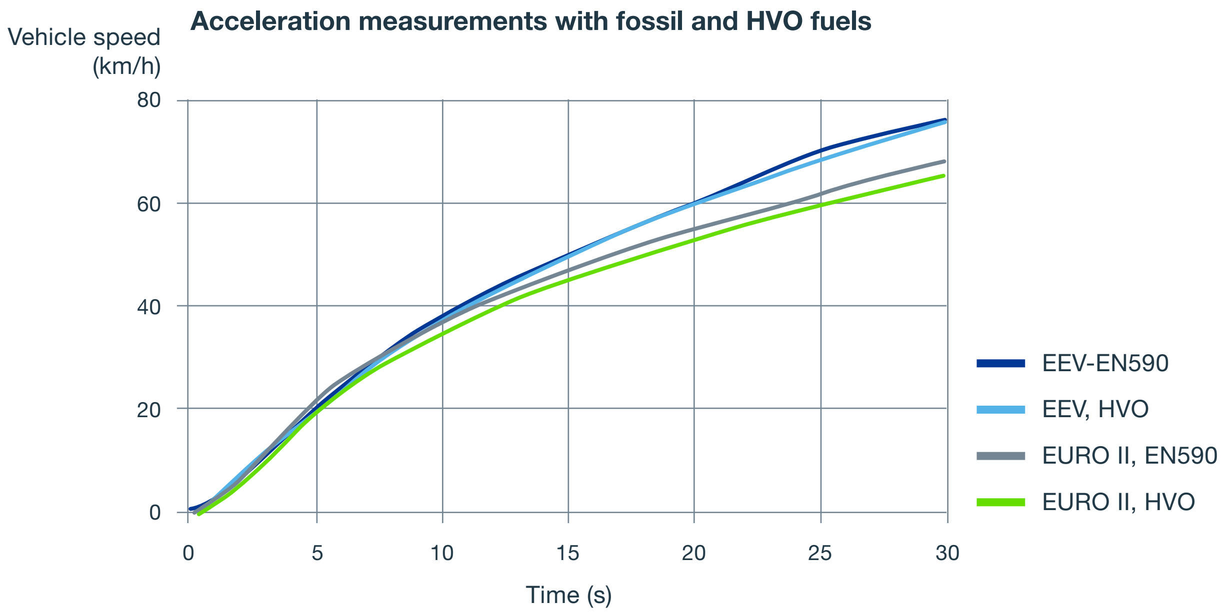
Neste Renewable Diesel

- similar maximum power and acceleration time with fossil diesel in modern vehicles (common rail fuel injection)
- slightly lower performance with older engines due to lower volumetric heating value of neat Neste Renewable Diesel

In modern engines, the amount of fuel injected into the combustion chamber is controlled by the energizing time of the fuel injector and fuel pressure. The engine control unit calculates the right signal length and timing for the requested engine load and speed conditions. Thus the maximum power output of the engine is related to the efficiency of the engine, injector energizing time, fuel pressure, and energy content of the fuel. In some modern common rail injection systems, it has been seen that with the same indicated injection duration, more paraffinic fuel is actually injected. With this type of injection system, Neste Renewable Diesel produces the same engine power and torque as EN 590 diesel. The maximum power of the engine can be even higher, if compared to winter grade diesel [Sugiyama et al. 2011].

In older injection systems (in-line pump, distributor pump, pump-line-nozzle, pump injector), the volume of fuel injected is almost equal with Neste Renewable Diesel and EN 590 diesel. Thus the maximum power is reduced some 3...5% with neat Neste Renewable Diesel because of the lower volumetric energy content compared to EN 590 diesel. The slightly better engine efficiency with Neste Renewable Diesel cannot compensate the lower volumetric energy content.

Passenger car tests have shown no measurable differences in power output with neat Neste Renewable Diesel compared to summer grade diesel fuel. Since differences in vehicle performance are negligible between neat Neste Renewable Diesel and diesel fuel in modern vehicles, Neste Renewable Diesel does not have any noticeable effects when it is used as a blending component.



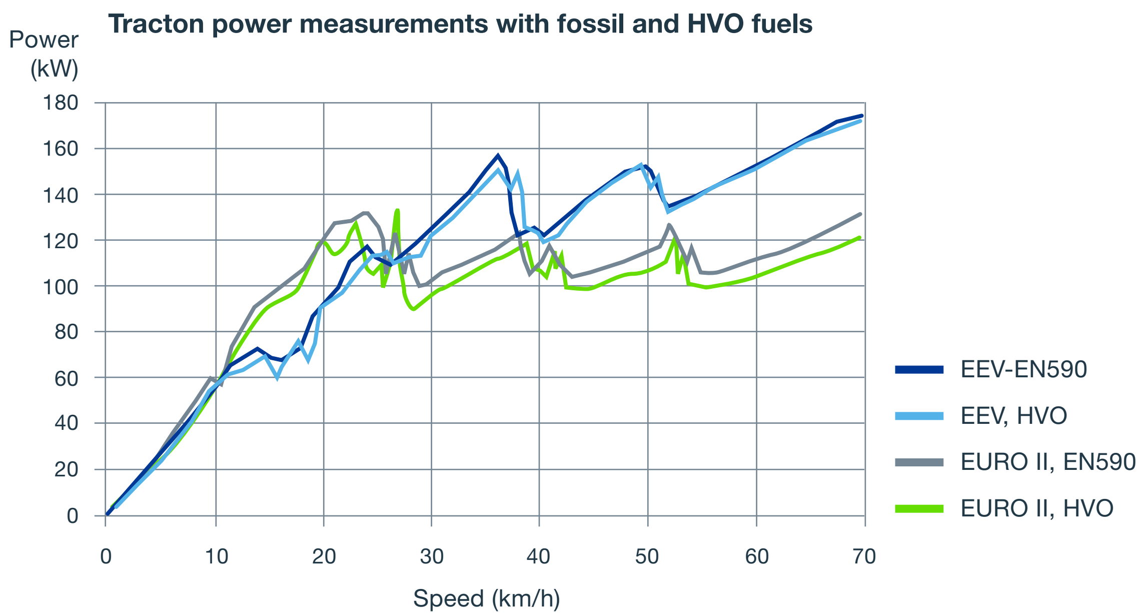


Figure 13. Acceleration performance and traction power of Euro II and EEV city buses in a dynamometer. Euro II bus was equipped with an in-line injection pump representing old technology, and EEV bus with a modern common rail fuel injection system [Nylund et al. 2011].

Engine oil dilution and deterioration

Neste Renewable Diesel

- similar or better engine oil condition due to reasonable distillation range and hydrocarbon type chemistry

Distillation curve shows how much of a fuel sample is evaporated at each temperature when temperature is increased gradually. In this case, gas chromatographic distillation (GC) was used in order to see heavy boiling fractions clearly which may not be the case with the common atmospheric distillation (Figure 14). Distillation characteristics have an effect on how fuel is evaporated when it is sprayed into the combustion chamber. Fractions boiling at too high temperatures may not burn completely or they may wet cylinder walls. Neste Renewable Diesel is well inside that range of diesel fuels but FAME boils at remarkably higher temperatures.

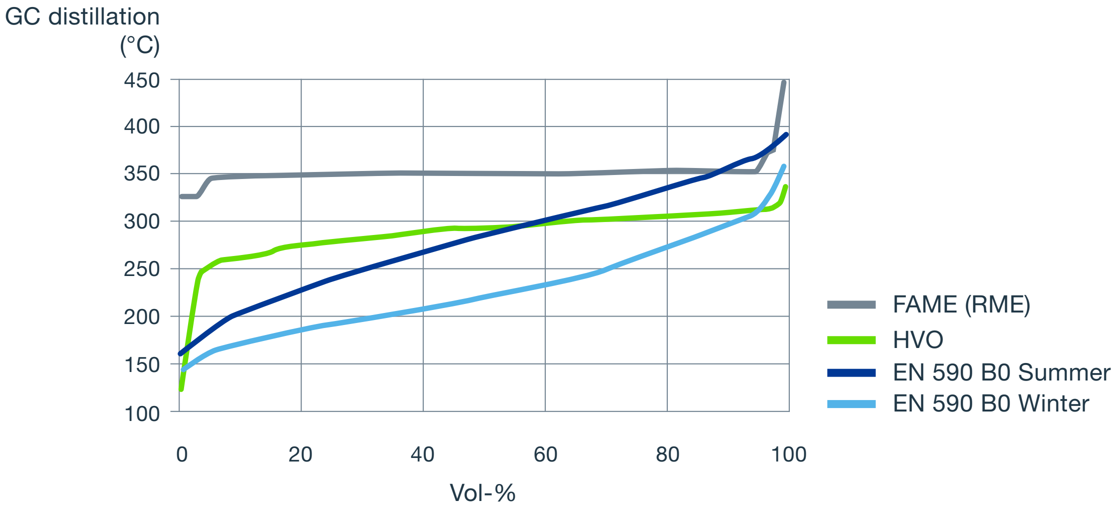


Figure 14. GC distillations of typical diesel fuels without biocomponents (meeting EN 590), neat FAME and neat Neste Renewable Diesel (HVO). Note that the temperature scale of GC distillation is different from atmospheric distillation which is commonly used for diesel fuels.

A new challenge has arisen with modern vehicles with particulate filters (DPF). They need to be periodically cleaned, “regenerated”, by increasing exhaust temperature to above +500 °C so that the soot collected is combusted. This kind of temperature cannot usually be achieved during normal driving. In most cars today, temperature increase is assisted by injecting an additional amount of fuel into the cylinders after actual combustion strokes. However, the highest boiling fuel fractions may not evaporate compeletely, therefore they may wet cylinder walls and then enter into the engine oil through piston rings. As a result engine oil will be diluted reducing viscosity of the oil, which is a well-known challenge related to FAME use as a blending component since the use of FAME increases final boiling area. This can be seen from distillation characteristics of both summer and winter grade fuels (Figures 15 and 16). Neste Renewable Diesel does not cause additional engine oil dilution due to its distillation range.

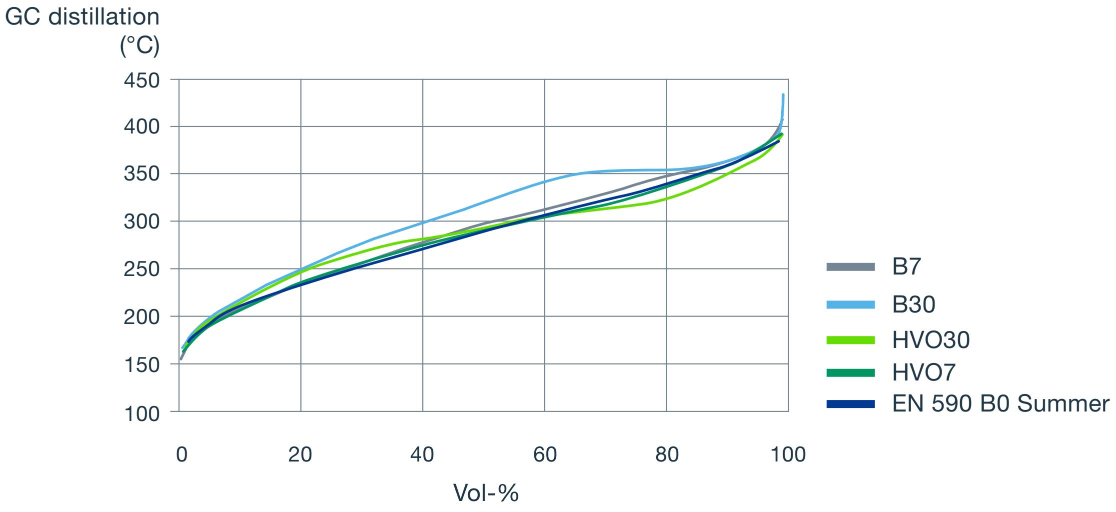


Figure 15. GC distillations of summer grade fuel and its blends with biocomponents (numbers show vol-% of bio added). Note that the temperature scale of GC distillation is different from atmospheric distillation which is commonly used for diesel fuels.

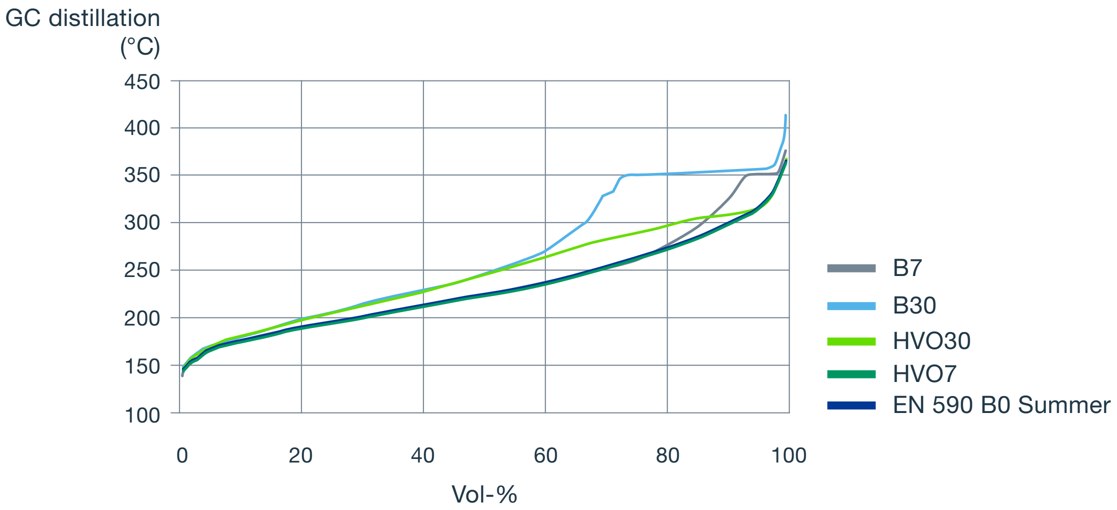


Figure 16. GC distillations of winter grade fuel and its blends with biocomponents (numbers show vol-% of bio added). Note that the temperature scale of GC distillation is different from atmospheric distillation which is commonly used for diesel fuels. (B30 may not be suitable fuel also because of cold operability).

When some FAME enters into crankcase oil, the ester type composition may also cause harmful chemical reactions in the oil during the long engine oil drain periods used today. Since Neste Renewable Diesel consists of hydrocarbons, it does not cause chemical incompatibility with the engine oil if some Neste Renewable Diesel enters into the crankcase. Therefore, Neste Renewable Diesel does not risk engine oil condition or engine durability, and there is no need for any additional measures like changing engine oil more often than traditional high quality fossil diesel fuels.

Engine oil dilution has been tested in an engine test which simulates DPF regenerations. However, diesel fuel without any biocomponent was not tested since bio-free grade was not relevant as a reference fuel in Germany where the tests were performed (Figure 17). Engine oil dilution with 30% HVO was clearly lower than with 5% FAME in the fuel.

Engine oil dilution has been tested in an engine test which simulates DPF regenerations. However, diesel fuel without any biocomponent was not tested since bio-free grade was not relevant as a reference fuel in Germany where the tests were performed (Figure). Engine oil dilution with 30 % HVO was clearly lower than with 5 % FAME in the fuel.

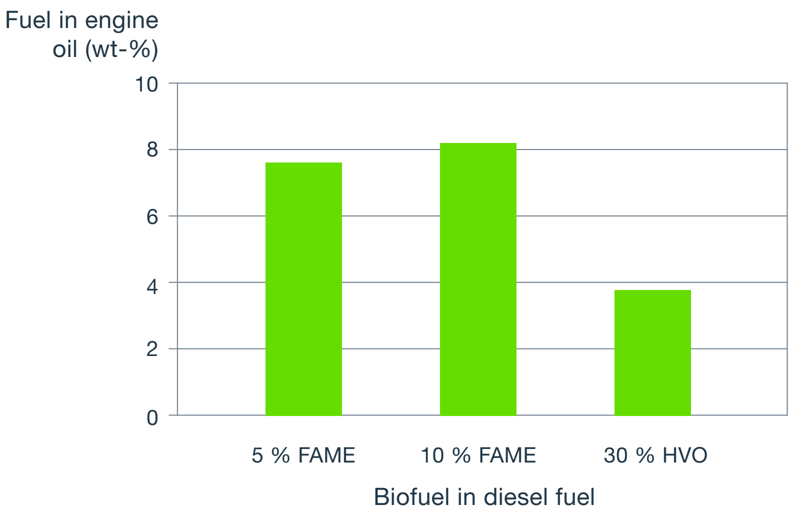


Figure 17. Engine oil dilution during a 55.5 h test with a car engine simulating DPF regeneration [Baumgarten et al. 2008].

Injector fouling

Neste Renewable Diesel

- low tendency for injector fouling as neat and in diesel fuel blends
- the same detergent additives suitable as for standard diesel fuels

Deposit formation in fuel injectors of engines is a phenomenon that shall be limited in order to keep engine power output and exhaust emissions constant over the entire lifetime of a vehicle. Injector fouling has been tested with a Peugeot DW10 Common rail direct injection engine and Peugeot XUD9 indirect injection engine.

The DW10 test is based on the CEC F-98-08 test method, which represents Euro 5 standard fuel injection equipment with a maximum injection pressure of 1600 bar. The method measures injector fouling directly from engine power, and lower power loss means cleaner injectors. Without Zn addition, Neste Renewable Diesel showed clean injectors. Neste Renewable Diesel combined with an effective detergent showed clean injectors also with Zn dosing. Neste Renewable Diesel blend (20%) behaved like EN 590 B0 (DF-79-07 reference fuel) (Figure 18).

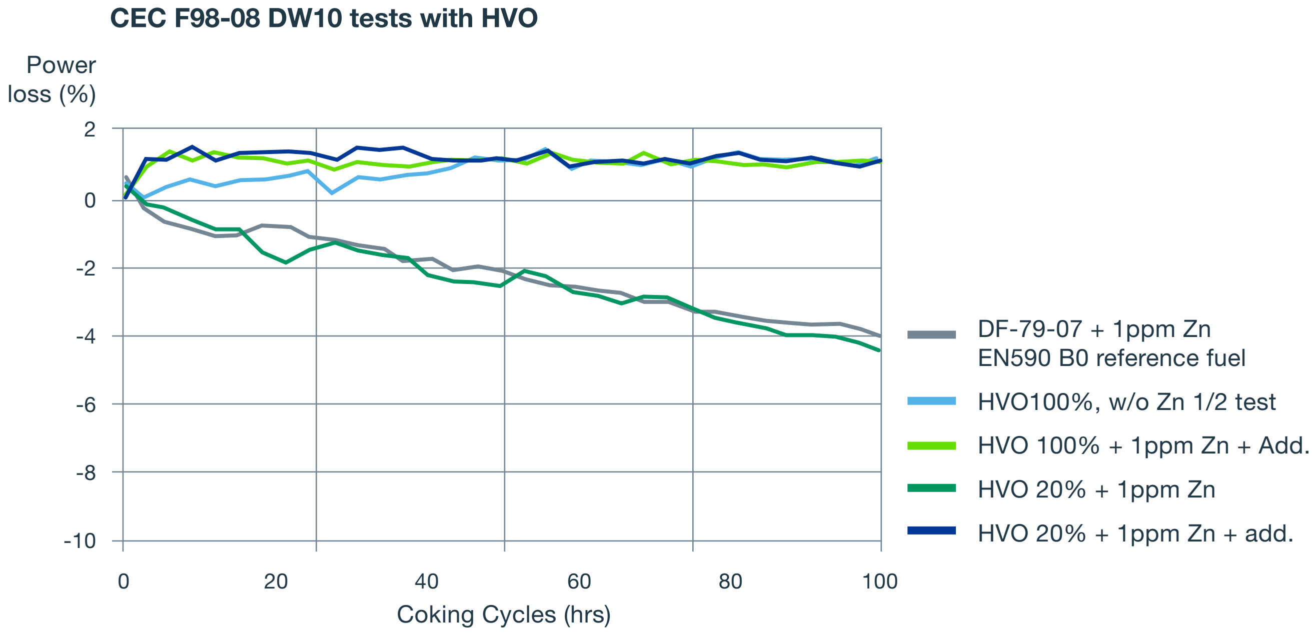


Figure 18. Injector fouling tests with DW10 engine [Neste Engine Laboratory tests].

The XUD9 test is based on a widely used old CEC F-23 test method which has been modified according to some engine updates. Because of that, the numerical scale of the results is not binding, but in any case a lower value means cleaner injectors. Neste Renewable Diesel showed cleaner injectors than a high quality standard diesel fuel both as such and as a 30% blend (Figure 19).

Performance additive packages containing, for example, detergent, corrosion inhibitor, and antifoam agents are used commonly in high quality diesel fuels. Although Neste Renewable Diesel performs well in injector fouling tests (XUD9), an additive package shall be considered at least for corrosion protection for cases where some water condensates in fuel logistics or vehicle fuel systems.

Sodium (Na) contamination in diesel fuel has been suspected to cause harmful internal deposits in fuel injectors. Neste Renewable Diesel should not have such negative effects since sodium content has been in all measurements below detection limit of analytical methods.

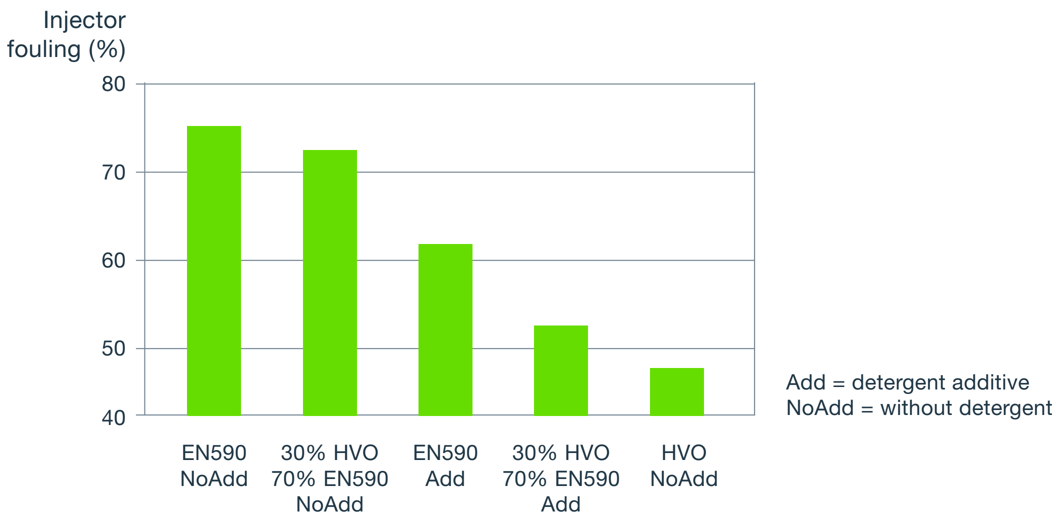


Figure 19. Injector fouling test results with XUD engine. Lower values are better. [Neste Engine Laboratory tests].

Auxiliary heaters

Neste Renewable Diesel operates in fuel burning auxiliary heaters as well as or even better than fossil diesel. As opposed to FAME, Neste Renewable Diesel does not have any problems with cold properties; therefore, it operates without trouble also in cold conditions.

A test with Webasto auxiliary heaters was conducted in 2013 in Finland. Deposit build-up in the combustion chamber was assessed. A test cycle consisting of a 10 minute heating period and 50 minute cooling period was used. The cycle was run consecutively for 21 hours after which the heater was pulled apart and the combustion chamber examined. The difference between commercial fossil EN 590 diesel and 100% Neste Renewable Diesel was clear (Figure 20). Even after this relatively short test, the combustion chamber of the fossil diesel heater had some deposits clearly visible while the Neste Renewable Diesel heater was practically clean.

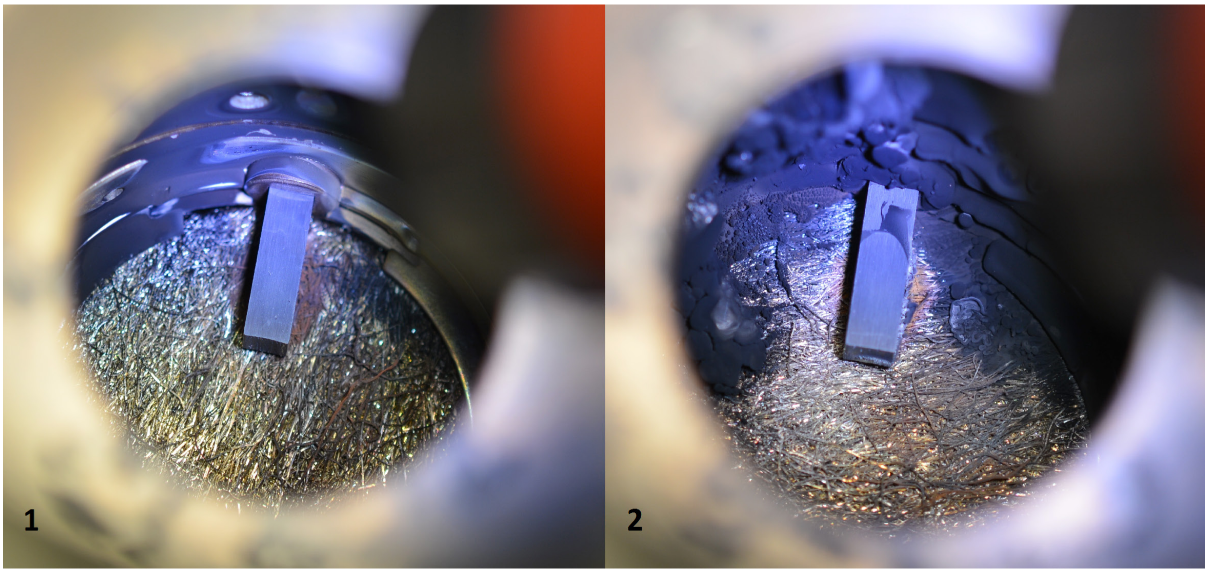


Figure 20. Combustion chambers of Webasto auxiliary heaters after the 21 hour test. A heater using 100% Neste Renewable Diesel on the left (1) and a heater using fossil EN 590 diesel on the right (2).

Statements made by automotive and engine manufacturer industry

Automotive and fuel injection system companies

- prefer advanced paraffinic type biocomponents
- HVO supported by Worldwide Fuel Charter (WWFC) in order to avoid concerns associated with FAME

The Worldwide Fuel Charter (WWFC), published by engine and automotive manufacturer associations, was updated in 2013. The new fifth edition (September 2013) does not allow the use of FAME at all in the best fuel category 5. FAME was not allowed in category 4 of the previous fourth edition (September 2006), either. HVO is fully allowed without any blending limit in all fuel categories if the final fuel blend meets the limits of each category.

The fifth edition of WWFC can be downloaded from

http://www.acea.be/uploads/publications/Worldwide_Fuel_Charter_5ed_2013.pdf

where part ”Technical Background” defines comprehensively challenges and limitations related to the use of FAME and supports the use of HVO as a way to increase renewable content of diesel fuel:

- page 53 ... 54 for FAME
- page 55 ... 56 for HVO

The European Automobile Manufacturers Association ACEA reported in April 2010:

> *”Political support and appropriate policy tools are needed now to encourage the development and wider market access to new and more sustainable ‘drop-in’ advanced biofuels that could increase the biocontent in road transport fuels, e.g. HVO, BTL, cellulosic (or advanced) ethanol.“*

Bosch, Continental, Delphi, Denso and Stanadyne, all of them manufacturing diesel fuel injection systems, told in September 2009:

> *“The FIE manufacturers support the use of bioparaffins obtained by hydro-treatment or co-processing of plant oil. Due to their paraffinic nature and high fuel and transport system compatibility, bioparaffins are also well-suited for blends with biogenic portions above 7%.”*

For European heavy-duty vehicles, the latest Euro 6 emission standards were introduced by Regulation (EC) 595/2009, with technical details specified in Regulation (EC) 582/2011. The new emission limits became effective from 2013 on for new type approvals, and from 2014 onwards for new registrations. The Euro 6 emission limits are comparable in stringency to the US 2010 standards. Regulation (EC) 582/2011 introduced also requirements on universal fuel range type-approval. If the manufacturer permits to operate the engine on a fuel not fulfilling the EN 590 CEN standard, the manufacturer needs to demonstrate the capability of the parent engine to meet the Euro VI emission and in-service conformity requirements on the fuel declared. Until March 2016 there has been the following approvals from manufacturers to use paraffinic diesel in their Euro 6 engines:

Volvo Press release June 22nd, 2015:

> *”Volvo Buses’ 5-litre and 8-litre Euro 6 engines are certified to the paraffinic fuels CEN TS 15940 standard, which in addition to HVO also covers tall oil diesel and gas-to-liquid (GTL) fuels”. Volvo also stated that: ”Volvo Buses also approves HVO as a fuel for all buses with Euro 5 engines, with no reduction in service interval”.*

Scania press release on October 8th, October 2015:

> *”Scania has given the green light to hydrotreated vegetable oil (HVO) being used to power its Euro 6 range, provided the fuel used meets technical specification TS15940. Vehicles using HVO – which chemically mimics fossil-fuel-based diesel – can under optimal conditions achieve up to a 90-percent reduction in CO_2 emissions. HVO does not affect a vehicle’s characteristics or its maintenance requirements”.*

Daimler press release on February 22nd, 2016:

> *”Trucks from Mercedes-Benz fitted with engines from the OM 470, OM 471, OM 936 and OM 934 series meeting the Euro VI emissions standard may be operated with HVO from February 2016. This decision applies to all engine variants whatever their output category.”*
>
> *”Mercedes-Benz Trucks has established the acceptability of the alternative fuel for use in its engines by means of comprehensive testing. Since the characteristics of HVO mean that it is absolutely comparable to conventionally produced petroleum-based diesel fuel, no modifications to the engines or their peripherals are necessary. The injection process, fuel lines and seals remain unchanged. The same is also true of the intervals for oil changes and for cleaning the particulate filter, while there is also no restriction in terms of warranty and goodwill policy. Engine performance and torque data also remain the same when HVO is used. The approval applies to all fuels that comply with the prEN 15940 standard”.*

For U.S. markets renewable hydrocarbon diesel, such as Neste Renewable Diesel, fulfills ASTM D975 2-D Grade, the purpose of which is to use this kind of diesel in engine applications requiring a fuel with 15 ppm sulfur (maximum).

Optimizing engines for HVO

Neste Renewable Diesel

- moves NO_x particulate emission trade-off-curve towards origin
- moves NO_x fuel consumption trade-off-curve towards origin
- for engine designers more freedom to choose between low NO_x, low particulates and/ or good fuel economy
- up to 6...8% savings in mass fuel consumption: remarkable benefit also for CO_2
- already 30% blend shows benefits
- optimum solution: combine development of fuel, engine and exhaust after-treatment

Diesel engines today have been designed for fuel fulfilling the EN 590 diesel standard in Europe or relevant standards on other continents. There has not been a major need for diesel engines that can adapt to fuel composition like gasoline-FFV vehicles. Now that high quality paraffinic diesel fuels fulfilling EN 15940 such as HVO and GTL are available, users would benefit from optimized engine calibrations based on fuel quality.

Diesel engines run without operability problems with neat Neste Renewable Diesel, but more benefits are obtained if engines are optimized for Neste Renewable Diesel or high amounts of Neste Renewable Diesel in the fuel. This is caused by the fact that Neste Renewable Diesel gives more freedom under NO_x particulate emission and NO_x fuel consumption trade-off phenomena which are well known challenges for engine designers. The control of EGR is also essential for reducing NO_x, as well as optimizing urea feed for SRC catalysts according to the real need. There are also studies made with other paraffinic fuels (GTL) which show the development potential for optimizing the engine, fuel and exhaust aftertreatment together. By this approach “Diesel-FFV” vehicles could be designed as well as FFV-cars today, adapting themselves automatically for gasoline, 85% ethanol, or any mixture of these fuels. Another possibility could be to change engine mapping if vehicles are used by dedicated fleets which use only neat Neste Renewable Diesel as an alternative fuel.

Studies were conducted by changing engine software settings in a heavy duty engine (Table 11, Figure 21). With the default engine settings results were in line with other tests made on heavy duty engines. With advanced fuel injection timing fuel consumption can be reduced remarkably, up to 6 ...8% by mass, if NO_x reduction is carried out in an aftertreatment device. The reduced fuel consumption means smaller well-to-wheels CO_2 emissions which are important also for renewable fuels.

With retarded timing, NO_x can be reduced remarkably, but in this case fuel consumption will be increased. Preliminary studies show that even greater benefits can be obtained if the amount of EGR is optimized for Neste Renewable Diesel (HVO).

Table 11. Effect of Neste Renewable Diesel (HVO) on emissions and fuel consumption using different injection timing settings in a heavy duty engine without EGR and aftertreatment. Reference is EN 590 diesel fuel. [Aatola et al. 2008].

Injection timing >	Default	Advanced	Remarkably advanced	Retarded
NO_x	-6%	0%	+4%	-16%
Smoke	-35%	-37%	-32%	-32%
Fuel cons (mass)	-3%	-6%	-8%	0%
Fuel cons (volume)	+5%	+2%	0%	+8%

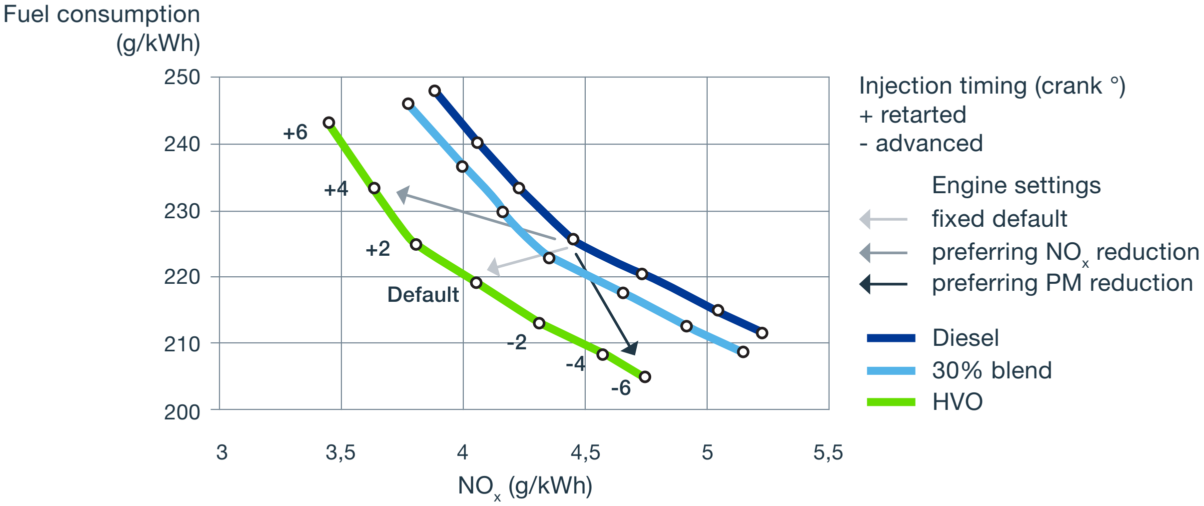


Figure 21. NO_x fuel consumption trade-off curves of diesel fuel, diesel fuel with 30% Neste Renewable Diesel (HVO) and neat Neste Renewable Diesel (HVO). A modern direct injection heavy-duty engine, common rail fuel injection with different fuel injection advance settings [Aatola et al. 2008].

Field trials

Neste Renewable Diesel

- extensive trials in many countries
- fleets up to 300 vehicles
- mileages even over 300,000 km/vehicle
- all year round including severe winters

Extensive field trials have been carried out with Neste Renewable Diesel in Finland, Sweden, Germany, and Canada. The fuel has performed excellently in these trials, both at 100% content and a variety of blending ratios. The trial uses of the fuel have not resulted in any operability issues or need for extra maintenance regarding fuel filters, fuel systems, fuel hoses, seals in fuel systems, engines or exhaust aftertreatment devices. The same applies to fuel logistics: the trial uses did not reveal any differences compared to fossil diesel fuel use regarding water, microbiological growth, storage stability and material issues.

About 300 buses were driving in the Helsinki area from 2007 to 2010 with Neste Renewable Diesel all year round down to ambient temperatures below -25 °C (-13 °F). Most of the buses used a fuel blend containing up to 30% of Neste Renewable Diesel in EN 590 fuel, while 11 buses run with Neste Renewable Diesel as such. The goal of this project was to improve quality of the urban air and to promote advanced biofuels in public transport. Both old and modern buses from several makers representing Euro II to EEV emission levels were included in the test fleet as well as some retrofit exhaust aftertreatment systems. A total of 50 million kilometers were run with the fuel blend and 1.5 million kilometers with the neat Neste Renewable Diesel. This means on average 170,000 km/bus with some of them driving clearly more in this test. Totally 22,000,000 liters of blend fuel and 1,000,000 liters of neat Neste Renewable Diesel were consumed. There was no need for any extra maintenance compared to standard diesel fuel use. Analyses of used engine oils did not show any differences compared to running with standard diesel fuel. Neat Neste Renewable Diesel was left in a refueling storage tank for 8 months after the test was completed. The fuel was clear and free from microbiological growth after the storage time. [Nylund et al. 2011]

An all year round field trial in Germany started in 2008 with 10 Mercedes-Benz trucks and 4 Mercedes-Benz buses. They run on 100% HVO already over 3 million kilometers in total and over 200,000 km/vehicle on average. This trial was scheduled to last for three years in total and ended in 2011. Both field trial tests have included also numerous exhaust emission measurements.

A trial with 75 vehicles using 2% Neste Renewable Diesel during the winter and 5% during the summer was conducted in an arctic environment in temperatures down to -44 °C (-47.2 °F) in Alberta, Canada between 2006 and 2009. Federal and provincial governments together with Shell Canada sponsored the tests. Neste Renewable Diesel blend operated without any problems.

In Finland, a field trial with neat Neste Renewable Diesel started during the spring 2010 with more than 60 passenger cars. The fleet consisted of various vehicle brands and different engine and injection system technologies. The objective was to prove the suitability of neat Neste Renewable Diesel for severe winter conditions and various driving conditions. Some of the vehicles underwent additional check-ups regularly for more detailed investigations. During this field trial more than 200,000 liters of neat Neste's Renewable Diesel was consumed, and the cars travelled more than two million kilometers. No fuel-related issues arose during the field trial. This field trial was successfully concluded at the end of 2014.

In Germany under project Diesel regenerativ [Krahl 2011], two fleets of passenger cars run over 200,000 km with Neste Renewable Diesel blended with 2% and 7% RME in the course of a year without any fuel-related driver complaints. All vehicles were tested for regulated emissions at the beginning and end of the project period. The more extensive assessment of the non-regulated emissions was only carried out on three vehicles of emission standards Euro 3, Euro 5 and Euro 6. Engine oil samples were taken from all vehicles and analyzed over the test period. In sum, emissions reductions for hydrocarbons, carbon monoxide and particulate matter were identified in comparison to EN 590 B5 fossil diesel fuel. However, the nitrogen oxide values were slightly elevated.

In 2011, a field trial with two new 60 ton Scania 500R tanker trucks was started in Finland. The trucks have a 15.8 liter V8 Euro 5 engines using Scania PDE high pressure unit injectors. One truck was running on 100% Neste Renewable Diesel and the other on normal commercial EN 590 (B0) diesel fuel. Approximately 300,000 km were driven with both trucks until the spring of 2013. The injectors were then bench-tested and dismantled. There were no differences in performance or wear between the two vehicles. During the trial, no repairs or replacement parts were needed for the fuel system.

From 2011 to 2013, a durability field test was conducted. A model year 2011 Volvo V60 2.0 used as a driving school car (mostly city driving) was run on neat Neste Renewable Diesel fuel for 100,000 km. After the test, the engine with oxidation catalyst, particulate filter, fuel system and fuel tank were disassembled and each part analyzed to understand the long-term effects of HVO. The conclusion was that none of the analyzed parts showed any negative impact. Also, the oil dilution was analyzed in each service; it was concluded that Neste Renewable Diesel fuel does not cause high oil dilution.

Market experience

Neste Renewable Diesel market experience

- 100% renewable diesel sales is increasing globally, e.g., to private and public fleets
- up to 50% renewable diesel (HVO) blends have been sold since 2007
- all year round including severe winters
- thousands of service stations
- no modifications to fuel logistics or service stations
- no modifications to vehicles
- trouble-free logistics and operation both with blends and as such
- used as a blending component in a premium diesel fuel meeting Worldwide Fuel Charter ”WWFC” category 5

Finland

Service stations have sold EN 590 diesel fuel containing varying blending ratios of HVO in order to meet the national biomandate since 2007. The highest blending ratios have been 50%. Fuel has been used in cars, vans, trucks and buses, and in minor amounts in non-road mobile machinery. Today, there are approximately 2,700 service stations selling this blend, which means that practically all outlets in the country sell Neste Renewable Diesel blends.

Premium EN 590 diesel fuel containing at least 15% of Neste Renewable Diesel – claiming, for example, benefits of the higher cetane number – has been sold in Finland at 100 service stations since 2008 all year round with good experiences, even in severe winter conditions. The highest blending ratios were about 30%, and the fuel did not contain any FAME.

Four service stations have sold neat Neste Renewable Diesel for dedicated customers since 2010. This has been used mainly in cars. Since 2008, HVO as such has also been delivered into storage tanks of some bus fleets to be used in city buses.

During the fall of 2012, this premium grade was upgraded to meet Worldwide Fuel Charter (“WWFC”, fourth edition 2006) Category 4 diesel fuel specification, which is a target for fuels used in the most modern vehicles. The fuel is fully suitable and beneficial also for old diesel vehicles. The fuel was launched under the brand name of ”Neste Pro Diesel”. Neste Pro Diesel contains a minimum of 15% HVO (Neste Renewable Diesel). According to studies, Neste Pro Diesel lowers fuel consumption, produces less emissions, increases engine power, and fulfills the toughest cleanliness requirements [Hartikka et. al. 2013].

In the fall of 2013, the fifth edition of Worldwide Fuel Charter was published. The fifth edition introduced category 5 for highly advanced requirements for emission control and fuel efficiency. For diesel fuel, the fifth category establishes a high quality hydrocarbon only specification that takes advantage of the characteristics of certain advanced biofuels, including Hydrotreated Vegetable Oils (HVO) and Biomass-To-Liquid (BTL). Neste Pro Diesel fulfills the requirements of the toughest 5th category.

The biomandate in Finland is counted from the total sales of bioenergy in traffic fuels per calendar year. This means that an oil company is able to choose between different biocontents and biocomponents in gasoline and diesel fuel. In principle, an oil company could cover the mandate by selling only fossil gasoline and a lot of Neste Renewable Diesel in diesel fuel, or only a lot of E85 and fossil diesel.

All of the Neste Renewable Diesel blend and neat Neste Renewable Diesel deliveries have taken place all year round including also severe winters. Vehicles including the ones driving with neat Neste Renewable Diesel have been standard vehicles without any modifications. No technical modifications have been made to pipelines, storage tanks, tanker trucks and service stations. Experience shows that Neste Renewable Diesel blends have behaved similarly to fossil fuels regarding corrosion, storage stability, microbiological growth, water separation, elastomeric materials, delivery pump filters etc. issues that could appear in the logistic chain.

USA, Austria, Sweden and Other countries

Renewable Diesel has been delivered from Neste's Porvoo, Rotterdam and Singapore plants for many bulk customers in Europe and North America to be used for meeting biomandates and for blending premium diesel fuels with good experiences. Increasing volumes of renewable diesel is used as such, i.e. neat, by customers that are especially aware and keen on bioenergy or reduced tailpipe emissions.

California presents an example of the increasing use of neat Neste Renewable Diesel. The state's ambitious targets for CO^2 savings have encouraged cities like the City of San Francisco, Oakland, and Walnut Creek to switch to renewable diesel in their municipal fleets. In Oregon, the City of Corvallis is betting on biofuels as it switches a third of its fleet to renewable diesel in summer 2016. Some retail stations have also converted their fuel stations to sell renewable diesel under their own fuel brands.

Austria has been a forerunner in the use of 100% Neste Renewable Diesel. Since 2013, thousands of different vehicles, from small agricultural machinery to trailer trucks, have been running on Neste Renewable Diesel. Introducing Neste Renewable Diesel to the market has not required changes in existing fuel logistics – the same storage tanks, trucks, pumps and meters are still in use without any modifications.

Sweden is the latest market within which Neste Renewable Diesel use has been increasing rapidly. There, the fuel distributors have launched branded fuels with high Neste Renewable Diesel blends as well as started to sell 100% Neste Renewable Diesel fuels mainly to fleet markets to support the ambition of customers to move away from fossil fuels.

The experience of almost ten years has proven that Neste Renewable Diesel blends meeting the fuel standards. It is a safe high-quality fuel option for the use without requiring any changes to fuel logistics or vehicles. The only reported incidents are related to 100% Neste Renewable Diesel use in vehicles more than 10 years old; the change in fuel quality has been a trigger for fuel leaks. This is due to the fact that NBR sealing materials used in these vehicles were not designed for changes in fuel quality. NBR is compatible with Neste Renewable Diesel and compatible with aromatic diesel, but not compatible with FAME. Some NBR material that has been exposed to variable levels of aromatics in diesel and various levels of FAME over the years has survived until the FAME and aromatics are no longer present in the fuel and have created a leak.

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Acronyms

AMS	Accelerated Mass Spectrometry
ASTM	International organization for standardization (previously American Society for Testing and Materials)
BTL	Bio-to-Liquids fuel made from biomass by Fischer-Tropsch synthesis
Bx	x = maximum allowed FAME content in diesel fuel
CEC	Co-ordinating European Council (for engine etc. test methods)
CEN	European Committee for Standardization
CFPP	Cold Filter Plugging Point
CN code	Combined Nomenclature for customs and trade statistics
CO	Carbon monoxide (tailpipe emission)
CO_2	Carbon Dioxide (direct tailpipe emission or well-to-wheels emission)
CTL	Gas-to-Liquids fuel made from coal by Fischer-Tropsch synthesis
CWA	CEN Workshop Agreement (possible 1st step for preparing a standard)
DCN	Derived Cetane Number
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EN	European Standard prepared by CEN
E95	Fuel for modified diesel engines containing 95% ethanol and additives
FAME	Fatty Acid Methyl Ester (biodiesel)
FBP	Final Boiling Point (distillation curve)
FBT	Filter Blocking Tendency
FFV	Flexible Fuel Vehicle
FIE	Fuel Injection Equipment
FQD	“Fuel Quality Directive”, directive 2009/30/EC
GC	Gas Chromatographic distillation
GTL	Gas-to-Liquids fuel made from natural gas by Fischer-Tropsch synthesis
HBD	Hydro-generated Biodiesel
HC	Hydrocarbons (tailpipe emission)
HDRD	Hydrogenation Derived Renewable Diesel
HFRR	High Frequency Reciprocating Rig (device for measuring fuel lubricity)
HVO	Hydrotreated Vegetable Oil
ILUC	Indirect Land Use Change
IMO	International Maritime Organization
LCS	Liquid Scintillation Counting
LPG	Liquefied Petroleum Gas
MARPOL	International Convention for Prevention of Pollution from Ships
NBR	Nitrile Butyl Rubber
NEXBTL^{TM}	Neste’s brand and trademark for HVO process
NO_x	Nitrogen oxides (tailpipe emission)
PAH	Polycyclic Aromatic Hydrocarbons (tailpipe emission)
PM	Particulate Matter (tailpipe emission)
PME	Palm oil Methyl Ester (biodiesel)
REACH	European Community Regulation on chemicals and their safe use
RED	“Renewable Energy Directive”, directive 2009/28/EC
RME	Rapeseed Methyl Ester (biodiesel)
SLBOCLE	Scuffing Load Ball On Cylinder Lubricity Evaluator
SME	Soybean Methyl Ester (biodiesel)
SMG	Saturated Monoglycerides (impurities from FAME)
^{TM}	Trademark
TS	CEN Technical Specification (possible 2nd step for preparing a standard)
XTL	BTL, CTL and GTL fuels made by Fischer-Tropsch synthesis