High blends of renewable fuels for the heavy-duty fleet in the Netherlands

Which fuel options, engine adaptations and current barriers for deployment exist?

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Executive summary

With climate policy targets targeted towards a sharp decline of greenhouse gas emissions in the Dutch road sector in coming decades, action is required to move away from a reliance on fossil fuels as the dominant source of energy. This study examines renewable fuel options which could be used for heavy-duty vehicles in high-blend applications, or which could completely replace fossil diesel altogether. The study identifies different fuel options and whether their deployment requires engine modifications, and it assesses the major barriers to implementing modifications, as well as to increasing the total volume of renewable fuels.

Background and scope of the study

EU and Dutch climate targets for 2030 require a sharp reduction of greenhouse gas emissions, of 55% compared to 1990 levels, across all economic sectors.[1] Sector specific emissions targets have been stated by Dutch government, indicating that the emissions from the national mobility sector in 2030 should maximally be about 22 million tonne CO_2.[2] This is a significant challenge when compared to 30 million tonne CO_2 emissions in 2023.[3]

The ambition for achieving emission reduction in the transport sector is further supported by various European regulations on CO_2 emission standards for heavy-duty vehicles which require a reduction of tailpipe emissions from these vehicles by 90% by 2040.[4] Furthermore, the introduction of a new (separate) Emissions Trading System (EU ETS2), will increasingly restrict the volume of fossil fuels that fuel suppliers can deliver to the road sector (combined with small industry and buildings) from 2027 onwards, and may demand during the 2030s a renewable fuel volume two to three times more than today.[5] This will effectively force vehicle owners to seek renewable (non-fossil fuel) sources of energy to power their vehicles in the coming decades.

For a certain time, it is expected that the Dutch heavy-duty vehicles as well as the international heavy-duty vehicles that tank in the Netherlands will still be largely based on internal combustion engines. Therefore, during the transition towards an eventually mostly electric heavy-duty fleet, renewable fuels will be needed as an interim solution to contribute to achieving the established net-zero targets.

In current road fuels (for both light-duty and heavy-duty vehicles), a small share of renewable fuels is blended with fossil fuel. This concerns mainly ethanol in petrol and biodiesel and renewable diesel in diesel, while furthermore a small share of renewable methane is used natural gas vehicles in the fleet. In 2023, about 40% of the energy consumption in the national road transport market was petrol, almost completely for passenger vehicles. Around 54% was diesel,[6] mainly for the heavy-duty segment. The remainder consists of LPG, methane and electricity. In the current fleet heavy-duty vehicles, diesel engines dominate, see Figure 1.

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[1] The EU in 2021 set a target of 55% of reducing net greenhouse gas emissions in 2030 by at least 55% compared to levels in 1990 in the European Climate Law [Regulation (EU) 2021/1119]. In 2019, the Dutch Climate Agreement (between corporate, societal and government organisations) stated the target to reduce Dutch national greenhouse gas emissions in 2030 with 49% compared to 1990 [Klimaatakkoord 2019]. This was formalized in the Climate Act, which was later brought in line with the EU target and now also requires 55% emission reduction. Note that this 55% is a generic target without further specification of sector contributions [Klimaatwet 2019, amended mid 2023]. Sector specific targets were further defined by the Ministry of Economic Affairs and Climate, in the Climate Plan [Klimaatplan 2021-2030].

[2] Stated by Dutch Minister for Climate and Energy in letter to the Parliament [Minister voor Klimaat en Energie 2023, Kamerbrief 26 april: Voorjaarsbesluitvorming Klimaat].

[3] CO_2 emissions reported by CBS in line with the IPCC national accounting methodology [CBS, Emissies broeikasgassen (IPCC), voor mobiliteit, per jaar]

[4] [EU 2019, Regulation (EU)2019/1242 setting CO_2 emission performance standards for new heavy-duty vehicles].

[5] The EU Emissions Trading System ETS was amended in 2023 to amongst others establish a second, parallel system, called ETS 2, for emissions from buildings, road transport and smaller industry [EU 2023, Directive (EU)2023/959 amending the ETS].

[6] Energy use in Dutch transport per energy carrier is reported by the Netherlands Environmental Assessment Agency PBL [PBL 2024, Klimaat- en energieverkenning 2024, Tabellenbijlage Tabel 38b: Energieverbruik per energie drager sector mobiliteit in petajoule (vastgesteld en voorgenomen beleid)]

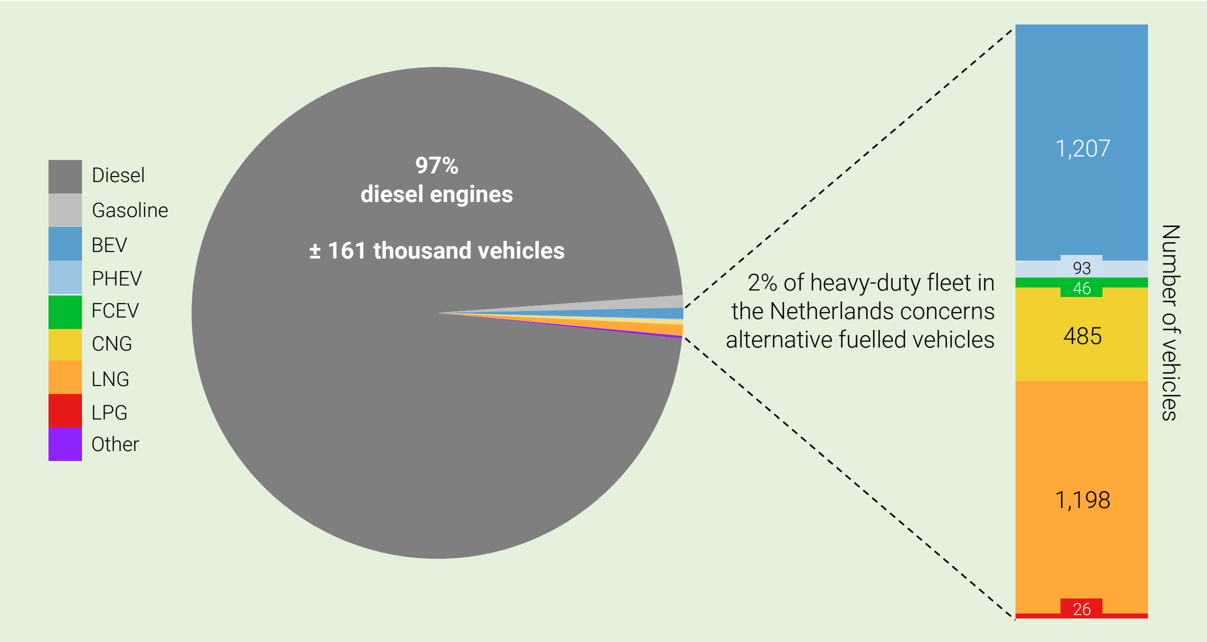

Figure 1. Number of heavy-duty vehicles registered in the Netherlands in 2024, split out to drivetrains. Data for total, BEV, FCEV and PHEV vehicles in December 2024 from RVO: N2 and N3 vehicles, but only the heavy-duty variations [RVO, 31 December 2024, sustainable mobility database]. Data for LPG, CNG and LNG trucks based on the share of alternative fuelled heavy-duty vehicles in the Netherlands [European Commission, 2024 data, European Alternative Fuels Observatory for the share of alternative fuelled heavy-duty vehicles in the Netherland] based on national registration by RDW.

Observing on the one hand, that most heavy-duty vehicles in the Netherlands until 2040 may have an internal combustion engine, and on the other hand, that climate policy will soon require sharply decreasing emissions from transport, it becomes likely that higher fractions of renewable fuels will soon be needed throughout the coming years and the 2030s.

Therefore, the Netherlands institute for Transport Policy Analysis (KiM), issued this study to review potential options for achieving high blends of renewable fuels in heavy-duty vehicles in the Netherlands. The KiM outlined three specific research questions:

1. Which alternative fuels can be used in diesel in existing or new engines in high blends or even completely replace diesel.
2. What adaptations are needed for the use of high blends? Consider modifications in the vehicles and their drivetrains, changes to the fuels themselves, and contractual changes such as warranty conditions.
3. What are the barriers that prevent such modifications, in terms of regulations, costs/payback time, development time, information, or other barriers perceived by vehicle manufacturers, fuel producers or fleet owners.

Note that this project focuses on high blends of renewable fuels. The term "high blend" is not officially defined, but usually indicates that the share is significantly above what is allowed in the quality specifications of mainstream fuels. Since currently up to 7% biodiesel by volume is allowed in mainstream diesel and up to 10% ethanol by volume is allowed in mainstream gasoline, the market usually assumes that high blends contain 20% or more renewable fuels. Such high blends cannot automatically be used in the (majority of the) existing fleet. For the purpose of this study, we also consider higher fractions of renewable diesel or biomethane that can be used without any problems in respectively diesel and gas vehicles. In short, we consider any higher fraction of renewable fuels, of about 20% and above.[7]

A variety of sustainable fuel options have been considered which can be applied in heavy-duty vehicles and which can be considered for the predominantly diesel engine vehicle fleet.

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[7] Note that the blend walls or upper limits of 10% ethanol in mainstream gasoline and 7% biodiesel in mainstream diesel are defined on volume basis. Due to a significant difference in energy content, these values represent both a share of about 6% on energy basis. For the scoping of the study, the 20% lower boundary of "high blends" is only indicative and could be on volume or energy basis.

Manufacturers are consolidating on new truck engine options

In the past, vehicle manufacturers developed engines and fuelling systems for the use of various types of renewable fuels in their vehicles.[8] But during the past decade, manufacturers have been directing their efforts towards a narrowing range of engine options because of (1) an increasing policy focus on electric vehicles which forces manufacturers to focus their attention and resources, (2) diminishing perspectives for renewable fuels, as a result of a cautionary policy approach and complex legislative rulesets (3) stricter tailpipe emission standards for heavy duty vehicles which complicate flexible fuel options and (4) a narrowing time-window to commercialise any entirely new developments in internal combustion engine vehicles, and consequently less time for returns on such investments.

Therefore, manufacturers focus their development efforts to engines that build on existing engine technology. This results in a smaller range of engines that are compatible with renewable fuel options than what was expected a decade ago. The near-term heavy-duty vehicle market, as a combination of the current fleets and what can be expected in the coming years, is thus dominated by compression-ignition diesel engines. Renewable fuel solutions that (after limited adaptations) work in these engines are better positioned than solutions that require new drivetrains or significant adaptations.

Besides diesel and electrification, some manufacturers develop solutions for the use of hydrogen in internal combustion engines. Especially, high pressure direct injection (HPDI) in diesel engines is promising here. This technology is also developed for LNG (which can be liquid renewable methane), and this can benefit the roll out in the market before hydrogen is widely available.[9]

This study focuses on options to enable higher blends of renewable fuels in the existing fleet of predominantly diesel engines, especially in the 2030 – 2040 timeframe. This includes considering drop-in options that can be applied directly, and options that require adaptations to these engines. Furthermore, with regard to gas engines (a small share of the fleet), we consider the fuel options that could be deployed without further adaptations, as well as (early) developments in reactivity-controlled compression-ignition (RCCI) technologies that could open opportunities for several sorts of alternative fuels.[10]

Main options for renewable fuels in the existing fleet

The main application of renewable fuels in heavy duty vehicles at this moment is in the form of low blends of FAME biodiesel in fossil diesel. The EN590 fuel quality standard for diesel sets a limit to a maximum share of 7% (on volume basis) for FAME blended in diesel, reflected by the fuel label B7.[11]

All FAME biodiesel that is currently used in the Netherlands is produced from waste feedstocks, such as waste vegetable oil and animal fat, conforming with the Annex IX list of the Renewable Energy Directive.[12]

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[8] A wide overview of fuel-engine combinations is provided in earlier work [studio Gear Up 2020, To drop-in or to adapt the engine, Amsterdam the Netherlands].

[9] HPDI for hydrogen and HPDI for LNG use the same core technology and share many components. They can utilise existing manufacturing infrastructure, with reduced capital investments, thus expediting time to market [website Cespira on HPDI H2 | Technical specification brochures by Westport on HPDI for LNG and HPDI for hydrogen]. HPDI technology is further explained in the Annexes.

[10] [Doosje E et al 2014, Experimental demonstration of RCCI in heavy-duty engines using diesel and natural gas, In: Proceedings of the 2014 SAE World Congress, Detroit Michigan, SAE Technical Paper 2014-01-1318, Society of Automotive Engineers (SAE)].

[11] In 2018 the European Commission introduced fuel labels, to provide better communication for consumers to understand which fuels fit for which vehicles. Each vehicle is labelled with a specific fuel label and only fuel from a fuel pump at a fueling station that has the same label should be used. For EN590 diesel the label is B7. It is important to note that the label does not indicate the actual share of renewable fuel. The B7-label indicates that it is an EN590 compliant fuel with a maximum of 7% FAME by volume, while in practice it may contain less [EC 2018, Press release: EU fuel labelling: clearer information for consumers and operators].

[12] The composition of feedstocks used in biofuels used in the Netherlands are annually reported by the Netherlands Emission Authority (NEA) [NEA 2024, Rapportage energie voor vervoer in Nederland 2023].

Due to specific aspects of FAME, especially with regard to viscosity and cold flow properties, this fuel can face some technical challenges for application at high blend levels. Several vehicle manufactures have approved specific vehicle models and engine types to run on specific higher blend levels of FAME, like B20 or B30 or even B100, when complying with quality standards EN-16709 (for B20 and B30) or EN14214 (for B100). The manufacturers guarantee that their vehicles can operate with these higher blends of biodiesel, provided that the owner complies with certain requirements, such as increased maintenance intervals.[13]

Some types of renewable fuels can be used in higher fractions or 100% in "all" diesel trucks. This concerns paraffinic diesel fuels that meet the EN15940 fuel specification (corresponding to the XTL fuel label).[14] These paraffinic diesel fuels can be produced via two distinct pathways. Today, Hydrotreated Vegetable Oil (HVO), which is produced from lipids and marketed as "renewable diesel", is commercially available, with nearly 10 billion litres production capacity worldwide (about 15 Mtonne, or over 650 PJ).[15] Alternatively, via catalytic synthesis pathways, a much wider range of feedstocks can be converted to diesel (and other) fuels – these technology pathways are called "Anything-To-Liquid" or XTL, which has become the name for the overarching fuel label.[16] These synthetic pathways are not yet commercially available.[17]

The XTL fuel (from either pathway) is called a drop-in fuel, because it can be used up to very high fractions in diesel, without impacting performance, reliability or emissions, in nearly all Euro V and VI engines. Also, it can be applied in the existing heavy duty vehicle fleet using via existing fuel infrastructure. Most truck manufacturers support the use of this renewable diesel in at high and full blend proportions, as long as it meets the EN15940 fuel standard.

Another promising pathway to produce diesel type fuels is upgrading of pyrolysis oils. First, a thermal process converts biomass residues to pyrolysis oil, which can subsequently be hydrotreated in dedicated stand-alone facilities, or co-processed in existing oil refineries. The product is called Hydrotreated Pyrolysis Oil (HPO), which could be used as a drop-in in diesel. The technology to produce road-diesel quality HPO is not yet commercially available.[18]

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[13] The German Association Quality Management Biodiesel AGQM provides an overview of current approvals for running heavy-duty vehicles on higher blends of FAME [AGQM 2022, Approval list of engine and commercial vehicle manufacturers for operation with biodiesel (B10 | B20 | B30 | B100)].

[14] The European fuel quality standard EN15940 covers paraffinic diesel fuels produced via the two different production pathways. The standard can be bought from Member State standardisation bodies such as NEN in the Netherlands [EN15940:2023, Automotive fuels - Paraffinic diesel fuel from synthesis or hydrotreatment - Requirements and test methods].

[15] IEA reports the development of the global HVO production capacity for 2019-2022 [IEA 2023, Renewable Energy Market Update 2021, Outlook for 2021 and 2022].

[16] The main synthetic conversion pathway is based on Fischer-Tropsch catalysis, known as FT. The feedstock could be biomass, which is first gasified to produce a synthesis gas primarily consisting of carbon monoxide and hydrogen. These components react to create long paraffinic hydrocarbons, from which fuel fractions, including diesel are derived [Hamelinck 2004, Outlook for advanced biofuels, PhD thesis, chapters 3 and 4]. Also, renewable hydrogen in combination with CO_2 captured from point sources or atmosphere can be used as feedstock for FT synthesis. Alternatively, synthetic diesel can be produced via the Mobil Methanol-to-Diesel conversion process, on basis of renewable diesel (which could be produced from for instance biomethane or renewable hydrogen) [TNO 2021, Evaluation of different routes for e-diesel and e-kerosine supply in the port of Rotterdam, TNO report 2021-R12731].

[17] The technology, market and commercial readiness of various advanced conversion technologies including the FT pathways is assessed by amongst others the EU Joint Research Centre [JRC 2019, Advanced Alternative Fuels Technology Market Report EUR 29937 EN, European Commission, Luxembourg].

[18] Dutch company btg-neXt develops commercial technology for the upgrading of pyrolysis oil [btg-neXt 2024, website]. When produced via the co-processing pathway, the HPO product will have diesel characteristics and performance, and can be used as a drop-in fuel. If produced via stand-alone hydrotreatment, the fuel is currently suitable for heavy-duty engines in the marine sector, as tested by TNO and TUe [Han et al 2023, Combustion and emission characteristics of hydrotreated pyrolysis oil on a heavy-duty engine, Fuel 351:128888]. It is expected that the HPO can be made compliant with road diesel quality, but this would likely require further tweaking of the process [Chen et al 2024, Diesel production via standalone and co-hydrotreating of catalytic fast pyrolysis oil, Energy Advances 3: 1121-1131].

Finally, OMEx has been suggested as a potential "drop-in" option. OME_x is a hydrocarbon with interspersed oxygen atoms, that can be produced from (renewable) methanol.[19] It would not literally be a drop-in fuel, because the chemical properties differ significantly from diesel, and high blends would not remotely comply with the EN590 standard.[20] But, the fuel can be combusted in a diesel engine, as a high blend with diesel or in a dual fuel mode, with good fuel efficiency and emission performance.[21] Various pathways for OME_x production are being developed, but not yet available at industrial/commercial scale.[22]

As was noted above, a small part of the heavy-duty fleet has non-diesel drivetrains. In natural gas vehicles now running on compressed or liquid methane (CNG or LNG respectively), it is possible to directly deploy 100% biomethane in the form of bioCNG or bioLNG. In LPG vehicles, a 100% bioLPG (a co-product of HVO) can be directly deployed.

To increase the level of renewable fuels in the entire fleet, we should however focus on the diesel engines. When looking beyond the available drop-in options, the vehicles also could be adapted to use higher levels of other types of renewable fuels. With limited adaptations it is (technically) possible to use FAME biodiesel up to 100% with most existing diesel engines. DME can also be used in diesel engines, with relatively limited adaptations,. It is also possible to convert existing compression-ignition engines to a dual fuel set-up to allow the application of other renewable fuel types, such as: methane, DME, methanol, ethanol, hydrogen, or ammonia. The adaptation option of choice depends on the existing engine and motor management system in the vehicle, in combination with the targeted renewable fuel.[23]

Addressing the barriers to retrofitting existing vehicles

While the costs of adaptations to existing vehicles may be limited, in many cases the vehicle owner would lose the manufacturer's warranty which may have insurance consequences and other costs. Also, following modification, the vehicle would have to be recertified, to confirm that it still meets the legal requirements with regard to safety and emissions. This recertification process is costly in terms of money and time. Finally, in some cases maintenance intervals may become more regular, which represents downtime and costs for fleet owners.

These risks associated with the modification of existing diesel vehicles may be manageable, and the costs may be limited relative to other possible options (including the development of entirely new trucks). Addressing these barriers requires action from stakeholders, likely including the government, such as spreading the risks, providing alternative guarantees, and group recertification programs for adapted vehicles.

Addressing the barriers to scaling-up renewable fuel production

The successful deployment of fuel/engine combinations also depends on the availability of renewable fuels. Achieving Dutch and European climate targets will require high volumes of

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[19] OME stands for oxymethylene ether. OME_x is a mixture of several OME fuels with a different chain length (n) of the CH_2O-groups in the molecular structure CH_3-O-(CH_2-O)$_n$-CH_3. OME_0 would be the same as DME. OME_1 has the molecular structure CH_3-O-CH_2-O-CH_3 et cetera. OME_x usually refers to a mixture of primarily OME_3, complemented with OME_4 and OME_5 [Sun 2025, Design of experiments optimized OMEx-diesel blends on a heavy-duty engine Part 2: Engine performance and exhaust particle analysis with EGR variation, Fuel 388:134435].

[20] OME_x has a higher cetane number ≧ 65, a higher density, and a higher maximum boiling temperature than diesel [Pitsch 2024, Potential of oxymethylene ethers as renewable diesel substitute, Progress in Energy and Combustion Science 104: 101173].

[21] Research indicates that OME_x could be used in high blends in diesel engines [Van Beers 2024, Effects of diesel B7/OMEx blends on emission and combustion characteristics in a heavy-duty, Master Thesis TU Eindhoven]. The high oxygen content and the non-direct carbon bonds inhibit soot formation and also the nitrogen oxide emissions are limited [Benajes 2020, Potential of using OMEx as substitute of diesel in the dual-fuel combustion mode to reduce the global CO2 emissions, Transportation Engineering 1:100001]

[22] Dahmen states that the commercial development depends on technical R&D aspects such as catalyst development [Dahmen et al 2017, The bioliq process for producing synthetic transportation fuels, Energy and Environment, 6(3) Article e236], but it will certainly also depend on the interest in, and potential demand for OMEx as a renewable fuel.

[23] Engine and vehicle adaptation options to allow the use of various types of renewable fuels in diesel engines, are discussed in the Annex of this report.

renewable fuels. Between 2030 and 2040, when the emission reduction targets become more strict, while heavy-duty electric vehicles are not yet dominant in the Dutch fleet, this will lead to a high demand for renewable fuels, which could be 2 to 3 times larger than today.[24]

However, after that period, the fuel demand is foreseen to decrease, when electric vehicles replace internal combustion engine vehicles. The temporary high demand (between 2030 and 2040 mainly) presents challenges for making a business case to invest in scaling up renewable fuel production capacity, which would require short payback times, or smart follow-up or exit strategies. For instance, fuels developed for road transport may find application in aviation or maritime (directly, or after applying a subsequent conversion step), while technology pathways and feedstocks can also play a role in the biobased economy.

Policies related to climate action in transport specifically ask for advanced and therefore more costly renewable fuels: e-fuels, with very strict requirements on the sourcing of both the hydrogen and CO_2 that are required for e-fuel production,[25] and advanced biofuels, to be produced via technologies that are not mature today.[26]

The combination of potentially a brief market window between 2030 and 2040 and strict requirements on feedstocks and technologies, inhibits investments in renewable fuels production capacity. Investors need both market and policy certainty. If investments in renewable fuels production do not take-off in Europe over the coming years, then the future EU demand for renewable fuels may largely depend on imports and overseas investments.

[24] The EU ETS 2 (see footnote 5) demands a linear decrease of emissions from three sectors collectively: road transport, buildings and small industry. It effectively points to zero emissions in 2043. If the three sectors reduce their emissions in the same tempo, this implies that an increasing share of the (remaining) this likely requires a sharp increase in the demand for renewable fuels for transport between 2030 and 2040. As an increasing share of the fleet is becoming electric, the total demand for fuels decreases sharply from 2040 onwards [studio Gear Up 2021, The role of biodiesel in EU climate action – input for EBB roadmap to 2030 and 2050].

[25] The production of renewable hydrogen and e-fuels must meet the rules laid out by the European Commission on the production of RFNBOs [EC Delegated Regulation (EU) 2023/1184].

[26] As explained in more detail in the Annex of this report, the Renewable Energy Directive caps the contribution of crop-based biofuels and of some waste-based biofuels. It includes a subtarget for biofuels produced via advanced conversion technologies, from a limited list of feedstocks [amended Directive (EU) 2018/2001].

Contents

1 Introduction

In the amended Renewable Energy Directive (known as RED III), EU Member States are tasked to reduce greenhouse gas (GHG) emissions across all sectors by 2030, compared to a baseline level. In the transport sector, Member States are responsible for the implementation of national legislation to achieve either a 14.5% reduction in greenhouse gas emission intensity of transport fuels, compared to a fossil baseline, or by reaching a 29% minimum administrative share of renewable energy in transport.[27] The Netherlands has translated these targets into an "annual obligation" (Jaarverplichting) which is outlined in the Energy for Transport legislation. The Ministry of Infrastructure and Water Management is preparing the implementation, envisaged to be in force as of 1 January 2026. The Minister has already announced to implement a greenhouse gas emission intensity reduction approach. For the national road transport sector, the greenhouse gas emission reduction target is proposed to increase towards 22.9% in 2030.[28] When assuming that renewable fuels will on average achieve about 85% emission reduction, this would imply that the average fraction of renewable fuels in road transport would be about 27% in 2030.

In the European context specific regulation has been put in place to reduce the tail pipe emissions resulting from heavy-duty vehicles, as these vehicles represent a large share of road transport emissions.[29] The EU has set a target that in 2040 the CO_2-tailpipe emissions of newly registered heavy duty-vehicles are reduced by 90%. This will presumably lead to an acceleration of the electrification of heavy-duty vehicles after 2030. The full electrification of the fleet takes time, which may mean that a significant part of the heavy-duty vehicles on the Dutch roads may still have internal combustion engines beyond 2040.

At the same time, the European Emissions Trading System has been expanded to (amongst others) cover road transport.[30] A decreasing ceiling of emission allowances effectively allows zero end-use CO_2 emissions from fuels used in road transport by 2043. This implies that any remaining fuels used in road vehicles in 2043, will have to be renewable fuels. The emission ceiling of this so-called ETS 2 decreases linearly. The ETS 2 covers three sectors: road transport, buildings and small industry. If these three sectors achieve emission reduction in the same tempo, then this would require a steep increase of renewable fuels in the road sector already in 2030, plateauing for a decade and then decreasing fast as electrification decreases the demand for fuels beyond 2040. In previous work, we have estimated, that his could amount to 2 to 3 times more renewable fuels than today during the 2030-2040 period.[31] If emission reduction can be achieved faster in buildings or small industry, then the steep increase of renewable fuels in road transport can be delayed for some time. But eventually, towards 2040, when in those other sectors full emission reduction is achieved or the solutions are exhausted, then still a large volume of renewable fuels will be required in road transport.

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[27] The original Renewable Energy Directive was issued in 2009. In 2018, the Renewable Energy Directive was reissued, this is known as RED II to cover the 2021-2030 period. Both directives included targets for renewable energy in transport. In 2023, the so-called RED III amended the RED II and reformulated the target for renewable fuels to an 14.5% emission intensity reduction target for fuels (compared to a fossil baseline), which effectively requires a share of renewable fuels. Alternatively, Member States may comply with a 29% administrative target of renewable energy in transport, which includes multipliers for renewable electricity and several types of renewable fuels [Directive (EU) 2018/2001, consolidated version].

[28] The Dutch state secretary for Infrastructure and Water Management reported to the Parliament on the progress of the implementation of RED-III in transport. The sector specific target for "land" of 22.9% greenhouse gas emission reduction intensity in 2030, compared to fossil, is visualised in the letter, and specified in Annex 1 to the letter [Staatssecretaris Infrastructuur en Waterstaat 2024, Kamerbrief 26 april: Voortgang implementatie RED-III Vervoer, Bijlage 1: Voorgestelde hoogtes verplichtingen, sub-verplichtingen en limieten].

[29] [Regulation (EU) 2024/1610 strengthening CO_2 emission performance standards for heavy-duty vehicles].

[30] The EU Emissions Trading System ETS was amended in 2023 to amongst others establish a second, parallel system, called ETS 2, for emissions from buildings, road transport and smaller industry [EU 2023, Directive (EU)2023/959 amending the ETS].

[31] For details, see our study on the implications of the ETS 2 for the European Biodiesel Board [studio Gear Up 2021, The role of biodiesel in EU climate action – input for EBB roadmap to 2030 and 2050].

Nationally, the implications of climate action for the fuel mix have been assessed for the National Plan for the Energy System (NPE). It presents two different scenarios on the energy mix in the heavy-duty road segment for the period up to 2050.[32] The scenarios assume that 80% to 100% of the heavy-duty vehicles in the whole fleet will be electric by 2050. These scenarios shows that there is much uncertainty about the future composition of the fleet. The scenario of currently agreed and intended policies would even in 2050 still require a significant volume of renewable fuels, whereas a faster deployment of electric vehicles would reduce the demand for renewable fuels beyond 2040. This may require that the remaining liquid (and gaseous) fuels used in heavy-duty vehicles include of higher fractions of renewable fuels.

When considering these EU and national policies and legislations, it is expected that the share of renewables in road fuels will increase rapidly to above 20%. This cannot be facilitated by the currently most common renewable fuels (ethanol and FAME type biodiesel up to their blend walls) in mainstream gasoline and diesel. Some renewable fuels can be "drop-in" blended to higher percentages within the mainstream fuel quality requirements. The use of other renewable fuels in higher blend fractions may be possible after (limited) adaptations to the vehicles, as we explore in the current report.

To inform Dutch policy on climate action in the mobility sector, the Netherlands Institute for Transport Policy Analysis (Kennisinstituut voor Mobiliteit – KiM) would like to know what options exist, especially outside the "drop-in" options, to facilitate higher blends of renewable fuels in the heavy-duty segment – since it is expected that it will take longer to electrify heavy-duty vehicles than passenger cars, and therefore this segment most requires alternative interim solutions for climate action. KiM has outlined three specific research questions which are addressed in this project:

1. Which alternative fuels can be used in diesel in existing or new engines in high blends or even completely replace diesel.
2. What adaptations are needed for the use of high blends? Consider modifications in the vehicles and their drivetrains, changes to the fuels themselves, and contractual changes such as warranty conditions.
3. What are the barriers that prevent such modifications, in terms of regulations, costs/payback time, development time, information, or other barriers perceived by vehicle manufacturers, fuel producers or fleet owners.

The aim of this project was to investigate the use of renewable fuels in heavy-duty vehicles. studio Gear Up carried out desk research on the most promising fuel/engine combinations, held interviews with industry experts and conducted a 3-hour workshop with several industry stakeholders to discuss the most promising fuel-engine combinations, as well as the barriers to achieving high-blends of renewable fuels in heavy duty vehicles. An overview of consulted stakeholders can be found in Annex A

In this report, the broader context of CO_2 emission reduction and renewable fuels developments in the Netherlands, and specifically in the heavy-duty vehicle fleet is outlined in Chapter 2. Chapter 3 provides an overview of the options for renewable fuels and engine combinations. Thereafter, the leverage points and barriers on both the fuel and engine side to enable higher blends of renewable fuels in both new and existing vehicles are examined in Chapter 4. Recommendations are provided in Chapter 5 Finally, the annexes contain factsheets on engine technology and renewable fuels.

[32] The National Plan for the Energy System NPE is the vision of the Dutch government on the energy system until 2050 [Ministry of Economic Affairs and Climate 2023, National Plan Energy Systems]. Annex 4 to the NPE explores transition pathways, including an analysis of the developments in heavy-duty road transport [NPE Verdiepingsdocument C – Transitiepaden gebruikssectoren].

2 Renewable fuels in the national transport sector

2.1 Development of CO_2 equivalent emissions and energy consumption of the transport sector in the Netherlands

Emissions from all main sectors need to be reduced drastically to meet national targets. All economic sectors in the Netherlands have been reducing greenhouse gas emissions at a faster rate than the mobility sector, and emissions from mobility have not decreased in the last four years (Figure 2). Electrification and the increasing deployment of renewable fuels are currently mainly compensating for the increase in transport activities, which are still largely dominated by the use of fossil fuel (Figure 3). The transport sector requires significant reduction efforts to reach the national 2030 target.

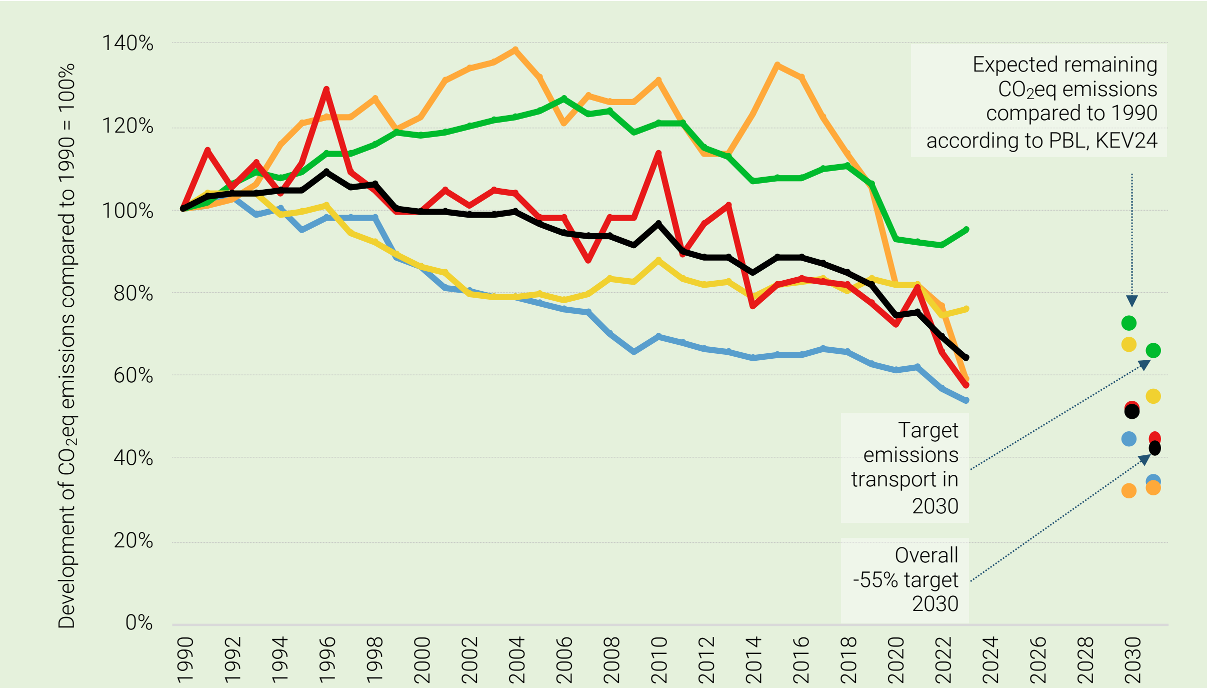

Figure 2. The development of CO_2eq emissions in the Netherlands since 1990 per sector and outlook towards 2030 according to KEV2024 and -55% emissions reduction target of 2030. Analysis by Platform Renewable Fuels, based on CBS data on CO_2 emissions, and PBL 2024, KEV 2024].

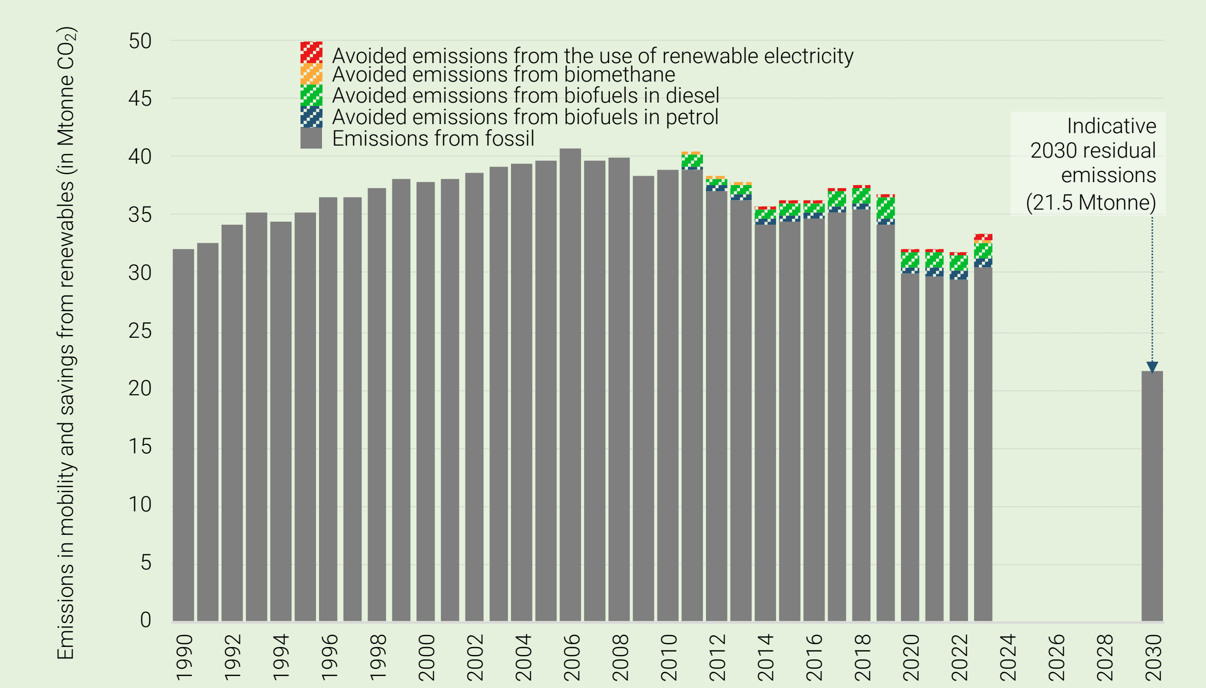

Figure 3. The emission reductions achieved in transport sector with the use of renewable energy since 1990 and outlook towards 2030. This figure assumes that renewable fuels achieve an average emission reduction of 84% (Analysis by Platform Renewable Fuels. Source: NEa, Annual obligation energy transport 2021-2023. 2030 estimate based on PBL, KEV22 and Decision Spring Memorandum 2023 to add 20 PJ of renewable fuels on top of the European target).

2.2 Development of renewable fuels and outlook towards 2030 in the Netherlands

In the last decade, the share of renewable energy in the transport sector has been increasing in the Netherlands, but it remains a small percentage compared to the incumbent fossil fuels. Renewable energy contributed to almost 20 PJ in the early 2010s with a continuous increase to date: presently reaching over 40 PJ in the past few years, see Figure 4 and Figure 5.

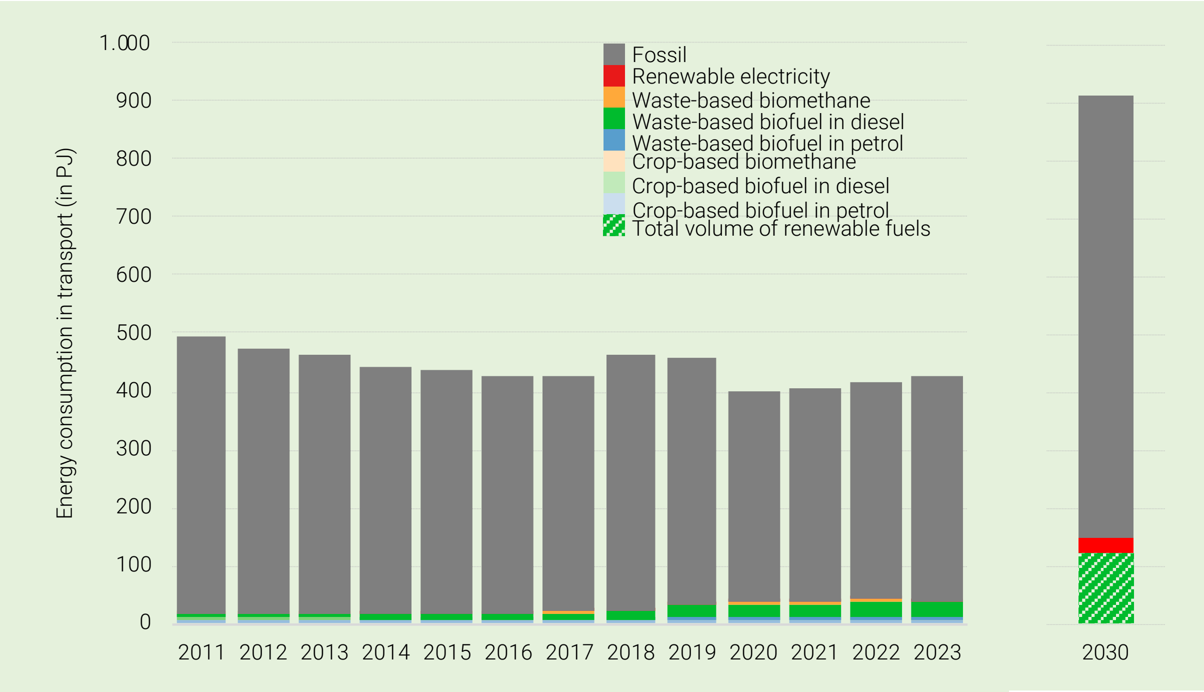

Figure 4. The development of fossil and renewable energy in the transport sector in the Netherlands since 2011, and outlook towards the 2030 obligation for renewable fuels in transport. Note that the 2030 scope of renewable fuels obligations is broader than for the historic data. Bunkering to international aviation and to a significant part international shipping is included in the 2030 scope. The combination of higher percentages with an increased scope requires much more renewable energy in transport in 2030 than today [Historic data based Nea 2024, Annual obligation energy transport 2021-2023 | 2030 estimate based on the Climate and Energy Exploration by Netherlands Environmental Assessment Agency, combined with the Spring Decision Memorandum 2023 plus 20 PJ on top of the European target, and combined with the assumption that renewable fuels achieve on average 84% emission reduction].

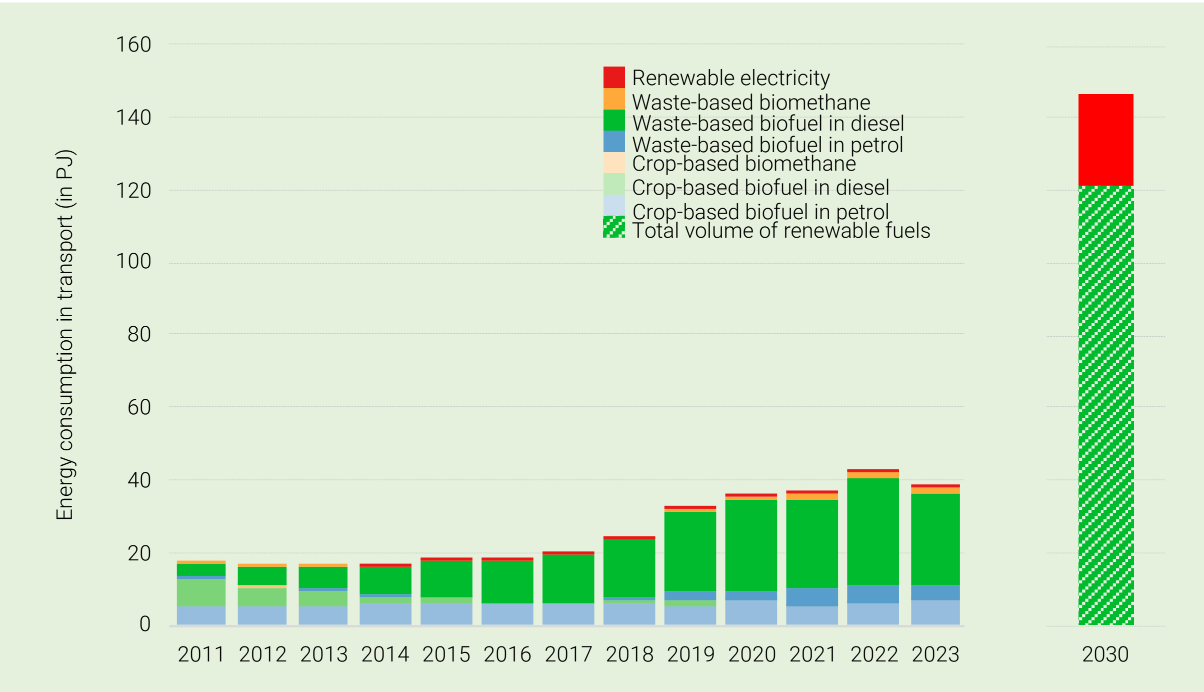

Figure 5. Zoom in on the development of renewable energy in the transport sector in the Netherlands since 2011 and outlook towards 2030. [data and method explained in Figure 4.

2.3 The role of heavy-duty road transport

The energy consumption in the national transport sector[33] in the Netherlands is thus heavily dominated by fossil energy. In 2023 the energy consumption in the national transport sector amounted to 398 PJ, including road, rail, aviation and inland shipping and excluding the fuels needed for international bunkering for aviation and shipping and non-road mobile machinery (Figure 6). Two categories prevail the energy consumption: fossil diesel and fossil petrol while the share of bio components in petrol and diesel contribute a small share. Considering the transport modalities, the shares from road freight transport and passenger cars takes up the largest portion of the energy consumption in the national transport. Road freight transport presents a relatively smaller number of vehicles in the total fleet; approximately 150 thousand trucks and 1 million vans compared to 9 million passenger cars.[34] Nevertheless, the share of the energy consumption of freight transport represents approximately a third of the total energy consumption in national transport due to longer distances driven and higher energy consumption per kilometre.

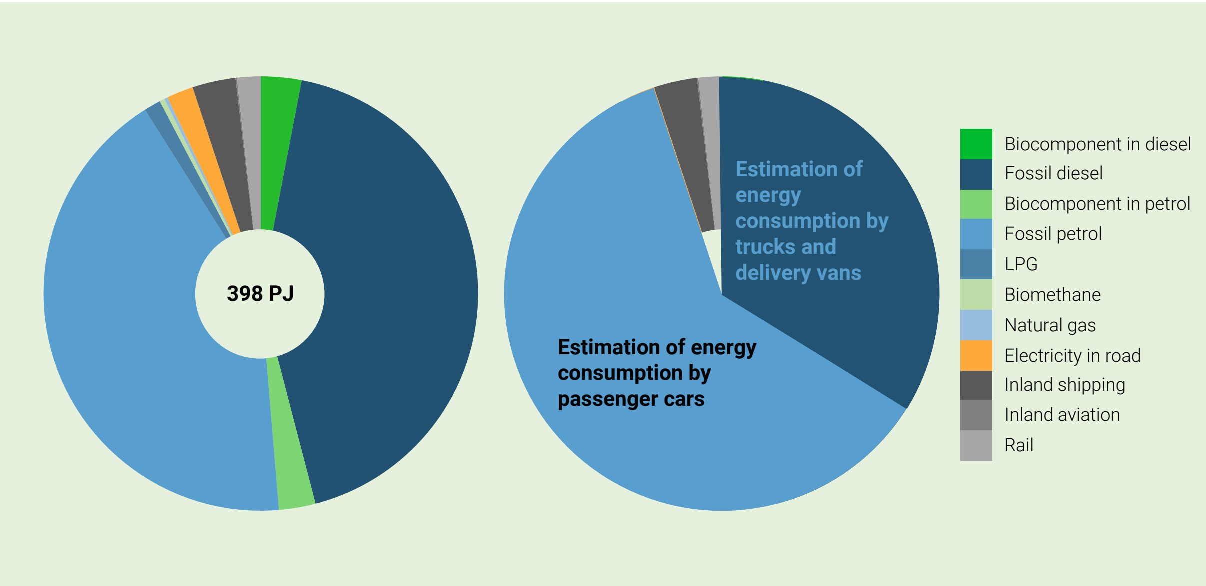

Figure 6. Left figure: The energy consumption of the transport sector in the Netherlands in 2023 (Excluding renewable fuels from international bunkering) [data from CBS Energy balance, supply, conversion and use, complemented with Eurostat SHARES data on the specific contributions of biomethane and electricity in road]. Right figure: Estimated division between passenger vehicles and freight transport [data from CBS on kilometres driven by trucks, vans and passenger cars on the Dutch roads ("verkeersprestaties"), combined with the gasoline and diesel consumption of vehicle-fuel combinations by KiM 2021 Trendprognose wegverkeer 2021-2026]. Only energy use in the national transport sector is included. Non-road mobile machinery (agriculture, fishery, construction) and international bunkering for aviation and shipping are excluded.

2.4 Current Dutch truck fleet

The striking vast majority of trucks in the Dutch fleet is driving with diesel engines, see Figure 7. The introduction of battery electric vehicles has been gaining ground although their share in the whole fleet is still minor. Vehicles that drive on gaseous fuels (CNG/LNG) have a small and rather stable share in the fleet. The share of heavy-duty vehicles running on hydrogen in the Netherlands is near-zero. Therefore, to achieve a significant impact with renewable fuels, it is necessary to address the heavy-duty vehicles running on diesel.

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[33] The Dutch National transport sector implies the fuels that are used within the Dutch geographical boundaries for transport. Data scope is explained in the caption of Figure 6.

[34] 2023 data from CBS [CBS Motorvoertuigen actief; type, leeftijdsklasse, op 1 januari].

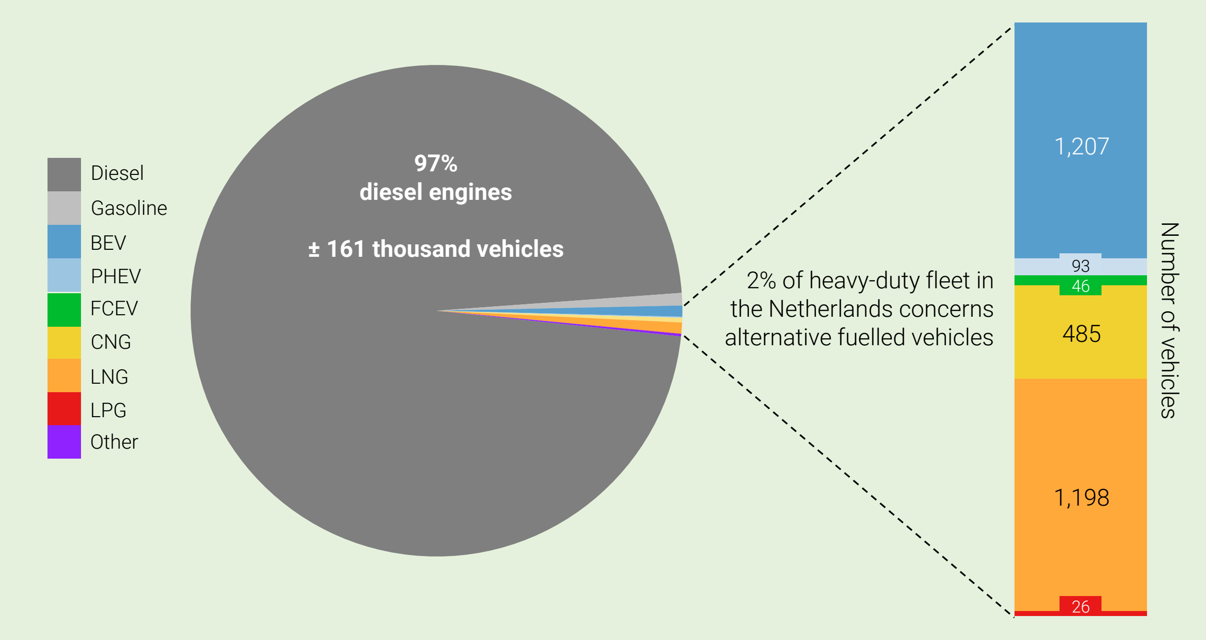

Figure 7. Number of heavy-duty vehicles in the Netherlands in 2024, split out to drivetrains. Data for total, BEV, FCEV and PHEV vehicles in December 2024 from RVO ([RVO, 31 December 2024, alternative fuelled heavy-duty vehicles in the Netherlands]. Data for (H2, LPG, CNG and LNG based on data provided in the European Alternative Fuels Observatory [European Commission, 2024 data).

3 Overview of options for renewable fuels and engine combinations

Theoretically, many fuel-engine combinations are possible in heavy-duty vehicles. In Table 1 below, the most current and potential near-term combinations are listed. As noted in the previous chapter, by far most of the heavy-duty vehicles in the Netherlands have a conventional compression ignition engine, usually called a diesel engine. Some vehicle manufacturers are expected to introduce high pressure direct injection systems in the coming years (such as HPDI by Westport). The Reactivity Controlled Compression Ignition (RCCI) system is not currently available on the market, but research is advanced, and this technology seems to be attractive for retrofitting existing compression ignition engines. Both HPDI and RCCI are compression ignition engines, but with options to increase injection pressures, optimise combustion timing and allowing the use of a range of renewable fuels.

Below the table, in Section 3.2, the main options and variations of renewable fuels that we have identified in this research are discussed. Details on engine technology are discussed in Annex B of this report. Details on renewable fuel options and necessary engine adaptations are discussed in Annex C.

Table 1. Options to introduce renewable fuels in the existing fleet, either via drop-in, or via (limited) adaptation of the existing engine or fuel system in the vehicle, as identified in the current research. The fuels are indicated by their uniform appearance, without specifying their renewable nature or production pathways. For instance, methanol could be biomethanol or e-methanol, CNG is assumed to be biomethane based CNG, synthetic diesel could be produced from biomass (gasification), renewable electricity (e-FT pathway) or methanol (MtD pathway), etcetera.

Engine type				
	Regular compression ignition (CI)	High pressure direct injection (HPDI)	Reactivity controlled compression ignition (RCCI)	Spark ignition (SI)
Options per alternative fuel type for existing and new vehicles (ex-factory)				
FAME biodiesel	Up to 10% in most vehicles, and ≧20% in approved vehicles			
HVO	100% in approved vehicles			
Renewable synthetic diesel	100% in approved vehicles			
Renewable OME_x	Potentially high, but not yet approved			
Renewable CNG				100% in approved vehicles
Renewable LNG		High with pilot fuel		100% in approved vehicles
Options per alternative fuel type, for new types of vehicles that may be introduced in coming years				
Renewable Methanol		High with pilot fuel		
Renewable Hydrogen		High with pilot fuel		Up to 100%
Options per alternative fuel type, requiring adaptations in the engine and fuel system in the vehicle				
FAME (>10%)	Up to 100%			
Renewable CNG	Dual fuel with diesel		High with pilot fuel	
Renewable LNG			High with pilot fuel	
Renewable LPG	Dual fuel with diesel			
Renewable Methanol			High with pilot fuel	Up to 100%
Ethanol	Up to 95% as ED95		High with pilot fuel	
Renewable DME	Up to 100%		High with pilot fuel	
Renewable Ammonia			High with pilot fuel	
Renewable hydrogen			High with pilot fuel	

3.1 Renewable fuel use in the current and forthcoming fleet

The main application of renewable fuels in heavy duty vehicles at this moment is in the form of a low blend of FAME biodiesel in fossil diesel. In the Netherlands, the blend fraction is maximally 7% by volume and hence the fuel is called B7. FAME biodiesel is mainly produced from vegetable oil and animal fat. The blend meets the EN590 quality standard for mainstream diesel.

It is possible to use FAME biodiesel in higher blends, like B20 or B30 or even B100. Several vehicle manufactures have approved specific vehicle models and engine types to run on specific higher blend levels of FAME, like B20 or B30 or even B100, when complying with quality standards EN16709 (for B20 and B30) or EN14214 (for B100). The manufacturers guarantee that their vehicles can operate with these higher blends of biodiesel, provided that the owner complies with certain requirements, such as increased maintenance intervals.[35] The FAME quality standard EN14214 was originally developed for rapeseed-based biodiesel, and rapeseed-based FAME still best meets the quality standards. When other feedstocks are being used, some characteristics may fall outside of the standard, especially viscosity and cold flow properties. This can sometimes be compensated by the combination of feedstocks, and the use of some feedstocks is limited when deploying higher blends.

Some types of renewable fuels can be used in higher fractions or 100% in "all" diesel trucks. This concerns paraffinic diesel fuels that meet the EN15940 fuel specification (corresponding to the XTL fuel label).[36] These paraffinic diesel fuels can be produced via two distinct pathways. Today, Hydrotreated Vegetable Oil (HVO), which is produced from lipids and marketed as "renewable diesel", is commercially available, with nearly 10 billion litres production capacity worldwide (about 15 Mtonne, or over 650 PJ).[37] Alternatively, via catalytic synthesis pathways, a much wider range of feedstocks can be converted to diesel (and other) fuels – these technology pathways are called "Anything-To-Liquid" or XTL, which has become the name for the overarching fuel label.[38] These synthetic pathways are not yet commercially available.[39]

The XTL fuel (from either pathway) is called a drop-in fuel, because it can be used up to very high fractions in diesel, without impacting performance, reliability or emissions, in nearly all Euro V and VI engines. Also, it can be applied in the existing heavy duty vehicle fleet using via existing fuel infrastructure. Most truck manufacturers support the use of this renewable diesel in at high and full blend proportions, as long as it meets the EN15940 fuel standard.

Some other types of renewable fuels are or have been suggested, as potential drop-in options. This mainly concerns OME_x, with some characteristics resembling diesel. It is expected that OMEx could be used at high fractions in diesel engines. However, OME_x is not yet commercially produced, and it is not completely clear to what blend fraction it could be used in diesel – in view of the differing characteristics this may not be 100% drop-in.

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[35] The German Association Quality Management Biodiesel AGQM provides an overview of current approvals for running heavy-duty vehicles on higher blends of FAME [AGQM 2022, Approval list of engine and commercial vehicle manufacturers for operation with biodiesel (B10 | B20 | B30 | B100)].

[36] The European fuel quality standard EN15940 covers paraffinic diesel fuels produced via the two different production pathways. The standard can be bought from Member State standardisation bodies such as NEN in the Netherlands [EN15940:2023, Automotive fuels - Paraffinic diesel fuel from synthesis or hydrotreatment - Requirements and test methods].

[37] IEA reports the development of the global HVO production capacity for 2019-2022 [IEA 2023, Renewable Energy Market Update 2021, Outlook for 2021 and 2022].

[38] The main synthetic conversion pathway is based on Fischer-Tropsch catalysis, known as FT. The feedstock could be biomass, which is first gasified to produce a synthesis gas primarily consisting of carbon monoxide and hydrogen. These components react to create long paraffinic hydrocarbons, from which fuel fractions, including diesel are derived [Hamelinck 2004, Outlook for advanced biofuels, PhD thesis, chapters 3 and 4]. Also, renewable hydrogen in combination with CO_2 captured from point sources or atmosphere can be used as feedstock for FT synthesis. Alternatively, synthetic diesel can be produced via the Mobil Methanol-to-Diesel conversion process, on basis of renewable diesel (which could be produced from for instance biomethane or renewable hydrogen) [TNO 2021, Evaluation of different routes for e-diesel and e-kerosine supply in the port of Rotterdam, TNO report 2021-R12731].

[39] The technology, market and commercial readiness of various advanced conversion technologies including the FT pathways is assessed by amongst others the EU Joint Research Centre [JRC 2019, Advanced Alternative Fuels Technology Market Report EUR 29937 EN, European Commission, Luxembourg].

As was noted above, a small part of the heavy-duty fleet has non-diesel drivetrains. In natural gas vehicles now running on compressed or liquid methane (CNG or LNG respectively), one can directly deploy high levels of biomethane in the form of bioCNG or bioLNG.

In the LPG vehicles (also only a small share of the heavy-duty fleet), one can directly deploy high levels of bioLPG (a co-product of HVO). LPG may possibly be mixed with up to 30% DME.[40]

3.2 Deploying renewable fuels in retrofitted vehicles

To increase the level of renewable fuels in the entire fleet, we should focus on the diesel engines. When looking outside the drop-in options, the vehicles could be adapted to use higher levels of other types of renewable fuels. With limited adaptations it is (technically) possible to use high levels of FAME biodiesel in most vehicles.

It is also possible to retrofit existing compression-ignition engines to a dual fuel set-up for other types of (renewable) fuels, such as methane, DME, methanol, ethanol, butanol or ammonia. The adaptation option of choice depends on the existing engine and motor management system in the vehicle, in combination with the targeted renewable fuel.

Retrofit options per renewable fuel type are further explored in Annex C.

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[40] The option of DME-LPG blends in compression ignition is reported by a few researchers [for instance Nguyen et al 2024, Exploring the feasibility of dimethyl ether (DME) and LPG fuel blend for small diesel engine: a simulation perspective, International Journal of Renewable Energy Development 13(3):559-571 | Stepanenko and Kneba 2019, DME as alternative fuel for compression ignition engines – a review, Combustion engines 177(2):172-179], but there are no consistent recent insights in what is required to enable this option.

4 Enabling higher blends of renewable fuels in heavy duty vehicles

Considering the context in which heavy-duty vehicles and renewable fuels have developed in the Netherlands, several points of leverage have been identified either as opportunities or barriers to enable higher blends of renewable fuels in heavy duty vehicles.

4.1 Vehicles manufacturers focus on electrification, further consolidate on diesel engines

In the past, vehicle manufacturers developed engines and fuelling systems for the use of various types of renewable fuels in their vehicles.[41] Vehicle manufactures innovate within the boundaries set by the regulation and the (expected future) market. But the rules have become stricter and the potential market has become narrower, leading the manufacturers to focus on fewer options than in the past.

The increasing policy focus on electrification forces manufacturers to focus their (current) attention and resources. At the same time, the policy has become less supportive of a long-term perspective renewable fuels, with cautionary policy views on conventional biofuels and complex regulation of advanced and waste-based biofuels and e-fuels. Options for fuels in general are also complicated by increasingly stricter tailpipe emission standards for heavy-duty vehicles. By 2040, most (90%) of the new heavy-duty vehicles sold to the EU market shall not have an internal combustion engine. Only a small part (10%) of the sold vehicles can have an internal combustion engine, provided that it can only use renewable fuels. Any new engines for alternative fuels can thus from 2040 onwards only be placed in that 10% segment, while research and development into new options necessitates considerable amount of time and resources before vehicles become commercially available. This implies that the time-window to commercialise combustion engines ends largely by 2040, which rapidly narrows the time for returns on investments. We elaborate on these elements below.

From the regulatory point of view, vehicle manufacturers must reduce their tank-to-wheel emissions and comply to emission standards such as the European emissions performance standards imposing increasingly lower tailpipe CO_2 emissions from the vehicle. Furthermore, the Euro VI standard for newly registered heavy-duty vehicles requires reduction in NO_x and PM emissions. However, by emphasizing the emissions from the exhaust side, certain renewable fuel options that were once interesting in the past are no longer being pursued: they may greatly reduce lifecycle emissions (well-to-wheel), but still have the same tailpipe emissions (narrow well-to-wheel perspective). This is for instance the case with heavy-duty vehicles driving with bioLPG or ED95. Consequently, OEMs have been focusing on a narrowing range of technologies in the past years while limiting the development of other options. More consolidation in the market means that many OEMs have narrowed their focus on the developments of a few diesel compression engines and options to use hydrogen either via spark ignition or compression ignition engines, and they focus on battery electric vehicles.

In addition, the rise of zero emission zones in the built environment have been further restricting the options that OEMs can bring into the market. OEMs have thus adapted their catalogue to provide new vehicles adhering to the latest standards by shifting their attention towards the development of battery electric vehicles (BEV). Many OEMs have announced their commitment to the development of BEV while keeping an eye on potential of hydrogen in the long-term. Furthermore, certain OEMs are pursuing research and development on the application of dual fuel engines with high pressure direct injection technology as an option for renewable natural gas and the use of hydrogen in the future.

[41] A wide overview of fuel-engine combinations is provided in earlier work [studio Gear Up 2020, To drop-in or to adapt the engine, Amsterdam the Netherlands].

Besides regulation and standards, OEMs release new vehicles to the market on the basis of (expected) market demand and competition. Customers have been increasingly concerned with climate action, further incentivising OEMs to develop vehicle technologies that are aligned with the demand. Nevertheless, given that customers prefer having choice in their vehicle options and want to avoid lock-in into a specific option, it is difficult for OEMs to be the sole supplier of a certain vehicle technology. Therefore, OEMs focus on limited options for the European market. Fuel efficiency, price of the vehicle along with the ability to drive long distance and refuelling opportunities along the way are other important factors influencing customers' vehicle preference or choice. Currently, the price of electric vehicles is still higher than that of internal combustion engines vehicles, making the choice for combustion ignition engines more favourable in the short term, even if the total costs of ownership are attractive in the long term. In addition, after 5 to 8 years of service, vehicles must be able to cascade to second-hand market, often sold onwards to eastern and southern European markets. As a result, in literature and interviews we observe a consolidation in the technologies that OEMs provide to the market, dominated by compression-ignition diesel engines.

On the vehicle side, the barriers to enabling higher blends of renewable fuels in heavy-duty vehicles are thus as follows:

- A focus on tail-pipe emissions (tank-to-wheel) pushes carbon containing renewable fuel options out of scope and disregards their potential to deliver significant greenhouse gas emission reductions on well-to-wheel basis.
- Ambitious targets and stringent European emission regulations have led manufacturers to drop many of the options that were once considered, and to focus mainly on the development of battery electric vehicles.
- Policy and regulation is less supportive of renewable fuels. Crop-based and waste-based biofuels are capped, advanced biofuels are subject to limited feedstock options, e-fuels face complex regulation on the sourcing of renewable hydrogen and of carbon dioxide.
- Even if manufacturers had sufficient time and resources to develop vehicles for specific renewable fuels options, the room to market such vehicles becomes limited due to the (near) phase out of internal combustion engine heavy-duty vehicle sales by 2040.

Therefore, manufacturers focus their development efforts to engines that build on existing engine technology. This results in a smaller range of engines that are compatible with renewable fuel options than what was expected a decade ago.

4.2 Adaptation of existing internal combustion engines for higher fuel blends comes with (non-technical) challenges

The near-term heavy-duty vehicle market, as a combination of the current fleets and what can be expected in the coming years, is thus dominated by compression ignition diesel engines. Renewable fuel solutions that (after limited adaptations) work in these engines are better positioned than solutions that require new drivetrains or significant adaptations.

The technical aspects of retrofit options were alluded to in Section 3.2 and are covered in per fuel in Annex C. Aside from the technical aspects, there are other challenges:

- Warranty: The manufacturer warrants a performance provided that the vehicle is operated according to prescribed conditions, including a specification of the fuels that are used. Any retrofit of the vehicle, and even a different fuel use without vehicle adaptations, in principle voids the warrant.
- Certification: Vehicles are guaranteed to perform according to strict safety and emission standards. They are allowed to drive on the road after a lengthy and costly official certification procedure. If a vehicle is retrofitted, or even when a different fuel is being used outside the options for which it was certified, then basically, the vehicle would need to be re-certified. Non-certified use is illegal.
- Communication: Fleet owners may not understand all the options that they can choose from. Certainly, it is difficult to understand the total costs of ownership for the various options, and how these could be impacted by developments of market prices and support policies.

- Maintenance and other downtime: some options require more frequent maintenance. For other options, the fuelling may require additional (safety) measures. This can imply an investment in time and people (which should also be considered in the total costs of ownership).

Engine adaptation is a cost-effective intervention with a high potential, however a number of challenges must be considered.

In first instance, engine adaptations can be expensive if carried out on a restricted number of vehicles. But when done on fleets via standardised processes, the costs can drop to several thousand euro per vehicle, which is negligible compared to fuel costs and (as an investment) to a switch to electric vehicles.

Adaptions of vehicles further require recertification which necessitates their testing in specialised facilities to ensure the emissions requirements are met. Although the complete testing of a single vehicle is time intensive, and expensive. In principle the full vehicle must be recertified, and every vehicle may be different. It should be explored if group re-certification of adaptations for certain engine groups or engine types could be accepted. The main requirement (with regard to local emissions) is that the vehicle, after the retrofit, does not perform worse than before.

Another challenge relates to the hesitance from the side of manufacturers and possible warranties issues. They do not want to or cannot take responsibility for the changes. Loss of warranty will also impact insurance costs.

Another barrier to drive the acceptance of engine adaptation relates to the need to provide guidelines and explanations on the benefits of such intervention to stakeholders. Strong communication efforts will be required to convince stakeholders such as manufacturers, fleet owners, and drivers on the performance aspects, environmental impact and savings. Building a skilled task force to manage these adaptations, certifications and outreach is essential to overcome these bottlenecks. Garage and fleet owners play a pivotal role here, as they can undertake these modifications with the support of skilled technicians.

Programs like France's initiatives to stimulate E85 adaptation kits for passenger vehicles provide a blueprint for incentivizing and facilitating these adaptations. The tool kit is a simple tool recognised by the French government which allows the modification of engines to run on E85 or neat gasoline or any in-between blend. The vehicle warranty is taken over by the kit installer.[42] In addition the French government arranged a lower taxation of ethanol, which makes the price attractive to consumers.[43] The deployment of such intervention on a national level could enable higher blends of renewable fuels.

4.3 Fostering innovation, cooperation between sectors and consumer engagement to enable higher blends of renewable fuels

The introduction of a new (separate) Emissions Trading System (EU ETS 2), will increasingly restrict the volume of fossil fuels that fuel suppliers can deliver to the road sector (combined with small industry and buildings) from 2027 onwards, and may demand during the 2030s a renewable fuel volume two to three times more than today.[44] This implies that the European

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[42] The program is explained for instance by producers association bioethanol [Website bioéthanol, Superethanol-E85: the first E85 conversion box is approved for cleaner, greener, cheaper driving]. Several companies offer the fast installation of E85 kits in cars, for just several hundred euro per installation [for instance see website of EcoFuelBox].

[43] ePURE shows how the lower taxation of bioethanol leads to lower fuel prices at French gas stations [ePURE 2020, E85 – an ethanol blend to fuel Europe's clean mobility].

[44] The EU Emissions Trading System ETS was amended in 2023 to amongst others establish a second, parallel system, called ETS 2, for emissions from buildings, road transport and smaller industry [EU 2023, Directive (EU)2023/959 amending the ETS]. The ETS 2 demands a linear decrease of emissions from three sectors collectively: road transport, buildings and small industry. It effectively points to zero emissions in 2043. If the three sectors reduce their emissions in the same tempo, this implies that an increasing share of the (remaining) this

renewable fuels production capacity requires a significant ramp up.[45] This gives rise to new economic opportunities and innovations for new industry players who can pave the way towards a fossil free society.

However, after that period, the fuel demand is foreseen to decrease, when electric vehicles replace internal combustion engine vehicles at an increasing pace. The temporary high demand (between 2030 and 2040 mainly) presents challenges for making a business case to invest in scaling up renewable fuel production capacity, which would require short payback times, or smart follow-up or exit strategies.

For instance, fuels developed for road transport may find application in aviation or maritime (directly, or after applying a subsequent conversion step), while technology pathways and feedstocks can also play a role in the biobased economy.

Policies related to climate action in transport specifically ask for advanced and therefore more costly renewable fuels: e-fuels, with very strict requirements on the sourcing of both the hydrogen and CO_2 that are required for e-fuel production,[46] and advanced biofuels, to be produced via technologies that are not mature today.[47]

The perception that renewable fuels in heavy-duty vehicles are only a temporarily necessary option complicates investment decisions, as investors hesitate to commit resources to a solution with an uncertain long-term role. The link between these biofuels and the other markets (for their feedstocks, intermediate and final products as well as for their conversion technologies, could derisk investments. For instance, renewable fuels play a crucial role in the de-fossilisation of the maritime and aviation sectors as well as in the transition for the chemical industry.

Another challenge relates to the supply of feedstocks for renewable fuels. The security of supply of certain currently important feedstock is not guaranteed. For instance, used cooking oil is currently imported from Asia at a significant scale, but the countries of origin may want to keep it for their own energy and material security, or the EU may restrict the imports due to concerns about the origin of that feedstock. Geopolitical uncertainties increase the risks. Risks can be decreased by way of diversification of feedstocks and their origin countries.

Thus, the combination of potentially a brief market window between 2030 and 2040 and strict requirements on feedstocks and technologies, inhibits investments in renewable fuels production capacity. Investors need both market and policy certainty. If investments in renewable fuels production do not take-off in Europe over the coming years, then the future EU demand for renewable fuels may largely depend on imports and overseas investments.

To spur investments may require a combination of a realistic outlook on the development of the market for renewable fuels: the increasing demand in road transport, the decrease, and the follow-up markets. In view of the regulatory barriers to some types of renewable fuels it may help to report in a transparent way about the sustainability, and steer on performance of individual supply chains rather than on feedstock categories or conversion pathways.

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likely requires a sharp increase in the demand for renewable fuels for transport between 2030 and 2040. As an increasing share of the fleet is becoming electric, the total demand for fuels decreases sharply from 2040 onwards [studio Gear Up 2021, The role of biodiesel in EU climate action – input for EBB roadmap to 2030 and 2050].

[45] According to Eurostat, the current EU production capacity in 2023 was 21.4 Mtonne “biodiesel” (FAME+HVO), 6.6 Mtonne “biogasoline” (bioethanol), 0.3 Mtonne biojet, and 6.7 Mtonne “other liquid biofuels” [Eurostat nrg_inf_lbpc on Liquid biofuels production capacities]. The total EU production of biodiesel was about 21 Mtonne, and of ethanol was about 4 Mtonne according to USDA FAS [USDA FAS 2024, EU Biofuels annual 2023]. This implies a small overcapacity. A 2 to 3-fold production increase requires a ramp-up of production capacity.

[46] The production of renewable hydrogen and e-fuels must meet the rules laid out by the European Commission on the production of RFNBOs [EC Delegated Regulation (EU) 2023/1184].

[47] As explained in more detail in the Annex of this report, the Renewable Energy Directive caps the contribution of crop-based biofuels and of some waste-based biofuels. It includes a subtarget for biofuels produced via advanced conversion technologies, from a limited list of feedstocks [amended Directive (EU) 2018/2001].

4.4 Adequate fuelling infrastructure is essential to the adoption of higher blends of renewable fuels

The use of high blends of renewable fuels in heavy duty vehicles requires adequate supply and fuelling infrastructure. The renewable fuels discussed can be distributed to fleet depots and gas stations by tank trucks – this step will for most fuels not be problematic as tank trucks for the safe transport of many goods exist. The transport of ammonia, including its loading and unloading, requires specific safety precautions due to its toxic nature.[48]

At the fleet depot or gas station, fuels that closely resemble diesel can be stored in the existing storage tanks and distributed via the standard dispensers. Also, LPG, LNG and CNG are already distributed and dispensed via (some) existing gas stations and fleet depots.

But other options generally require some additional measures. For instance, FAME biodiesel at high blends and 100% can age and oxidise, which can lead to high viscosity and the formation of gums and sediments that clog filters. This process is accelerated by the presence of oxygen and certain metals, and sunlight, while the viscosity effect is most felt at lower temperatures. Aside from measures to slow down the oxidation, the storage facilities may also require extra tests on a regular basis.[49] Storage of methanol requires additional safety precautions (in-tank vapor control to avoid ignition), and cathodic protection and regular control of metal tanks to avoid corrosion.[50] Storage of DME is similar to LPG, in pressurised storage tanks.[51] Storage of ammonia is deemed to be safe, if strict safety precautions are taken. This would imply underground, refrigerated storage in double-walled tanks, and a distance of 120-400 m from residential areas or areas otherwise frequented by the general public,[52] which renders it unsuitable for distribution by public gas stations, but which could be facilitated at fleet depots. Hydrogen already is stored at publicly accessible gas stations, and this will increase amongst others driven by the Alternative Fuels Infrastructure Regulation.[53]

The existing storage options at gas stations and fleet depots is usually limited. In some cases, an alternative fuel may replace an existing fuel, requiring certain adaptations to the existing storage tanks (as noted above). If the renewable fuel would be an additional option to the fuels already present, then new storage is needed. This is not always possible as space may be limited. The fuels that require significant safety measures due to explosion and toxicity risks, are stored on a safe distance from the forecourt. Many gas stations do not have the space to accommodate for this.

Finally, the dispensing of alternative fuels into the vehicles also often requires new pumps and nozzles.

Overall, the deployment of new fuelling infrastructure is costly and requires significant planning, and the options per gas station are limited: not all options are possible, and a choice must be made between the possible options. Only in some (limited) cases, multifuel options may be considered.

Clearly, the fungibility of drop-in synthetic renewable diesel, bioLNG/CNG and LPG with existing infrastructure facilitates their deployment. For other fuels, parts of the fuelling infrastructure would have to be adapted or developed as discussed above. Lack of supply infrastructure will hamper the deployment of renewable options. Especially when targeting long distance transport (which is likely the case, as urban and rural transport will increasingly be electrified), the availability of a renewable fuel along "corridors" across Europe will be essential for its successful deployment.

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[48] [For instance, see Schenk Transport, website blog A complete guide to transporting ammonia].

[49] [USDOE 2023, Biodiesel Handling and Use Guide (Fifth Edition)].

[50] [Methanol Institute 2016, Atmospheric above ground tank storage of methanol].

[51] [USDOE, website Alternative Fuels Data Center: Dimethyl Ether].

[52] [Risø 2005, Safety assessment of ammonia as a transport fuel].

[53] The Alternative Fuel Infrastructure Regulation (AFIR) requires an increasing availability of hydrogen across the main roads in Europe [Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure].

5 Recommendations

In the coming decade, the diesel engine is still dominant in heavy-duty road transport. The strong emission reduction required by amongst others the EU ETS 2 and Dutch national legislation means that an increasingly high level of renewable fuels will have to be deployed in especially those diesel engines. We foresee the following options as most important:

1. Options that are prominent today will play an important role still in 2030-2040. For FAME biodiesel, the full available space within the specifications should be used. This is currently 7% by volume and in some Member States 10% by volume. This space is not yet exhausted with the current mandates.
2. Further increase with HVO as a drop-in fuel as far as is possible. This is likely limited by feedstock supply: waste oils are ultimately limited in volume, but also subject to international supply risks. Most crop oils are limited by legislative caps. Some crop oils are not capped and have a potential for growth (for instance on degraded land, or when grown as catch or cover crops), but their production is (still) limited.
3. Apply biomethane to the maximum in the existing CNG and LNG vehicles, and in hydrogen prepared HPDI vehicles. This seems a cost-effective option, but the number of vehicles is limited because fleet owners see a high price of natural gas. However, on basis of total cost of ownership, 100% biomethane is cost attractive compared to other 100% renewable fuel-engine combinations.
4. Top the drop-in option in the existing diesel engines with renewable synthetic diesel (XTL labeled), which can be produced via a variety of advanced conversion pathways. This requires significant investments in production capacity. Some pathways partly link to existing refinery capacity (HPO and MtD), or link to SAF and biobased materials via the gasification platform (FT).
5. A share of methanol or DME in existing diesel engines, since these fuels can be used in maritime, and methanol is a main platform chemical that will find a larger market. Engine technologies exist for heavy-duty trucks, but their introduction is facing market and regulatory barriers.

The retrofitting of existing vehicles is another viable option to enable higher blends, and likely faster than the introduction of “new” engines to the market. The costs are usually acceptable, but challenges exist with regard to the loss of warranty and the obligatory recertification of adapted vehicles. Also, vehicle adaptation should be supported by education of drivers and fleet owners on the use of renewable fuels.

5.1 Support the production scale-up of drop-in renewable diesel

Synthetic renewable diesels (labelled as XTL) are commercially available and can be used in high blends in heavy-duty vehicles without any engine adaptations, as accepted by vehicle manufacturers, and meeting emission standards. Barriers to the scale-up of such options are mostly relating to the availability of the fuels and their feedstocks (in the case of HVO from waste lipids), and the production costs when produced via advanced conversion pathways.

The production of advanced biofuels from cellulose biomass (for instance via gasification and Fischer-Tropsch synthesis, via Methanol-to-Diesel, or via hydrogenation of pyrolysis oil) requires a high investment. The investment can be derisked by considering that pathways can produce multiple products for multiple sectors.

With regards to the small portion of LNG, CNG and LPG vehicles driving on the Dutch roads, the transition to the use of renewable methane and renewable LPG as drop-in is already possible. The adoption of such fuels could be further incentivised by the government by providing tax benefits.

5.2 Support vehicle retrofitting for higher blends of renewable fuels

Engine adaption in the existing fleet is a cheap solution, investment-wise, to introduce higher blends of renewable fuels for heavy-duty transport. Retrofits can be arranged in cooperation with truck service points that (could) specialise in such retrofitting. The main challenges are non-technical.

Retrofitting engines must be re-certified to ensure that vehicles are meeting the required safety and emission standards. For a single vehicle, or a single fleet owner this is a significant barrier (in terms of both cost and time). Recertification may become more attractive when adaptations are made for a larger portion of vehicles, and if groupwise re-certification is possible.

Another challenge is associated with the warranty of the vehicles. As manufacturers do not want to take the responsibility that their vehicle may no longer meet certain standards, or that the performance is as originally guaranteed, measures have to be put in place to address these concerns. Here, the introduction of E85 conversion kits in France could serve as an example, where the manufacturer's warranty is taken over by a different organisation.

Currently, the main barrier to adaptation, and to the deployment of renewable fuels in general, is the higher costs compared with fossil diesel. When mandates and decreasing ETS 2 emission ceilings force the deployment of increasing renewable fuel volumes, the warranty and re-certification barriers become more prominent. It is advised to solve these, so that the market sees more options to incorporate renewable fuels, outside the drop-in options.

5.3 Increase awareness and trust

Enabling higher blends of renewable fuels also requires communication efforts to inform fleet owners on costs (initial investment, cost of ownership), practical consequences (requirements to drivers, safety aspects, maintenance downtimes) and sustainability aspects (well-to-wheel greenhouse gas savings and transparency on the feedstock-to-fuel supply chain).

Fleet owners will like to ensure that they can not only use the vehicle for the present purpose, but also that they can resell it elsewhere after a while.

When targeting long distance transport, the availability of a renewable fuel along "corridors" across Europe will be essential for its successful deployment.

Annex A Consulted stakeholders

Table 2. List of stakeholders consulted by way of interviews.

Name	Company / Organization	Topic addressed
Adriano Cordisco	ReFuel Solutions	Market solution for biodiesel
Alexander Wijn	DAF Trucks	OEM perspective on fuel and engine market development and barriers
Bart Somers	Technical University of Eindhoven	Perspective on fuel and engine developments
Bas ten Broeke	Westport Fuel Systems	High Pressure Direct Injection (HPDI)
Bas ter Horst	HAN University of Applied Sciences	Technological developments for fuel and engines
Harmen Huiskens	Finco Energies	Perspective on fuel developments
Jan Schouten	Volvo	OEM perspective on fuel and engine market development and barriers
Jim Looise	Finco Energies	Perspective on fuel developments
Kai Zhao	Methanol Institute	Perspective on fuel and engine developments with a focus on methanol and China
Lars Mårtensson	Volvo	OEM perspective on fuel and engine market development and barriers
Luc Vinckx	Advisor on regulatory affairs related to fuel and engine standards	Regulatory barriers and after-market adaptation
Marc Feijen and Rishwen Chander	Netherlands Vehicle Authority (Rijksdienst voor het wegverkeer, RDW)	Regulatory perspective on vehicle certification and meeting standards
Michel Voorwinde	Dutch trade association for mobility BOVAG	Options for engine adaptation and higher blends
Ortwin Costenoble	PAC – AC Analytical Controls (previously employed with NEN)	Fuel specifications and standardization
Peter van Gompel	TNO (Dutch applied science and technology research organization)	Engine development and adaptations
Prof. Thomas Willner	Hamburg University of Applied Sciences	Market development with a focus on Germany
Valerie Corre	Tereos	Market development with a focus on France and ED95

Annex B Basics of internal combustion engines

Basics

To understand the options and limitations of engine-fuel combinations considered in this report, it is useful to have a basic understanding of how internal combustion engines work. There are many detailed descriptions in the public domain, we only provide a summary here.[54]

There are two main types of internal combustion engines as displayed in Figure A-1.

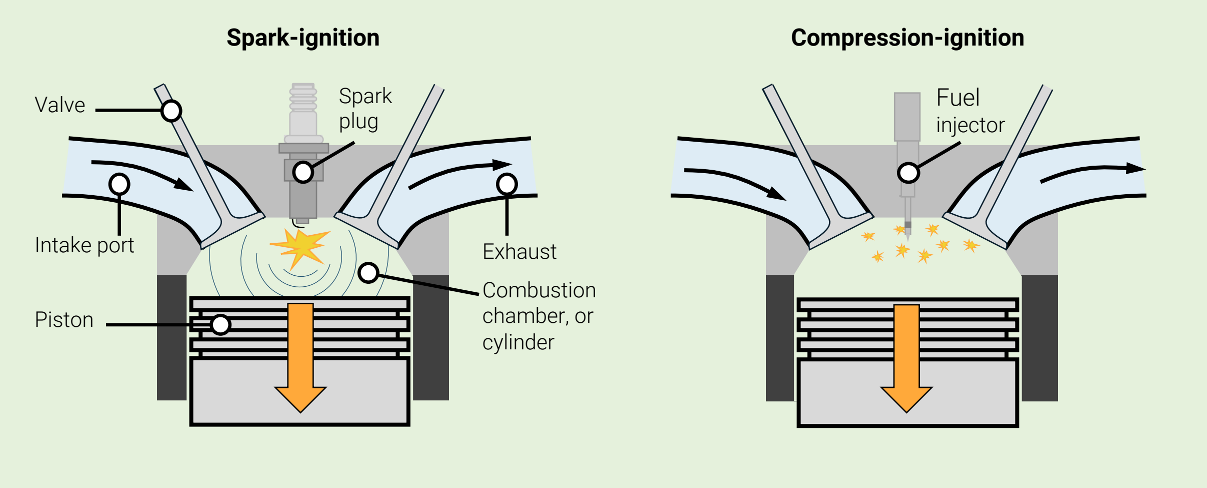

Figure A-1. Spark-ignition engine (left) and compression-ignition engine (right). In the spark-ignition engine, the compressed fuel-air mixture is ignited by a spark plug: the ignition begins in a single point and the flame front propagates as a wave through the chamber. The combustion of the fuel generates heat which strongly increases the pressure that drives the piston down and turns the crank. In the compression-ignition engine only air is compressed, which increases the air temperature. When the diesel fuel is injected into this hot air, it auto-ignites and starts combusting. Instead of traveling through the cylinder, the flame stays located around the usually multiple jets which are injected.

Spark-ignition engines currently mainly run on gasoline. They are typically used for light and medium duty vehicles, like passenger cars and vans, although these vehicles also have compression-ignition engines in some cases.

Compression-ignition engines currently mainly run on diesel. They are typically used for heavy duty vehicles, like trucks and buses, although they are also applied in passenger cars.

The choice for a spark-ignition or compression-ignition engine depends mainly on the application. Diesel engines have a 20-30% higher fuel efficiency, can deliver more power (torque) which allows to carry heavier loads, have a longer lifespan (although this results from their design focus on durability), and often the diesel fuel is cheaper than gasoline (although that is mainly dependent on politically informed excise levels). On the other hand, the diesel technology is more expensive, typically has higher NO_x and PM emissions (but which can be reduced by exhaust gas treatment[55]), makes more noise, and can be harder to start in cold weather.

Since, in this report, we focus on heavy-duty performance, we mainly consider the compression-ignition engine. Nevertheless, we discuss the spark-ignition engine as well, since some renewable fuels may be introduced via that option.

Most commonly, both types are designed with four strokes in a cycle:

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[54] [Encyclopedia Brittanica 2024, Diesel Engine].

[55] Exhaust gas treatment systems refer to the reduction of pollutants and emissions released from the exhaust of vehicles, using methods such as: selective catalyst reduction (SCR) and diesel particulate filters (DPF) [Bao et al 2022, Exhaust Gas After-Treatment Systems for Gasoline and Diesel Vehicles. International Journal of Automotive Manufacturing and Materials].

- Intake: the piston moves down, and the intake valve opens. It lets in air, or a mixture of fuel and air.
- Compression: the piston moves up and compresses the air-fuel mixture. In case of direct injection (see next paragraph), the fuel is injected during this phase.
- Combustion: the fuel combusts through spark-ignition or auto-ignition, which pushes the piston down again.
- Exhaust: the piston moves up and the exhaust valve opens to let the combusted gas out.

During the four strokes, the crank is thus rotated two times. Engines can be designed with more or less strokes. Two-stroke engines are used in motorcycles and large shipping engines.

Direct fuel injection in compression-ignition engines

The combustion of fuels in a compression-ignition engine is controlled by the fuel injection. Injection is the process of introducing the fuel, so to get a combustible air-fuel mixture.

Direct injection (DI) is the most common in modern compression-ignition engines. The fuel is injected directly into the combustion chamber, at a high pressure, resulting in better fuel atomization and more efficient combustion. Direct injection makes it possible to use the injection-timing to control the timing of the combustion process. Both too early and too late combustion would result in lower efficiency, higher emissions, and the risk of engine damage.

The exact location and working of the fuel injection is fundamental in the design of the engine, as it influences performance (power), efficiency (fuel use per delivered work), emissions and maintenance.

Direct injectors (in diesel) usually achieve pressures of around 2,000 bar, to guarantee a good evaporation of the fuel. For good controllability they have to open and close fast and precisely in a very short time (<2 milliseconds). Their tips have to withstand harsh conditions in the combustion chamber. Also, direct injection needs parts outside the engine, especially a high-pressure pump, which sends the high-pressure fuel via a fuel rail to all the injectors (of all the cylinders). All these high precision parts require a clean and well lubricating fuel, which is a point of attention when alternative fuels are used.

In short, the fuel injection technology is central in the research on compression-ignition engines.

High-pressure direct injection

A special form of direct injection, high-pressure direct injection (HPDI), has been developed in the past decade, to enable the use of alternative fuels in compression-ignition engines. The injector is designed such that it can inject two fuels via a single injector. This allows a diffusive (diesel-like) combustion.

High pressure direct injectors achieve a pressure of 3,000-5000 bar or more, which is much higher than common direct injectors. This improves the fuel atomization during the delivery in the combustion chamber, which in turn increases the fuel efficiency. It also allows for higher compression ratios in the engine, which also increases the fuel efficiency.[56]

HPDI allows to use existing compression-ignition engine architecture to operate with a variety of alternative fuels, including (bio)methane (in the form of LNG mainly, see Annex C.7) and hydrogen (C.9).

HPDI engines are currently typically designed to run mainly on natural gas (or renewable variants such as biomethane or e-methane) in a dual fuel set-up with diesel as a pilot fuel. Only a small amount of diesel (about 5% of the total fuel volume) is still required to ignite the natural gas, as a "liquid spark plug", because the natural gas has a high auto-ignition temperature that cannot be achieved by compression alone. This pilot fuel can also be an alternative diesel-type fuel, such as HVO, FAME or e-diesel. Note that these engines are not

[56] The compression ratio is the ratio between the largest and the smallest volume of gas in the combustion chamber during a cycle. If this ratio is larger, then effectively more power is transferred to the piston and to the crank.

designed to run on diesel only, as the compression ratio is too high.[57] Consequently, the diesel injector does not have the full capacity anymore, for a diesel-only operation. This means that these engines cannot be operated with complete flexibility, switching between pure diesel or pure gas.

These injectors typically have a concentric needle that allows the injection of two fuels independent of each other. First, the small amount of diesel is injected. This injection takes place near the end of the compression stroke, just before the piston reaches the top-dead-centre position (since it is only a small amount of diesel, this hardly increases the pressure and does not slow down the piston). When the diesel ignites, the second fuel is injected (in a larger quantity) at the top-dead-centre position, to provide the most optimal boost to the piston.

The best injection strategy for dual fuels in an HPDI set-up is subject to much research.[58]

Other strategies for dual fuel gas-diesel operation

Heavy duty vehicles can also drive on natural gas without the HPDI system. Other options exist, some of which may be useful for adapting existing engines to run on diesel / gas blends:[59]

- Conventional dual fuel (CDF) combustion uses an early port injection of a low reactivity fuel (such as natural gas or methanol) during the intake stroke, followed by a diesel direct injection near top-dead-centre. The natural gas in this case well distributed in the cylinder, and the small amount of pilot diesel fuel ignites the combustion. This approach was mainly used throughout the 1990s.
- Reactivity controlled compression-ignition (RCCI) is being researched since 2011. Also here, the main and lower reactive fuel (usually natural gas) is introduced during the intake stroke by way of port fuel injection. Almost at the end of the compression stroke, a second fuel with a high reactivity (diesel) is direct injected in the cylinder as a pilot fuel to ignite the combustion. Besides (renewable) natural gas, many other alternative fuels may be used as main fuel, such as hydrogen, LPG, ethanol, methanol, butanol, or ammonia.[60] The engine cold starts in diesel only mode (direct injection only), and after 10 seconds switches to RCCI mode. Contrary to HPDI, the engine can also run on diesel only (if the alternative fuel is not present) because the compression ratio is the same as for normal DI engines, and on any blend of the two fuels. However, the engine is currently still less efficient than HPDI when running on natural gas or hydrogen, and initial emissions (before exhaust gas treatment) are still higher. RCCI is still in research phase and not (yet) implemented by OEMs.
- In Partially premixed charge compression ignition (PCCI), a significant part of the fuel is pre-mixed (diesel + natural gas) and injected before the top-dead-centre position of the piston, and a final pilot amount is injected at the top-dead-centre to ignite the fuel mix. The concept was first published in 2017, and is still in the research phase. This technology may allow more efficient combustion and lower emissions, while keeping flexibility in the

[57] Running HPDI engines on diesel only is theoretically possible. However, this would have significant challenges (higher flame temperatures would require additional cooling; more fouling occurs due to lack of gaseous fuels cleaning effect), it would not have any advantages over common rail diesel injection systems which offers simpler and more reliable performance for diesel only, while it is more expensive, and since it is optimised for gaseous fuels, it would lead to less efficient combustion of diesel compared to systems specifically designed for diesel (website Alternative Fuel Vehicle Institute AFVi, Understanding HPDI Natural Gas Fuel Systems).

[58] [Wang et al 2024, Diesel-natural gas dual fuel injection strategy effects on engine ignition delay and cylinder pressure evolution, Case Studies in Thermal Engineering 53(2024):103795].

[59] [Hall 2021, Advances in combustion control for natural gas-diesel dual fuel compression ignition engines in automotive applications: A Review].

[60] [Gharehlar et al 2024, Hydrogen/diesel RCCI engine performance assessment at low load, International Journal of Hydrogen Energy, 58: 200-209 | ArenaRed website item RCCI – Reactivity controlled compression ignition and presentation].

blend ratio of two fuels. However, combustion control is still challenging and must be further improved.[61]

RCCI can be regarded as an improved version of CDF, where RCCI is completely electronically controlled (which was not possible in the 1990s for CDF). This implies amongst others that the air-fuel ratio of the main fuel can be carefully controlled, the fuel mix is more homogeneous. In CDF, the combustion was uneven and led to higher emissions of NO_x and PM, while these emissions are expected to be ultra-low in RCCI.[62]

CDF (and RCCI when introduced) is an interesting option for retrofitting existing vehicles.[63] It would allow vehicles to run on any blend of the alternative fuel and diesel fuel.

Options with spark-ignition engines

For natural gas engines, spark-ignited systems are by far the most numerous, and account for more than 90% of the gas-engine market in road transport. Since the combustion is initiated by a spark, no pilot fuel is needed. They are usually applied for medium and light duty vehicles, but increasingly also used in heavy duty vehicles. Spark-ignition for heavy-duty has a higher cylinder pressure, to produce more power and torque. Vice versa, when spark-ignition is applied in heavy-duty transport, this is mainly to enable driving on (renewable) natural gas. Or, in other words, such vehicles primarily already drive on natural gas. Note that these vehicles mainly find local applications (urban trucks, waste collection trucks). For long haul, the more efficient and more powerful compression ignition engine remains preferred.

Achieving high performance through engine optimisation

To achieve high performance when running on renewable fuel, the engine must be optimised specifically to the properties of the fuel. This means engine valve timings may have to be modified, which requires new design developments of camshafts (which is the part of the engine which open and closes the valves to let the air-fuel mixture in and out of the combustion chamber).[64] These modification apply to a variety of renewable fuels that are address in this report, in addition to the adaptations that are detailed in Annex C.

[61] [Jain et al 2017, Effect of fuel injection parameters on combustion stability and emissions of a mineral diesel fueled partially premixed charge compression ignition (PCCI) engine, Applied Energy 190:658-669].

[62] [Reitz and Duraisamy 2015, Review of high efficiency and clean reactivity-controlled compression ignition (RCCI) combustion in internal combustion engines, Progress in Energy and Combustion Science 46:12-71].

[63] [Chojnowski and Karczewski 2022, Analysis of the market structure of long-distance transport vehicles in the context of retrofitting diesel engines with modern dual-fuel systems, Combustion Engines 188(1):13-17].

[64] [Gautam 2022, Replacement of Diesel Fuel by DME in Compression Ignition Engines: Case for India, in: Diesel Engines and Biodiesel Engines Technologies, IntechOpen].

Annex C Alternative fuels

This section of the Annex explores various alternative fuel options that could be used to achieve a reduction in greenhouse gas emissions to meet the targets set out in the transport sector. First an overview of the legislative categories of these renewable fuels is provided in Annex C.1. The remaining sections explore these alternative renewable fuel options in more detail, including specific fuel characteristics, the engine requirements for these fuel options and specific barriers to increasing volumes of these fuels used in the market.

C.1 Legislative categories of renewable fuels

EU and Dutch legislation distinguish several types of renewable fuels:

- Biofuels based on "food and feed crops". The name is a bit confusing, since their potential application for food or feed is not relevant, and edibility is also not important in the legal definition of this category. In this category of fuels, the feedstock is defined as (1) sugar, starch or oil containing, (2) grown as a main crop, and (3) on agricultural land. Feedstock that does not meet one of these three requirements is not a food and feed crop. Examples of typical food and feed crops are soybean and sunflower (which can be used for FAME or HVO production, see Annex C.2 and Annex C.3), sugar beet, sugar cane and maize (for ethanol production, see D.10). The legislation caps the use of fuels based on these feedstocks, in fulfilling the targets of the Renewable Energy Directive (EU) 2018/2001 (known as the "RED II"). In the Netherlands a contribution of only 1.4% of these fuels is allowed for the "jaarverplichting".
- Annex IX A feedstock, the Directive sometimes calls these advanced biofuels, although not all the feedstock on this list would require an advanced conversion technology. The RED II and the proposal for the RED III set sub targets for this category.
- Annex IX B feedstock, these are waste and residues that can be converted with mature technologies, for instance used cooking oil and animal fat. Their contribution to achieving the RED II is also capped. In the Netherlands, the contribution of these fuels to the "jaarverplichting" is maximally 10%.
- Renewable Fuels of Non-Biological Origin (RFNBOs) are often known as e-fuels. Typically, they are produced from renewable hydrogen, which in turn is produced by electrolysis of water, using renewable electricity. Often the hydrogen is combined with CO2, which then has to comply with strict rulesets.[65] These fuels concern derivatives of hydrogen, including fuels such as methanol.
- Recycled carbon fuels (RCFs) were introduced in the RED II. These are non-renewable fuels, produced from fossil waste streams (for instance from steel waste gas, or tyres). There is currently no sub target for this category of fuel, the greenhouse gas emission and the calculation methodology is somewhat disadvantageous for RCFs. These fuels do not count to the overall renewable energy target for the Member State nor do they count towards the Dutch national annual obligation.

C.2 Fatty Acid Methyl Esters (FAME)

Fatty Acid Methyl Ester (FAME) is commonly referred to as "biodiesel". It is usually produced from vegetable oils or animal fats. In Europe. It is the most common of the renewable fuel options available on the market today.

Production and feedstocks

FAME biodiesel is produced through a "transesterification" process. In this process, the feedstock which consists of (tri)glycerides and fatty acids are reacted with methanol (about 10% on mass basis) in presence of a catalyst (usually sodium or potassium hydroxide). The product is a methyl ester. This is basically a long hydrocarbon chain (typically 12-20 carbon atoms). The production technology for FAME is relatively simple, which leads to relatively

[65] These eligible CO_2 sources are mentioned in European Commission Delegated Regulation (EU) 2023/1185: Greenhouse gas methodology for RFNBOs and RCFs.

low production costs, and which allowed a large production capacity increase, especially during the 2000 – 2010 period.

Typical feedstocks for FAME are oil crops (rapeseed oil predominantly, furthermore soybean oil, sunflower oil), and waste oils such as mainly used cooking oil, further animal fat, and a smaller volume of a wide variety of waste streams that emerge from oleochemical industry.

Note that the use of food and feed crop-based feedstocks is capped under the Renewable Energy Directive. Only the use of crops produced on non-agricultural land (for instance abandoned or degraded land), or produced not as the main crop (for instance as a sequential crop), is not limited by the directive (see Annex C.1).

Waste oils are ultimately limited in their volumes. Currently, a large part of the used cooking oil in FAME and in HVO biodiesel in the EU market stems from Asia, currently in particular from China, Vietnam and Indonesia. Asian countries may restrict their exports to the EU as they increasingly would use the feedstock for their national biofuel production and use.

Note that FAME uses largely the same feedstocks as HVO (see Annex C.2). Only, when used in FAME the use of some feedstocks is technically a bit more restricted by the final use. For use in low blends in diesel, all the feedstocks can be used. For use in high blends in approved vehicles (see next paragraph), the feedstock is more restricted by the EN14214 quality standard and would require a larger share of rapeseed feedstock, which is usually a food and feed crop, and hence its contribution to achieving Dutch targets is capped.

Fuel properties and challenges

FAME biodiesel can (in principle) be used in diesel engines, but the chemical properties are slightly different to that of a conventional diesel. Therefore, it does not behave in the same way as conventional fossil diesel in typical engines.

One concern of using FAME in regular diesel engines is the viscosity of the fuel, which increases with decreasing temperature. This can result in issues when using FAME at cold temperatures. These "cold flow properties" can affect whether the fuel is safe to use during colder seasons of the year. The Cold Filter Plugging Point (CFPP) is known as the temperature at which crystals form in the fuel which can cause a test filter to plug. At cold temperatures, FAME can freeze or gel, which can clog the vehicle filters or prevent the fuel from being pumped. This can prevent the vehicle from operating[66].

Furthermore, when running on FAME in diesel engines, metals may accumulate in the catalyst. This can poison the catalyst and brings down the efficiency of the vehicle. As a result, when running a vehicle on high blends of FAME, this can require more frequent maintenance intervals, such as, Exhaust Gas Recirculation (EGR).

Finally, FAME can present a risk on the durability of engines. This is because can result in forming sludge which can plug diesel particulate filters (DPF). Furthermore, FAME has a high boiling point, which can result in fuel condensation on the cylinder walls when fuel is injected late. This can lead to engine deposits and increased exhaust emissions.[67] However, research shows that, overall, the higher application of FAME can even reduce the volume of exhaust emissions (PM) and reduce the frequency of DPF regenerations.[68]

In summary, operating on FAME can present challenges that must be addressed. This can demand more frequent maintenance intervals and requires aftertreatment systems. Modern vehicles often utilise aftertreatment systems to reduce harmful exhausted emissions. For example, Selective Catalytic Reduction (SCR), Diesel Particulate Filters (DPF) and Exhaust Gas Recirculation (EGR).[69] At high blend applications of FAME, new market solutions present

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[66] [McGill et all 2008, Final Report Annex XXXIV: Biomass-Derived Diesel Fuels Task 1: Analysis of Biodiesel Options].

[67] [Website IEA Advanced Motor Fuels, Compatibility: how much FAME biodiesel can be blended in diesel fuel?]

[68] [Concawe 2016, Impact of FAME Content on the Regeneration Frequency of Diesel Particulate Filters (DPF)].

[69] [IEA AMF 2021, Heavy duty vehicles performance evaluation].

possible adaptive measures, which could be applied to achieve higher blend applications (see the next subsection).

Adaptations to existing engines to permit high blends of FAME

The technical barriers associated with high blend applications of FAME could also be addressed through special adaptive measures to accommodate for the fuels use in typical diesel engines. For example, the installation of a "bio-diesel kit" which ensures the compatibility of even pure FAME (B100) applications in conventional diesel engines with even the lowest quality standards of FAME.[70] The installation of this kit is used to heat the fuel as it circulates the internal fuel system. Furthermore, the kit is designed to provide periodic cleaning with an alternative fuel (HVO or diesel). These adaptive measures improve the fuel feeding system in the vehicle, which prevents clogging at high blend levels.

Fuel standards

Engine manufacturers certify their vehicles to run on specific blend volumes of FAME, to guarantee their performance operating at this blend level and meet emission performance regulations. The current maximum concentration of FAME is limited in the specification for mainstream diesel fuel which permits up to 7% in the European EN590 specification for diesel fuel

In most existing heavy-duty vehicles, it is technically possible to apply FAME in diesel engines at higher blend levels (above the mainstream concentration of 7% by volume). In some cases, vehicles are approved by the engine manufacturer to run entirely on FAME (B100, 100% concentration of FAME). Vehicles approved to run on B10, B20, B30 or B100, require strict adherence to the respective quality standard.

The following specifications are relevant for the application of biodiesel:[71,]

- EN590 → specifies requirements for automative diesel fuel (for use in vehicle engines using up to 7% FAME by volume.
- EN 16734 → covers diesel fuel with biodiesel up to 10% FAME by volume.
- EN 16709 → FAME B20 and B30 diesel fuel is a mixture of up to 20% by volume in total and up to 30% by volume in total, respectively
- EN 14214 → fuel specification for 100% FAME, called B100.

Regulatory and information barriers

While the use of higher blends in non-approved vehicles may be technically possible in some vehicles without the need for adaptation, the vehicle owner risks the loss of the warranty guarantee on performance. Given the strict regulatory standards for heavy duty vehicle engines, this can mean that it can be difficult to run on higher blends of FAME and meet Euro VI emissions standards.

Given the strict regulatory standards for heavy duty vehicle engines, this can mean that it can be difficult to run on higher blends of FAME and meet Euro VI emissions standards. The AGQM approval list[72], provides an overview of the FAME blend limits approved by certain OEMs per engine type in the European context. As shown in that document, several manufacturers apply blend limits in the range of B20-B30.If you drive on a FAME blend above this level and the vehicle breaks down, the responsibility then lies with the vehicle operator.

C.3 Hydrotreated vegetable oil (HVO)

Hydrotreated Vegetable Oil (HVO) is a fully renewable diesel which is made predominantly from vegetable oils and animal fats. The final product, however, much closer resembles fossil

[70] Find more information on the "bio-diesel kit" here.

[71] https://www.nen.nl/nen-en-14214-2012-a2-2019-en-256289 ; https://www.nen.nl/en/nen-en-16709-2016-en-212476 ; https://www.nen.nl/nen-en-590-2022-en-294451.

[72] An overview of heavy-duty vehicles approved to run on B10, B20 or B30 is given by AGQM, the German association for biodiesel quality management [AGQM 2022, Approval list of engine and commercial vehicle manufacturers for operation with biodiesel (B10 | B20 | B30 | B100)]

diesel. It is regarded to be of "drop-in" quality, because it is to a very high fraction fungible with the diesel infrastructure and application.

Conversion technology and feedstock

Production involves the conversion of fatty acids, including waste streams of cooking oils which would otherwise be discarded. These waste materials undergo an "hydrotreatment process". The hydrotreatment process involves the combination of a pressurised and heated steam with hydrogen in a reactor.

As is the case with FAME, the production capacity of HVO is determined by the availability of sustainable feedstock.

Fuel properties and standard

The output product is a very high-quality paraffinic component, which is essentially free of aromatics and obtains a high cetane number.[73] This makes it a very strong candidate to replace fossil diesel, as a sustainable alternative which combusts with a very "clean" flame.[74]

Due to the high-quality output product, HVO can be used at very high blend volumes or as a substitute to entirely replace fossil in regular diesel engines.[75] Therefore, this fuel offers an alternative substitute to fossil diesel without the requirement of engine adaptation. HVO is already a commercial technology and used today for transportation purposes.

HVO and XTL (next section) are together covered by the XTL quality standard EN 15940 for paraffinic diesel fuel produced via synthesis or hydrogenation.[76]

Cost barrier

Due to technologies associated with its production, HVO has a relatively higher production cost, and therefore retail price, than FAME and fossil counterpart.[77] However, production costs are largely dominated by feedstock (the costs of feedstocks is generally higher than the depreciated capital costs of the conversion installation), and therefore identifying sufficient volumes of feedstock will be integral to determining prices in the future.[78]

C.4 Synthetic diesel (XTL)

Synthetic fuels can be produced through multiple production pathways from ligno-cellulose biomass or renewable electricity

Production process and feedstock

The main conversion technology for synthetic fuels is called Fischer-Tropsch (FT).[79] It reacts carbon monoxide or dioxide with hydrogen, together called synthesis gas, over a catalyst. The synthesis gas can be produced by gasification of lignocellulose biomass. Alternatively, carbon dioxide (captured from industry or air) can be combined with renewable hydrogen from electrolysis (see Annex C.9.). Synthetic diesel is also called XTL, which is short for Anything-to-Liquids, where X can be power (PTL), biomass (BTL), gas (GTL) or coal (CTL). XTL technology can produce different types of fuels, including a diesel quality fuel. Actually, fossil-based GTL (gas-to-liquids) and CTL (coal-to-liquids) exist on a commercial production scale, while PTL and BTL are not commercially available.

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[73] The cetane number is used as an indicator of the combustion speed and compression required for the combustion of a fuel.

[74] [IEA Advanced Motor Fuels, website on emissions from synthetic diesel].

[75] Many major OEMs now approve the use of HVO in their vehicles [Neste overview of vehicle approvals].

[76] [NEN-EN 15940:2023, Automotive fuels - Paraffinic diesel fuel from synthesis or hydrotreatment - Requirements and test methods].

[77] See for example our earlier analysis [studio Gear Up 2020, To drop-in or to adapt the engine, Amsterdam the Netherlands].

[78] [IEA Bioenergy: Task. (2020), Advanced Biofuels – Potential for Cost Reduction].

[79] [IEA Advanced Motor Fuels, website on Paraffins for diesel blending].

Hydrotreated pyrolysis oil (HPO). is another category of synthetic fuel. This is made from pyrolysis oil derived from biomass or other sustainable feedstock.[80] The pyrolysis oil requires a chemical upgrading before it can be used as a transport fuel.[81]

Fuel properties and standards

These fuels are known for having excellent fuel properties: including a comparable cetane number to conventional diesel which can achieve significant emissions reductions compared with fossil diesel (including NO_x emissions and particulate matter).

Synthetic diesel can be used in existing diesel engines without the requirements for modification of vehicles or any requirement for mixtures with fossil diesel. However, the current production volumes are very low and these fuels are not widely available at commercial levels.

XTL and HVO are together covered by the XTL quality standard EN 15940 for paraffinic diesel fuel produced via synthesis or hydrogenation.

Cost barrier

The price of synthetic diesel is strongly influenced by the high capital costs of the Fischer-Tropsch production process. Decreasing the production costs will require the development of large-scale facilities, which likely involve investments of over 1 billion euro. Such investments have been proposed and explored several times by large oil companies (Shell, BP, Total), but in view of market prospects for the fuels, no investments at sufficient scale have taken place.[82]

C.5 Oxymethylene ethers (OME_x)

Oxymethylene ethers are mainly (to be) produced from methanol. OMEx has a fuel quality that somewhat resembles diesel, and it could be used as a blend component in existing diesel engine vehicles.

Production and feedstock

OME_x is generally produced from methanol, whereby parts of the methanol are converted to formaldehyde (FA), which is then reacted with the remaining methanol to yield OME_x. While the technologies for producing OME_x are well established and ready, it is not available at commercial scale.[83]

Fuel properties

OMEx has a molecular structure $H_3CO(CH_2O)_xCH_3$. It effectively looks like a DME molecule that has been extended with one or more groups, where x stands for the number of extra groups. The x thus indicates that the molecule is of variable length, and for use as a fuel, typically $1 \leqq x \leqq 5$. The liquid density and viscosity of OME_x (amongst other liquid fuel characteristics) depends on the chain length, which increases with longer chain lengths.[84]

OME_x has different names in the literature:

- Oxymethyl ether (OME_x or sometimes simply OME)
- OxyMethylene dimethyl Ether (also abbreviated as OME, or as OMDME)
- Polyoxymethylene dimethyl ether (PODE or POMDME)

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[80] See for example the work by BTGbioliquid, who produce a Fast Pyrolysis Bio-Oil (FPBO).

[81] [Website Brandstoffen.info, amongst others on hydrotreated pyrolysis oil].

[82] [Majewski 2023, Synthetic Diesel Fuel].

[83] [Schmitz et al 2017, Conceptual Design of a Novel Process for the Production of Poly(oxymethylene) Dimethyl Ethers from Formaldehyde and Methanol, Industrial and Engineering Chemistry Research 56(40):11519-11530].

[84] [Pitsch et al 2024, Potential of oxymethylene ethers as renewable diesel substitute, Progress in Energy and Combustion Science, Progress in Energy and Combustion Science 104:101173].

Note that OME_1 in turn is known under various chemical names, mainly methylal and dimethoxymethane (DMM), and that DME (see Annex C.9.) is effectively OME_0.

Fuel application in Heavy Duty Vehicles

OME_x is being tested for use in heavy-duty applications as a sustainable replacement for diesel. This fuel is in early stages of development and is not yet commercially available.[85] OME_x can be operated in a very similar way to fossil diesel. Because it has no C-C bonds, it combusts with very low levels of particulate matter. It is compatible with current engines, and therefore, can be used as an alternative to diesel in low blend applications. However, the current EN590 fuel specifications would have to be modified to permit high blend applications of the fuel, due to the high cetane number, density and boiling temperature, which violate the specification limits.[86]

Cost barrier

The production costs of (renewable) OME_x is largely dictated by the price of (renewable) methanol, as its production in generally based on methanol.[87] There is currently no large-scale production of OME_x. This alternative fuel will always be more costly than methanol and DME, and it would require considerable production capacity investment to supply significant volumes.

C.6 Compressed Gas (CNG)

Methane gas can be used in different applications across various sectors, such as, power generation, in the building sector, and as a feedstock in the chemical industry. It has gained interest as an alternative road transport fuel, for application mainly in light-duty vehicles.[88] It could also be used in the production of other renewable fuels, such as biomethanol.

Production and feedstock

Methane is the main constituent of natural gas (and CNG stands for compressed natural gas). However, it can also be produced as biomethane from anaerobic digestion, or as e-methane from combining renewable hydrogen with carbon dioxide over a catalyst.

Fuel properties and standards

Both methane from a biological-origin and fossil-origin can be used in either a compressed (CNG) or liquefied (LNG) form for transportation purposes.[89]

Bio- and e-natural gas is produced by the liquefaction of biomethane. Biomethane is obtained from renewable sources and can be obtained from various pathways and feedstocks:

- Anaerobic digestion: a mixture of methane and CO_2 is produced through the anaerobic digestion of municipal, manure, municipal and other streams of organic waste.
- Synthetic natural gas: produced through the gasification of lignocellulosic biomass and subsequent methanation or via electrolysis and methanation.[90]

European specifications for natural gas and biomethane as automotive market fuels were published in 2016/2017.

- NEN-EN 16723-1 (2016): Specifications for biomethane for injection in the natural gas network

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[85] [Mission innovation 2024, website ALIGN CCUS].

[86] [Pitsch et al 2024, Potential of oxymethylene ethers as renewable diesel substitute, Progress in Energy and Combustion Science 104:101173].

[87] [Tönges et al 2023, Techno-Economic Analysis of Large-Scale Production of Poly(oxymethylene) Dimethyl Ether Fuels from Methanol in Water-Tolerant Processes, Fuels 4(1):1-18].

[88] [IEA Advanced Motor Fuels, website on Methane (natural gas, biomethane)].

[89] [Söderena et al 2021, Heavy-Duty Vehicles Performance Evaluation, AMF Task 57].

[90] [EBA 2020, Bio-LNG in transport: making climate neutrality a reality].

- NEN-EN 16723-2 (2017): Automotive fuels specification

This specifies the requirements and test methods for biomethane at the point of entry into natural gas networks. Including the specification of requirements and test methods for qualities of gas: low-calorific gas and high-calorific gas.[91]

Use in spark Ignition Engines

Spark Ignition (SI) technologies are predominant for heavy duty vehicles operating on Compressed Natural Gas (CNG). Spark plugs are required in CNG powered vehicles because natural gas has a much higher ignition temperature compared with diesel.

The CNG is stored in multiple fuel tanks (or cylinders), which are located behind the cab of the vehicle. High-pressure gas is transferred from the fuel tank, this pressure is regulated to a level which is compatible with the engine injection system. The fuel is introduced into the inlet system, mixed with air during the intake stroke, and inside the cylinder ignited by a spark plug.[92]

Technical barrier:

CNG is compressed after processing; to less than one percent of its original volume. However, due to lower energy density, CNG vehicles require more space in the fuel tank than a regular diesel truck. Moreover, the tank must be strong to withstand high pressures and is typically heavy. This limits the range of vehicles running on CNG, which are more suitable for short and medium distances (rather than long haul). [93] Other technical limitations associated with Spark Ignition (SI) engines, including their relatively lower efficiency than diesel engines, have been discussed in Annex B.

C.7 Liquefied Natural Gas (LNG)

Natural gas can also be used in liquefied form, as either fossil-based liquefied natural gas (LNG), or liquefied bio- or e-natural gas (Bio- or e-LNG). Natural gas is cooled to a temperature of below -161 degrees Celsius. The fuel is typically cryogenically stored in a tank on the side of the vehicle[94]. LNG is typically used to meet longer range requirements of heavy-duty vehicles. In liquid form, natural gas provides a higher energy density than in a gaseous state, meaning that it can achieve longer transportation distances for heavy duty vehicles.

Production and feedstock

See production and feedstock information in previous section (Annex C.6)

Dual Fuel Compression Ignition (DFCI) engines for natural gas

Engine technologies have been developed, including high-pressure direct-injection (HPDI), which involve compression-ignition engines with dual fuel operation for LNG and diesel fuel This involves the installation of a cryogenic tank and high pressure liquefied natural gas ("LNG") pump.[95] This brings the natural gas into a high-pressure gaseous state. HPDI systems are compatible with LNG (and not CNG), because it is in liquid form, can be further pressurised. As well as benefiting from the higher energy density levels which are required for medium and long-haul heavy-duty vehicles.

The diesel is used as a pilot fuel for the main ignition source and the engine is subsequently powered by the LNG. The "substitution ratio" between diesel and LNG varies depending on the operation of engine technology that is used. The direct-injection system achieves higher fuel

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[91] [EN 16723 (part 1 and part 2): specifications for natural gas and biomethane for use in transport and biomethane for injection in the natural gas network].

[92] https://afdc.energy.gov/vehicles/how-do-natural-gas-class-8-trucks-work

[93] [DHL 2024, LNG and CNG Trucks: How Sustainable are Gas-Powered Trucks in Road Freight?].

[94] [Alternative Fuels Data Center, website item: How Do Liquefied Natural Gas Class 8 Trucks Work?]

[95] [Alternative Fuel Vehicle Institute AFVi, website item: Understanding HPDI Natural Gas Fuel Systems].

efficiency than an indirect injection system, achieving up to 95% substitution of natural gas for diesel.[96]

Cost barrier

Another barrier is that LNG is typically a higher cost option relative to compressed natural gas (CNG). Given the liquefaction process which requires capital investment and results in higher prices.

C.8 Renewable Methanol

Today, methanol is mainly produced from natural gas and used in the chemical industry as a platform chemical. The current global market is around 110 million tonne per/year. In recent years, methanol is gaining interest as a renewable fuel for the shipping sector. It can also be used in Heavy Duty Vehicles on road, which is currently done in China. This requires some adaptations to the engine and the fuel system. It can be used as a complete replacement of diesel or as a blending component[97].

Fuel properties and standards

There is a fuel standard for methanol in marine application and the standard for application in Heavy Duty is in development (ISO 6583, 2024).[98]

Renewable methanol production

Renewable methanol can be produced from a wide range of feedstocks including bio-based and waste-based streams as well as renewable hydrogen and CO_2.

The main pathways to produce renewable methanol are:

- From biomethane from existing biomethanol production facilities
- From syngas that could be produced from biomass via gasification
- From combining renewable hydrogen from electrolysers with CO_2

Renewable methanol provides high greenhouse gas saving potential, and its properties support a clean and efficient combustion. Straight methanol burns with low particle and NO_x emissions in adapted engines.

Methanol application in Compression Ignition (CI) engines

Compression Ignition (CI) engines can be used for methanol application in heavy-duty engines. However, the low cetane number of methanol makes this fuel unsuitable for conventional diesel engines. Studies on the potential of using renewable methanol in the Scania adapted ethanol engine for ED95 (see Annex C.10) have been tested and displayed clean combustion and low levels of gaseous emissions.[99] Modifications to these engines require increasing the compression ratio (28:1), introducing a special fuel injection system, and a catalyst to control aldehyde emissions.[100]

Conventional dual fuel (CDF) is a common approach for the combustion of methanol in a typical compression ignition engine (read more on this in Annex B). This solution can be applied through the addition of a methanol port fuel injection system, which can be retrofitted in existing engines. In addition to the injection of a pilot fuel (such as diesel) to simulate combustion in the engine. Dimethyl ether (DME, see more on this fuel in Annex C.11)

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[96] [Folkson 2014, Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance,Towards Zero Carbon Transportation].

[97] [Pu et al 2024). Renewable Methanol as a Fuel for Heavy-Duty Engines: A Review of Technologies Enabling Single-Fuel Solutions Energies 17(7):1719].

[98] [ISO 6583: 2024: Methanol as a fuel for marine applications — General requirements and specifications].

[99] [Aakko-Saksa et al 2019, Renewable Methanol with Ignition Improver Additive for Diesel Engines, Energy & Fuels 34(1): 379-388].

[100] [Hedberg 2007, The Scania Ethanol Story - 25 years of experience in sustainable transport, In XVI International Symposium of Alcohol Fuels, 8 January 2007, p20].

can also be used as an ignition improver additive for methanol Compression Ignition (CI) engines.[101]

When applying methanol at high blend ratios, to maintain safety and stability, the engine requires corrosion inhibitors, co-solvents, and alcohol compatible materials are required.[102]

Use of renewable methanol in a High-Pressure Direct Injection (HPDI) system

A further reduction of pollutants could be expected in high efficiency combustion engines and significantly increase the engine efficiency in dedicated engines.

High Pressure Direct Injection (HPDI) of methanol involves injection into the cylinder much like the ordinary diesel cycle. A small burst of pilot fuel (such as diesel) is injected beforehand, to assist the initial combustion, by raising the temperature in the cylinder. A larger injection of methanol follows. In this design set-up, modifications to the engine are limited to the fuel injection system and provide the possibility to operate on conventional diesel fuel, without performance loss.

There are different design possibilities for these injectors. Separate injectors can be used for the methanol and pilot fuel. Alternatively, an injector capable of distributing both types of fuel separately into the same unit.[103] Currently most of the market developments for methanol using dual fuel application utilising HPDI technologies are for marine and off-road vehicles. [104]There is some early research for using HPDI technologies for heavy duty vehicles.[105]

Use of renewable methanol in a spark ignition engine

Methanol has a high-octane rating and strong cooling effect from the heat of vaporization, which make the fuel less prone to pre-ignition. Therefore, this makes it well suited to spark ignition engines. These engines can be higher efficiency and power output than their compression ignition counterparts.

An alternative to using a pilot fuel to initiate combustion is installing a glow plug. As methanol has good surface ignition properties, this could offer a feasible alternative, in cases where pilot fuel systems are not a practical option[106].

Fuel infrastructure

For lower blend levels of methanol, no adjustments are required to the existing fuel infrastructure. For higher blend levels, an adjustment of the existing fuel infrastructure, especially regarding material combability and safety handling would be required.[107]

C.9 Renewable Hydrogen

Hydrogen is a renewable fuel, that can be used in heavy-duty applications, via different engine platforms. Hydrogen can be converted into synthetic liquid fuels, such as e-methanol, e-methane, e-ammonia (known as e-fuels), as discussed in Annex C.8, C.6 and C.12. However, in this section we focus on the direct application of hydrogen in heavy duty vehicles.

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[101] [Jennings and Short 2016, Enhanced Fuel and Method of Producing Enhanced Fuel for Operating Internal Combustion Engine].

[102] [Schröder et al 2020, Methanol as Motor Fuel Summary Report: IEA Advance Motor Fuels Annex 56].

[103] [Marine Methanol, website item: Methanol diesel High Pressure Direct Injection (HPDI)].

[104] See news announcement of Westport (February 26, 2024), Westport Announces Methanol HPDI™ Project with a Leading Global Supplier of Power Solutions for Marine Applications.

[105] [Minshuo et al 2024, Optimization of methanol/diesel dual-fuel engines at low load condition for heavy-duty vehicles to operated at high substitution ratio by using single-hole injector for direct injection of methanol, Applied Thermal Engineering 246].

[106] [Túner et al 2018, Engine Technology, Research, and Development for Methanol in Internal Combustion Engines: SUMMETH - Sustainable Marine Methanol, Deliverable].

[107] [Schröder et al 2020, Methanol as Motor Fuel Summary Report: IEA AMF Annex 56].

Production and feedstock

Most hydrogen is currently being produced from fossil sources, mainly natural gas. This hydrogen is referred to as "grey" hydrogen. If the CO2 emission from the production process is captured, then the product is called blue hydrogen. Subsequently, Renewable hydrogen is called green hydrogen. It can be produced as an e-fuel from renewable electricity via electrolysis of water (splitting into hydrogen and oxygen), or as a biofuel, either by processing biomethane in a conventional reformer, or via gasification of lignocellulosic biomass.

This implies that the feedstock basis is potentially wide. However, it should be noted that most current attention goes to the production via electrolysis.

Fuel properties and standards

Hydrogen has a high energy content on a mass basis, but a low volumetric energy density. This provides challenges for the storage and transport of hydrogen. It can be stored either in a tank in liquid form (requiring cryogenic temperatures), or in a high-pressure tank in a gaseous state.[108]

ISO standards establish safe practices for hydrogen production, storage, transport, and use. They support technological advancements to integrate hydrogen into existing energy systems and new applications.[109]

Engine developments for hydrogen, Spark Ignition (SI)

Developments in hydrogen use for heavy duty vehicle applications has mostly been in spark-ignition (SI) engines. Hydrogen application in spark-ignition (SI) engines comes with the risk of pre-ignition and excessively fast combustion, which ultimately results in lower efficiency. [110] There is research in the application of hydrogen and natural gas blend use in heavy duty vehicles with spark ignition engines.[111]

Engine developments for hydrogen, High Pressure Direct Injection (HPDI)

Other developments in the use of hydrogen in heavy duty applications focus on high-pressure direct injection (HPDI, see Annex B), where hydrogen is used as the main fuel in dual fuel engines. This solution where combustion takes place directly around the injected fuel jet. Offers increased combustion efficiency and therefore higher power engines.[112]

Meeting emissions standards with hydrogen vehicles

To comply with relevant emission standards, heavy-duty vehicles using hydrogen will require a combination of selective catalytic reduction (SCR) and exhaust gas recirculation (EGR). In the case of a dual fuel engine design, the engines could also obtain a diesel particulate filter (DPF) to remove particulate matter formed by diesel combustion. [113]

While HPDI dual fuel engine designs can achieve higher power performance, the NO_x emissions are relatively higher than Spark Ignition (SI) engine set-ups. Therefore, this may require additional aftertreatment for emissions control (such as is required in convention diesel engine design).[114] This includes a Selective Catalytic Reduction (SCR) to meet

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[108] [Cryospain 2024, Hydrogen fuel tanks for long-distance heavy vehicles].

[109] [ISO 14687:2019 Hydrogen fuel quality — Product specification; ISO 17268:2020 Gaseous hydrogen land vehicle refuelling connection devices; ISO 16111:2018 Transportable gas storage devices — Hydrogen absorbed in reversible metal hydride].

[110] [IEA Advanced Motor Fuels, website item on Hydrogen].

[111] [De Simio et al 2024, Natural Gas/Hydrogen blends for heavy-duty spark ignition engines: Performance and emissions analysis, International Journal of Hydrogen Energy 50].

[112] [For example, Liebherr to premiere its hydrogen prototype engines at Bauma 2022. Press release October 10.th, 2022].

[113] [IEA Advanced Motor Fuels, website item on Hydrogen].

[114] [TNO 2023, Hydrogen Combustion Concepts: Comparison of Port Fuel Injection with Spark Ignition and High Pressure Direct Injection (HPDI™) : Power Density, Efficiency, and Emissions].

emissions standards, with respect to NO_x levels and particulate filters to ensure particulate standards are adhered to.

Application of hydrogen in Fuel Cell (FC) vehicles

In passenger vehicles, the (future) application of hydrogen is often seen via fuel cell technology, which is effectively the reverse of the electrolysis reaction. However, the cost of developing fuel cell vehicles is higher than that of combustion engine counterparts being developed for hydrogen.[115] This mainly due to the high-cost nature of the use of expensive catalysts and other materials required for their development.[116]

C.10 Bioethanol (as ED95)

Introduction

Bioethanol is currently the predominant renewable fuel used in spark-ignition engines. It is mainly applied as low blends in gasoline (as E5 and E10, with respectively up to 5 and up to 10% ethanol by volume), but could be used in higher fractions, both in spark-ignition engines and in compression-ignition engines.

Production and feedstock

Ethanol is traditionally produced through the fermentation of sugar (for instance from beet or cane) or starch (for instance from wheat or maize). Also, some food industry waste streams contain sugars or starch that can be converted to ethanol via the same facilities. Ethanol can also be produced from cellulosic feedstock such as wood, grass and many types of (hemi)cellulose containing residues. This process is more complex, because first the cellulose and hemicellulose present in such feedstock must be "hydrolysed" to yield sugars (which are partly comparable to the sugars in beet and cane, and partly different). This requires a harsh process environment, such as steam or acid treatment. The eventual ethanol is usually called "cellulose ethanol".[117]

Hence, ethanol is currently mainly being produced from food and feed crops. Production from waste streams exists, but at a smaller scale. Production of cellulose ethanol is limited. Several commercial demonstration facilities have existed, but they were in the current market not economically viable, while the feedstock quality (often containing dirt and other contaminants) also still induces technical challenges.

Fuel properties and standards

There are fuel standards for the application of ethanol as a blending component for petrol, as well as a specific standard for which has been developed in Sweden for application in diesel engines.[118]

- The EN 15376 standard establishes specification for ethanol as a blend component into gasoline in the EU, for all blend levels up to and including 85% by volume.
- The EN 228 standard permits blends of up to 5% and 10% of ethanol by volume, in petrol.
- In Sweden, standard SS 15 54 37 is applied for alcohols for high-speed diesel engines.

Use of ED95 in a compression ignition engine

Of specific interest is ED95, an ethanol-based fuel which can be used is heavy duty vehicles with a specially modified Compression Ignition (CI) engine. The fuel is comprised of

[115] [studio Gear Up 2020, To drop-in or to adapt the engine, Amsterdam the Netherlands].

[116] [Arthur D. Little 2017, What's in the future for fuel cell vehicles?].

[117] [Website IEA Advanced motor fuels on ethanol].

[118] The EN 15376 standard establishes specification for ethanol to be blended into petrol in the EU in accordance with the EN 228 standard for petrol, and for blending at all levels up to 85% by volume (E85). The EN 228 standard in turn specifies two types of unleaded petrol: one that permits ethanol blends of up to 10% by volume, and one that permits (only) 5% ethanol by volume, intended for older vehicles that are not warranted to use unleaded petrol with a high biofuel content. In Sweden, standard SS 15 54 37 is specification for alcohols for high-speed diesel engines.

(approximately) 95% ethanol and 5% of performance enhancing additives. ED95 fuels and technology have been used in heavy-duty buses and trucks for 30 years, and over 700 ED95 vehicles have been on the (mainly Scandinavian) roads.[119]

Ethanol can be used in Compression Ignition (CI) engines by using an additive which improves ignition and lubricity. Some modifications are required for ethanol-use in diesel engine vehicles. These include introducing a special fuel injection system, an increased compression ratio, and a special catalyst to control aldehyde emissions.[120]

Barriers to using ED95

The engine must have a modified fuel system and a considerably higher compression ratio than standard diesel engines (28:1). Another key drawback is that ED95 fuel is not a widely available fuel option, and the technology has been developed by only/mainly one engine manufacturer (Scania),[121] who is no longer producing vehicles based on this technology (for any market worldwide).

C.11 Dimethyl ether (DME)

Dimethyl ether (DME) is a synthetically produced chemical commodity which can be used as a fuel in modified Compression Ignition (CI) engines. DME is not widely used as a fuel today, but demonstrations are ongoing. The main current application of DME is as aerosol propellant and it has been used for over 50 years in the chemical sector.[122]

Production and feedstock

DME is primarily produced from methanol, which in turn can be produced from natural gas, coal, from biomass through gasification, or from hydrogen and carbon dioxide (see Annex C.8). DME is a specific form of OME_X fuel (see Annex C.5), whereby x=0. Therefore, DME could also be referred to as OME_0.[123]

Fuel properties and standards

DME has a high cetane number and offers a clean combustion. However, in its natural state it is a gaseous fuel and requires a mild pressure to keep it in a liquid state (approximately 6 bars). Use of DME is challenging as it could result in leakage and wear in pumps and fuel injectors. Additives used to improve lubricity of some diesel fuel grades, and new additives, are currently being tested for application in DME.[124] Driving diesel engines on DME has been demonstrated by amongst others Volvo with 10 trucks driving on DME.[125] The marketing was limited by a lack of DME supply, and there seem to be no currently active projects.

There is an international standard (ISO 16861:2015) which defines the specific characteristics of DME for use as a fuel, in heating or industry applications to replace diesel fuel.

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[119] Swedish ethanol producer Sekab was together with vehicle manufacturer Scania long active on ED95 [Sekab 2020, Sustainability Report 2019: Development for green competition and sustainable growth]. Over 700 Scania ED95 buses were driving in Swedish cities such as Örnsköldsvik and Stockholm. In 2019, Scania a new ED95 truck to agricultural cooperative and ethanol producer Lantmännen Agroetanol, with a 410 hp Euro 6 engine with SCR aftertreatment. Scania notes that the compression ignition engine is comparable to conventional diesel engines and that the hardware modifications are limited. [Scania website: First Scania bioethanol truck hits the road]. In 2018, Sekab reports that many trucks and buses have been tested on ED95 in Norway, Sweden and Finland [Sekab 2018, Sustainable green chemistry solutions, presentation at Advanced biofuels conference].

[120] [IEA Advanced Motor Fuels, website: Diesel engines for additized ethanol].

[121] [Novakovic et al 2022, An Experimental Investigation of Directly Injected E85 Fuel in a Heavy-Duty Compression Ignition Engine. In SAE Technical papers: Powertrains, Fuels & Lubricants Conference & Exhibition, Society of Automotive Engineers].

[122] [CO2Focus 2022, D5.3 Market study on DME].

[123] [Sun et al 2024, Combustion characteristics of oxymethylene dimethyl ether-diesel blends: An experimental investigation using a constant- volume combustion chamber, Fuel, 360:130587].

[124] [IEA Advanced Motor Fuels, website item on DME].

[125] [Volvo group 2017, website item: Mack Trucks tests alternative fuel DME | Truck Star 2012, website item: Bio-DME blijkt prima brandstof].

Furthermore, ISO standard (ISO 22760: 2019) defines the general requirements for the use of DME in dual systems, including those intended for use in motor vehicles.[126]

Modification of existing engines for DME use

To use DME in existing compression-ignition engines, requires limited retrofitting of the vehicle and engine set-up, especially the installation of a new fuel injection system: feed pumps, high pressure pump and fuel injectors. While major changes to the piston and cylinder heads are not required, changes to the piston bowl and re-location of piston rings, may be necessary to optimise the design of the combustion chamber to suit the characteristics of DME.

Fuel infrastructure

In principle, transport and distribution of DME could use existing LPG infrastructure. This would require modifications to the pumps, seals and gaskets. New infrastructure for DME could be developed in regions where the LPG infrastructure does not exist.[127]

C.12 Ammonia

Ammonia is a chemical compound which exists naturally in a gaseous state. It is predominantly used in agricultural sectors as a precursor to synthetic fertiliser. It is considered as e-fuel, especially in the shipping sector, and as a hydrogen carrier for the international transport of renewable hydrogen (because that would allow transport in a more energy dense form).

Production and feedstock

Ammonia is predominantly produced from natural gas. First, hydrogen is produced by methane reforming, and then the hydrogen is reacted with nitrogen. This means that renewable ammonia could be produced as a biofuel from biomethane or as an e-fuel from renewable hydrogen (electrolysis, see Annex C.9).

Fuel properties and standards

Ammonia is a chemical compound which exists naturally in a gaseous state. Currently ammonia is predominantly produced from natural gas. First, hydrogen is produced by methane reforming, and then the hydrogen is reacted with nitrogen. This means that renewable ammonia could be produced as a biofuel from biomethane or as an e-fuel from renewable hydrogen (electrolysis, see Annex C.9). When used as a fuel ammonia burns without emitting carbon dioxide but combustion can create high levels of NO_x and particulate matter emissions, if not well addressed.[128]

Ammonia is being considered for application as a transport fuel, primarily in the shipping sector. It could be an interesting option for heavy-duty road applications, as it has the highest energy density of non-carbon mediums, making it is easier to transport and store than hydrogen and other derivatives of hydrogen.[129]

There is an international standard (ISO 7108:1985) which is for ammonia solution for industrial use. Furthermore, an international standard (ISO/WD 23397) is under development for the use of ammonia as a fuel in maritime engines.[130]

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[126] [ISO 16861:2015, Petroleum products — Fuels (class F) — Specifications of dimethyl ether (DME); ISO 22760-1:2019, Road vehicles — Dimethyl Ether (DME) fuel system components].

[127] [Semelsberger et al 2006, Dimethyl ether (DME) as an alternative fuel, Journal of Power Sources 156:497-511].

[128] [IEA Advanced Motor Fuels, website on Ammonia].

[129] [Jacobsen 2024, Ammonia: a cracking opportunity for hydrogen, on website of technology provider Topsoe].

[130] [ISO (7108:1985) Ammonia solution for industrial use — Determination of ammonia content — Titrimetric method; ISO/WD 23397Ships and marine technology — Ammonia fuel systems for ships — Vocabulary].

Ammonia use in reactivity- controlled compression ignition (RCCI) engines

Ammonia has a low calorific value and cetane number, which provides a challenge for its use in combustion engines. The RCCI route offers a potential avenue for ammonia to overcome this challenge using a pilot fuel (such as diesel) in a dual fuel application to stimulate the combustion process. Furthermore, this could help to tackle the high NO_x and particulate matter emissions.[131] However, this potential technological pathway is at early stages of research, requiring further development to make this a feasible option.

Fuel toxicity

Ammonia is highly toxic, even in low concentrations. Therefore, the handling of ammonia (during storage and distribution) is subject to strict safety precautions.[132] It is not foreseen that ammonia could be safely dispensed from general gas stations. This renders ammonia currently unfit for wide application in road transport, and further work is required to address these safety hazards for the use of ammonia as a transport fuel.

[131] [Fakhari et al 2024, RCCI combustion of ammonia in dual fuel engine with early injection of diesel fuel, Fuel 365:131182]

[132] [European Maritime Safety Agency 2023, Study Investigating the Safety of Ammonia as Fuel on Ships, EMSA, Lisbon].

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