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Green Deal Validation: Sustainability and applicability of biodiesel for sea vessels

TNO 2023 R10862V2
2 November 2023

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TNO 2023 R10862V2 – 2 November 2023

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Copy number	2023-STL-REP-100350743v2
Number of pages	74 (excl. front and back cover)
Number of appendices	3
Project name	Green Deal Validation GoodFuels MDF1
Project number	060.51010

Summary

TNO has investigated the GoodFuels MDF1 FAME type biodiesel and biodiesel in general in the context of the Green Deal validation program.

The validation includes the following:
- Environmental impact
- Practical application and scalability
- Economic aspects
- Future proofness

The conclusions with respect to the validation aspects and GoodFuels claims are summarised in the sections below. Apart from the assessment of the FAME type biodiesel MDF1, the scope has been broadened to include the 'advanced' type of biodiesel such as FT diesel.

Environmental impact
The main conclusions with respect to the claims of GoodFuels for MDF1 are summarised in the table below.

GoodFuels claim MDF1	Validation result
WTW GHG emission reduction of 84% - 95%	No specific MDF1 chain analysis performed. FAME produced from residue flows has a GHG reduction of 84%-88% based on generic numbers (REDII)
SO_x emission reduction	Up to 50 times lower SO_x emission level due to the very low FSC of MDF1 compared to MGO or ULSFO with 0.1% FSC by mass
No NO_x emission reduction	• For Tier I and Tier II engines: a NO_x increase is expected of about 3% with B30 to about 12% with B100, compared to ULSFO or MGO. • In most cases, NO_x emissions with B30 – B100 will continue to comply with Tier I and Tier II limit values. • For Tier III engines urea dosage for SCR system can be adapted such that NO_x emissions will remain the same. For engines with closed loop control this will be done automatically
BC reduction but no PM mass emission reduction	• No conclusions on general influence on PM mass emissions (in g/kWh) based on current results. • Strong (3 to 5 times) reduction of Black Smoke (BS, opacity) emissions proportional to the blend percentage

Practical application and scalability
With respect, to practical application and scalability of FAME type biodiesel, the following conclusions can be made:
- General positive feedback was received from ship owners, about the use of B30 to B100 (30% to 100%FAME) blends.
- Engine manufacturers are cautious. High-Speed engine manufacturers often recommend to limit FAME blends to B10 or B20. There were no directs blend limits for Medium-Speed engines, although manufacturers ask to check with them on a case by case basis.

- FAME quality used for blends must comply with the normal standards like EN14214 or ASTM D6751.
- The recommendations for the use of FAME blends for the Dutch shipping categories are summarized in the table below.
- The impact to operational aspects are limited to bunkering a slightly increased fuel quantity (plus ≈ 10%). Additionally, relatively simple measures, like more frequent inspections and cleaning of fuel tanks and filter system, limit or eliminate most potential risks.
- In general there are no limitations to the use of synthetic biodiesel such as HVO or FT biodiesel, provided that these fuels fulfil the requirements of the fuel standards EN15940.

Table 1-1: Recommendations for the use of FAME blends for the Dutch reference vessels.

<table>
<tr><th>Nb</th><th>Vessel type</th><th>Engine type</th><th>FAME biodiesel recommendation</th><th>General recommendation</th></tr>
<tr><td>1</td><td>General Cargo</td><td rowspan="2">Medium Speed</td><td rowspan="2">Up to B100 often possible</td><td rowspan="2">Check higher than B10 blends with engine supplier.

Centrifugal filter and day tank are generally already installed.</td></tr>
<tr><td>5</td><td>Dredging</td></tr>
<tr><td>2</td><td>TUG</td><td rowspan="4">High Speed</td><td rowspan="4">Limit FAME blend to B10 or B20
In some cases higher blends are supported by engine supplier</td><td rowspan="4">Install centrifugal filter and day tank for fuel circulation.

Check higher than B10 blends with engine supplier.</td></tr>
<tr><td>3</td><td>Offshore supply</td></tr>
<tr><td>4</td><td>Crew Tender</td></tr>
<tr><td>6</td><td>Super yacht</td></tr>
</table>

Economic impact

Regarding the economic aspects of FAME biodiesel, the following conclusions are made:

- The market prices of biodiesel and fossil diesel fuel vary a lot. In the period from April 2020 to February 2022, the biodiesel price almost doubled and the MGO price increased by more than a factor of four. In February 2022, the FAME biodiesel price was a factor 2.4 or 1179 €/TOE higher than the price of MGO (831 €/TOE).
- The FAME type biofuel production cost from fresh vegetable oil can vary between 800 and 1200 €/TOE. This is a lot lower than the UCOME[1] market price in February 2022 which was about 2020 €/TOE. The 'double counting' category within the RED of UCOME probably plays a large role in this relatively high price.
- FAME type biodiesel such as GoodFuels MDF1 will likely be lower priced in the long term than the 'advanced' category biodiesel.

Regarding 'advanced' (Annex IXA feedstock) biodiesel (e.g. FT biodiesel):

- The biodiesel supply for the maritime market in 2030 and later will likely need to be a combination of FAME type and 'advanced' biodiesel. The future cost of the advanced biodiesel production is expected to range between 800 and 1600 €/TOE (excluding profit margin and bunkering costs). There are large concerns about production ramp up and availability of advanced biodiesel up to 2030 and later.

[1] UCOME: Used Cooking Oil Methyl Esther, a FAME type.

- The future price of advanced biodiesel is also dependent on precise sustainability criteria, minimum volume requirements, production scale up options and market prices of other advanced sustainable fuels like methanol.
- Both FAME type and advanced biodiesel will likely remain one of the most important and also economic fuel options for existing vessels and new vessels to reduce the GHG emissions.

Future proofness

Future proofness is influenced by fuel production and economic aspects, as well as by the fit in the RED and maritime instruments for GHG reduction (both in comparison with other sustainable fuels).

In particular, the following conclusions with respect to future proofness of FAME type biodiesel are made:

- The use of FAME blends in the maritime sector has been very popular during the past years especially due to ‘opt-in’ possibility of the RED. In 2021, about 10 PJ or 270.000 ton FAME was supplied as bunker fuel blend in the Netherlands (≈2% of the total Dutch bunker quantity).
- For 2023 it has become impossible for FAME to comply with the Dutch feedstock (particularly the Annex IXA) requirements for the opt-in arrangement. This will severely disrupt the economic aspects of using FAME type biodiesel.
- From 2025 onwards, maritime GHG instruments such as FuelEU Maritime, ETS and IMO CII are likely to stimulate the use of FAME and ‘advanced’ biodiesel in maritime shipping. The feedstock types for FAME are generally categorised in Annex IXB, which is limited in volume[2] and also already used by road transport. This may limit the use of FAME biodiesel. On the other hand, other types of ‘advanced’ (Annex IXA) biofuels such as FT diesel, methanol or ethanol are not likely to be available in sufficient volume and most ships cannot use methanol or ethanol. So alternatives for FAME are very limited, which may positively influence the acceptability of FAME (category Annex IXB) such as MDF1.
- The current biodiesel production in Europe (primarily for road transport) is much larger than the quantity needed for maritime transport in 2030 (according to FuelEU Maritime).
- HVO, Hydrotreatment Vegetable Oil, biodiesel has the same advantages and limitations with respect to future proofness, since it is generally produced from the same feedstocks as FAME.

[2] The volume of REDII Annex IXB (Part B) is limited to 1.7% of the total fuel demand.

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Abbreviations

BC	Black Carbon
BS	Black Smoke
CH_4	Methane
CII	Carbon Intensity Indicator
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DM	Distillate Marine (fuel)
EC	Elemental Carbon
ETS	Emissions Trading System
FAME	Fatty Acid Methyl Ether
FSC	Fuel Sulphur Content
FT	Fischer Tropsch
GHG	Green House Gas
HFO	Heavy Fuel Oil
HS	High Speed (engine)
HVO	Hydrotreatment Vegetable Oil
IMO	International Maritime Organisation
LHV	Lower Heating Value
MCR	Maximum Continuous Rating
MDF	Marine Distillate FAME
MGO	Marine Gas Oil
MS	Medium Speed (engine)
MTOE	Million Ton Oil Equivalent
NH_3	Ammonia
NO_X	Nitrogen Oxides
PEMS	Portable Emissions Measurement System
PJ	Peta Joule (10^{15} Joule)
PM	Particulate Matter
PN	Particle Number
PPM	Parts Per Million
RED	Renewable Energy Directive (II or III)
RM	Residual Marine (fuel)
SCR	Selective Catalytic Reduction
SO_2	Sulphur Dioxide
SOG	Speed Over Ground
SO_X	Sulphur Oxides
TOE	Tonne of Oil Equivalent
UCO	Used Cooking Oil
UCOME	Used Cooking Oil Methyl Ester
ULSFO	Ultra Low Sulphur Fuel Oil

1 Introduction

1.1 General

1.1.1 Green deal

Firm climate objectives for sea shipping have been set by the International Maritime Organisation, IMO and the Dutch Green Deal goes one step further. The IMO agreements mean that the transport performance by seagoing vessels must improve to such an extent that CO_2 emissions per tonne-kilometre will be reduced by an average of 40-60% by 2030. IMO agreements are applicable to the grand majority of sea shipping, since IMO members include some 175 countries. The European Green Deal aims for an absolute reduction of 70-100% in 2050 compared to 2008, regardless of market growth. Up to now, the maritime sector is almost complete relying on fossil fuels like light or heavy fuel oil, MGO and LNG. Biodiesel is also used to some extend, but mostly because it can be used to realise road transport targets (' opt-in' option for RED) or for specific customers such as authorities.

These ambitious GHG reduction goals call for solutions that can be applied today, because ships that are put into service today will most likely still be operational in 2050. The potential of available sustainable maritime solutions is great and is constantly expanding, but none of the available solutions is suitable for all ship types and in all operational conditions. The decision to opt for a sustainable solution also depends on the business case in which the ship must be able to operate. Currently there is a lack of objective information on the match between sustainable solutions and type of business case.

In addition to direct CO_2 emissions, the emissions of the greenhouse gases CH_4 and N_2O and air-polluting emissions such as NO_x, NH_3, SO_x and particulate matter are of great importance. The emissions of NO_x, SO_x and particulate matter from shipping are relatively high and are decreasing slowly due to not very stringent emission legislation and fuel standards and slow fleet renewal.

The diversity of available sustainable maritime solutions makes it difficult to determine which solution is most suitable for application on a ship as this depends on many factors. For example, each solution differs in the required space on board, the layout of the ship and integration with other systems, as well as for the costs and earning capacity of the ship itself. There is a large array of available sustainable solutions for various ship types, for various operational conditions and lengths of shipping routes. It is therefore important that the effects of these solutions are made transparent in an independent manner and that through validation reliable information is collected so that these solutions can be weighed against each other (ref. NL Green Deal art.12 paragraph 3: "Knowledge institutions will work with the industry to provide independent insight into and validate the effects of the sustainable maritime solutions so that comparison of these solutions is possible and it is easier for shipowners and financiers to compare").

The results of the performed validations provide reliable information for all parties in the maritime chain, making it easier to choose sustainable solutions.

1.1.2 Validation process

Transparency towards all parties in the maritime chain (from ship owners, ship operators and other logistics operators, shippers, financiers, suppliers, shipyards, to government) is important in the implementation of these validations. The sector itself is investigating which sustainable maritime solutions have the greatest potential to accelerate the energy transition. The technologies with the greatest potential are then validated at independent knowledge institutions. We call this form a cluster study; the sector is represented in this by KVNR and NMT, the knowledge institutions involved are MARIN and TNO, possibly supplemented by an external party if this is necessary for the implementation of a concrete validation case. Transparency is achieved by making the results public through reports that present an overview of how the various sustainable maritime solutions, grouped by theme, perform in terms of social impact, technical impact and economic impact.

1.1.3 Green deal validation

The green deal validation program of the Ministry of Infrastructure and Water management (Ministry IenW) offers the opportunity to independently review reduction measures. The marine sector, represented by KVNR and NMT, plays an important role in putting forward the key solutions for GHG reductions which can be implemented or scaled up in the near future.

The validation needs to include the following aspects:
- Safety aspects
- Environmental impact: impact on reduction of GHG and pollutant emissions
- Scalability: applicability to the maritime fleet (categories)
- Economic aspects and future proofness

1.2 Goodfuels biodiesel

GoodFuels' MDF1 is a FAME type biodiesel which is made from organic waste streams such as brown grease. To ensure fuel sustainability, potential feedstocks are reviewed by an independent Sustainability Board of leading experts before being used for fuel production.

The following claims are made for GoodFuels MDF1-100 (100% FAME), with respect to emissions reductions:
- Produced from organic waste streams following REDII Annex IX. The life cycle GHG reduction is up to 85-90% CO_{2eq} as compared to their fossil alternative
- Almost no sulphur oxides emissions, substantially lower than MGO with 0.05% FSC (500 ppm)
- Reduction of Particulate Matter (PM) emission compared to MGO, especially at low load. This is due to the lower concentrations of aromatic hydrocarbons, higher cetane numbers (combustion quality) and higher oxygen content.

GoodFuels made no specific claims regarding NO_x emissions. They can be lower, the same or higher than HFO or MGO.

The validation is set-up more broadly than just GoodFuels MDF1, also because GoodFuels did not provide detailed information on the fuel chain emissions of MDF1. The validation concerns FAME in general as well as future biodiesel types such as HVO (hydrotreated vegetable oil) and FT (Fischer Tropsch) diesel.

1.2.1 Research questions

The main research question is whether biodiesel, and in particular GoodFuels MDF1, is a suitable option for GHG and pollutants emissions reduction for the Dutch reference ship categories.

More in detail, the research questions are:

- Are there regulatory hurdles associated with biodiesel use?
- What are the technical risks?
- Are there any health risks for ship personnel or passengers?
- What are the expected impacts of biodiesel on NO_x, SO_x and PM/BC emissions?
- Can it lead to a rise in NO_x level, which is higher than the normal variation with diesel fuels?
- Which instruments affect sustainable fuels for shipping, and in particular regarding GoodFuels MDF1
- What sustainable fuel volumes will be needed for Netherlands, Europe and worldwide for maritime shipping?
  - According to the currently defined instruments, such as FuelEU Maritime
  - According to zero GHG emissions in 2050?
- Which feedstocks will most likely be used for (drop in) biodiesel? And what are the corresponding production routes?
- How does the future availability compare to those of bio-methanol, bio-ethanol?

1.3 Structure of the report

This report address both the validation of GoodFuels' MDF1 biodiesel, as well as future types of biodiesel in general.

The technical impacts and safety aspects of the use of biodiesel are addressed in section 2. This include a review of the regulatory aspects, particularly the IMO MARPOL pollutant emissions aspects and the compatibility of biodiesel with the fuel specifications.

The environmental aspects are reviewed in section 3. This includes both the pollutant emissions (Tank-to-Wake) and the GHG emissions (WTW). The scalability with respect to the application of biodiesel to the Dutch reference ship categories is addressed in 4. Consequently, the economic aspects are addressed in section 5. Finally, in section 6, the future proofness of biodiesel is addressed. This is especially done in the light of the compatibility of biodiesel with the future policy framework with respect to GHG reduction.

2 Technical impacts and safety aspects

2.1 Fuel types and standards

The marine diesel type fuel specifications are laid down in ISO8217. A number of different fuel specifications is possible, identified by the first letter 'D' for distillate or 'R' for residual fuel. In most cases a maximum of 0.5% FAME is allowed in these fuels, with two exceptions: DMX fuel must be FAME free (0%). The DF grades; DFA, DFZ, DFB are allowed to have a FAME content of up to 7% (by volume). This FAME must fulfil the EN14214 or ASTM D6751 industry standards. Since 2020 also two new low sulphur Fuel Oil standards were introduced: VLSFO (very low sulphur fuel oil) to comply with the new global standard (FSC<0.5% from 2020 onwards) and ULSFO (ultra low sulphur fuel oil) to comply with the 0.1% FSC in emission control areas (ECA).

Table 2-1: Standards for maritime diesel fuels

Norm	FUEL	Limits for blending	Limits for Fuel Sulphur Content
ISO 8217	DF-fuels (Marine Gasoil) DFA, DFZ, DFB	Max 7% FAME. Specification FAME according EN14214 or ASTM D6751	DFA, DFZ: S < 1.0% DFB: S < 1.5%
	DM-fuels (Marine Gasoil) DMA, DMB, DMZ	FAME < 0.5% and no intentional addition	DMB: S < 1.5%
	RM-fuels (Heavy Fuel Oil) RMA30, RMB30, RMD80, RME180, RMF180, RMG380, RMH700, RMK700	FAME < 0.5%	RMA, RMB: S < 3,5% RMD: S < 4.0% RME RMK: S < 4.5%
	DM-fuel (Marine Gasoil) DMX	100% FAME free Especially for Cat 1 engines < 5 dm^3/cyl	DMX: S < 1.0%
Partly ISO 8217	Very Low Sulfur Oil (VLSFO)	FAME < 0.5%	S < 0.5%
Partly ISO 8217	Ultra Low Sulfur Oil (ULSFO)	FAME < 0.5%	S < 0.1%, according to sulfur directive 2005/33/EC

Despite these standards, a certain amount of bunkers supplied in the Netherlands often contain higher FAME contents. Mostly delivered are B20 to B30 (respectively 20% and 30% FAME), but also B50 and B100 are being delivered. FAME generally has very low sulphur content, so FAME blending will not cause a fuel to exceed the max sulphur content.

The main fuel type of this validation study is GoodFuels MDF1, generally supplied in the blend ratios B30 to B100.

An overview of the fuel properties of mostly used fossil fuels and biofuels is presented in the table below. The table shows that the specific energy content of pure FAME (B100) on a mass or volume basis are respectively 14% and 10% lower than for MGO. The specific energy content of HVO on a mass basis is about 3% higher than for MGO, while on a volume basis, this is 5%-6% lower. The reason for the lower energy content of FAME is the high oxygen content of FAME. About 14% of the fuel mass is oxygen. This is also the reason that the specific CO_2 emissions per g fuel is a lot lower than for MGO (2.81 versus 3.206 g/kg fuel). The specific CO_2 emissions per energy unit MJ, is almost identical as for MGO and HFO. The MJ fuel energy generally determines mechanical work (power) output of the engine. Note that these Tank-to-wake CO_2 emissions (which can be measured in the tailpipe) are independent from the Well-to-Wake specific CO_2 emissions. These are generally much lower for biofuels because of the CO_2 adsorption during the growing of the biofuel feedstock.

Table 2-2: Technical characteristics of different fossil and biodiesel fuel types. Source: TNO, MKC, TU Delft (2018), Dep of Energy, 2020, MAN Diesel 2006 and fuel analysis (MDF1-100)

Properties	Diesel HFO RM	Diesel MGO DMB	FAME EN14214	GoodFuels MDF1-100	HVO
Chemical structure	$C_{20}H_{42}$–$C_{50}H_{102}$	$C_{12}H_{26}$–$C_{14}H_{30}$			C_8 to C_{25}
Molecular weight (g/mol)	100 - 700	190–220 (170 – 180)			
Density (kg/m³) liquid	900 – 1000	850 - 900	860 – 900	880	780
Kin. Viscosity (cSt)	<700/50°C	< 11	3.5 – 5.0	3.5 – 5.0	2.9 - 3.5
CFPP (°C)		-43 to -9	-15 to -7	-	
Boiling point (°C)	121 - 600	180-360	330 – 350	-	
Lower heating value (MJ/kg)	40 – 42	42.6	36 – 38	37.2	44.0
Lower heating value (MJ/dm³)	38 - 40	36	32 - 33	32.7	34
Cetane number	> 20	> 35	> 51	> 51	84 - 99
Flammability limits (vol)		1.85 - 8.2			
Flash point (°C)	> 60	> 60	>120	101	
Carbon content		86%	76.5%	-	85%
Specific CO_2 (g/g fuel)	3.114	3.206	2.81	-	3.12
FSC (ppm m/m)		<1000	< 10	10 (< 25)	

2.2 Regulatory framework (pollutants, safety)

Biodiesel can influence the pollutants formation during the combustion in the diesel engine. The high cetane number of both FAME and HVO biodiesel should generally have a positive influence on (meaning reduction of) pollutants emissions such as NO_x and particulate emissions. This is because it stimulates auto-ignition and in that sense reduces for example the ‘ignition delay’, the delay period between injection and ignition of the fuel. This suppresses NO_x formation, because the average oxygen concentration is somewhat reduced.

The high oxygen content of FAME type biodiesel works the opposite way: the NO_x often increases, because addition oxygen is brought in the combustion process. This second effect of FAME dominates resulting in some NO_x increase, compared to distillate diesel fuel. This influence is proportional with the biodiesel blend percentage [Varatharajan, 2012].

2.2.1 MARPOL Annex VI

The pollutant emissions of ship engines are controlled via IMO MARPOL Annex VI regulations.

Fuel sulphur content and emissions of SO_x and PM are treated in regulation 14 of MARPOL Annex VI. Different limits apply in different ocean areas. The regulation requires that the fuel sulphur content (FSC) of marine fuel in a Sulphur Emission Control Areas (SECAs) does not exceed 0.1% m/m. Of the seas close to Europe, the Baltic Sea, and the North Sea and the English Channel are SECA ares. Further SECAS exist in the costal areas of the United States of America and China. From 1st of January 2020 a world-wide limit on maximum FSC of 0.5% will be enforced outside SECAs. This is a significant reduction from the currently allowed FSC of 3.5%. The FSC requirements can be met by using fuel fulfilling these requirements. Alternatively it can be met by using a SO_x scrubber such that the SO_x is removed from the engine exhaust gasses.

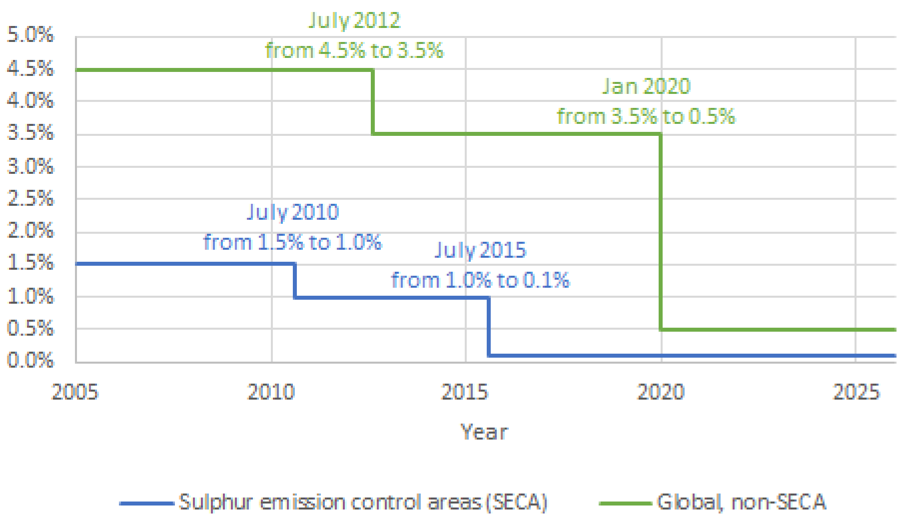

Figure 2-1: Fuel Sulfur Content (FSC) requirements for sea ships (% by weight).

The NO_x pollutant emissions of ship engines are regulated via IMO MARPOL Annex VI regulation 13. In particular, these are described by the IMO NO_x technical code ((MEPC.177(58) and MEPC.251.(66)) and apply to diesel engine with more than 130 kW power output. The maximum NO_x emissions are quite dependent on the maximum engine speed. The lower this max engine speed, the higher the limit value of specific NO_x emissions expressed in g/kWh (gram per unit of engine work). An overview of the (logarithmic) functions of the Tier I, II and III limit value and year of enforcement are presented in the table below.

Table 2-3: IMO MARPOL NOx requirements dependent on the maximum engine speed.

Tier	Ship keel laying date on or after	Total weighted cycle emission limit (g/kWh)		
		n = engine's rated speed (rpm)		
		n < 130	n = 130 – 1999	n ≥ 2000
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$	7.7
III	1 January 2016	3.4	$9 \cdot n^{(-0.2)}$	2.0

The NO_x emissions of the engine is calculated as a weighted average during the applicable ISO test cycle. In practise these are 4 to 5 engine points in the engine map.

In order to proof NO_x compliance, the EIAPP (Engine International Air Pollution Prevention) Certificate needs to be valid. This also requires mandatory periodic surveys when the vessel is in operation. The IAPP certificate is usually issued by a classification society on behalf of the flag state.

2.2.2 MARPOL Annex VI and biofuel

The options of using high-blend (>7%) biodiesel in line with the MARPOL rules are summarised in the DNV newsletter: DNV (2022):

- Up to 7% FAME (B7): is permitted without any need for action under Annex VI Regulation 13.
- For blends of 7% - 30% FAME (B7-B30): assessment of NO_x impacts is not required according to provisions of MEPC.1/Circ.795/Rev.6.
- For blends of more than 30% FAME (>B30): assessment of NO_x impact is not required if biodiesel can be used without changes to the NO_x critical components or setting. However, operators need to clarify this by one of the following options:
  a. Execute emissions measurements according to MARPOL Annex VI regulation 3.2
  b. Apply for use of biofuel as an 'equivalent' under MARPOL Annex VI regulation 4
  c. Apply for a unified interpretation by MEPC.1/Circ.795/Rev.6.

Options a and b need to be executed in cooperation with the flag state and classification bureau. According to the Dutch port state control, IL&T, the emission measurement (a) is always necessary for 30% FAME and up. Consequently the ship can apply for an exemption according to regulation 4.

Most 2-stroke and 4 stroke MS engines are already designed to use a wide variety of fuels such as MGO, LFO, HFO, ULSFO and the manufacturers usually allow high blends of FAME, even up to 100%. In these cases, the engine manufacturer need to declare that no changes are needed to the NO_x critical components and settings and that the engine will remain compliant with the NO_x limit value. A test performed on the parent engine will most probably be sufficient to demonstrate the latter.

2.2.3 Safety requirements

There are several (operational) risks associated with a FAME type biodiesel, such as leakages due to not fully FAME resistant elastomers or packings and filter plugging. Refer to section 2.3. For this reason precautions need to be taken (especially if the fuel is considered a special fuel according to MVR 4-2-1/13.9.6). For blends up to B30, a declaration of the engine manufactures is sufficient. For blends higher than B30, a risk assessment needs to be done. This includes testing of the fuel change over procedure an onboard verification of several aspects including documentation and crew understanding.

2.3 Impact on maintenance and reliability

2.3.1 Literature

Main conclusions of the observed challenges on board of different investigated vessels with biodiesel (FAME) blends are based on a short description about a number of relevant literature sources (Appendix A).

A number of references; (Alleman et al., 2016; Hsieh & Felby, 2017; Nayyar, 2010; NEN, 2021; Opdal & Hojem, 2007; Tyrovola et al., 2017; Verbeek et al., 2020; Zhou et al., 2020); identify that higher FAME blends tend to have negative impact on the maintenance and reliability of engine systems of the vessel. Possible consequences and risks from the use of high biofuels blends include:

- Microbial growth, causing filters and pipes to clog and corrosion of metal surfaces.
- The high oxygen content causes oxygen degradation, causing oxidation of the fuel and decrease in operational performance. Also, the long-term storage or shelf life of the fuel decreases significantly compared to conventional diesel.
- Acid degradation products of FAME can cause damage to the engine systems like fuel pumps, injectors and piston rings.
- The cold flow properties of FAME causes wax to be formed at low temperatures, which can in its turn lead to filter plugging.
- FAME softens and degrades certain rubber hoses, elastomer compounds and gaskets which are used in older engines.
- Deposits build up in the fuel tank by diesel can be dissolved by FAME which could then clog filters. Also water can possibly dissolve in FAME leading to problems in the low pressure fuel system or fuel filters.
- Degradation of engine lubricants.

These risks can be mitigated by good maintenance of the fuel and engine systems. These include frequent inspections and cleaning of these systems and more frequent replacement of the fuel filters and engine lubricant if needed. Also switching to synthetic hoses and seals that are biodiesel resistant will solve the degradation of rubber compounds.

Literature in Appendix A also highlight the positive impact of FAME on the internal systems within the vessel, which includes:
The higher oxygen content provides a more complete combustion.
The lubricity of the overall fuel is better compared to diesel. Higher blends may reduce the general wear on the engine systems.

2.3.2 Survey under ship owners

Six Dutch ship owners participated in a limited survey about the use of biodiesel in ships. Additionally, a shipping company and vessel owner were interviewed on the same topics. Six of them had experience with one or more types of FAME biodiesel blends. The two remaining ship owners had experience with HVO biodiesel (hydrotreatment vegetable oil) and with biogas (bio-LNG).

In most cases the usage of biofuel blends by the participants was spread over several ships with up to four ships per ship owner. In a few cases the base fuel of those vessels was MGO, but in a several cases it was ULSFO, VLSFO or HFO. In most cases, the FAME blends were only used for the main engines of the ship. The testing durations with biodiesel varied from badges from one hundred to several hundred tonnes in periods of a quarter year to several years. (Almost) all ships were equipped with Medium Speed (MS) diesel engines for the main propulsion.

De FAME biodiesel blends used were the following:
- B30: 3 shipowners
- B50: 3 shipowners
- B70: 1 shipowner
- B100: 4 shipowners

Maintenance with biodiesel
In general the ship owners were positive about the use of biodiesel. There were no significant issues reported high water with respect to maintenance or operational aspects. For one ship owner very content of the FAME fuel came up as an operational issue. Other participants however did not have this experience. On the question whether additional maintenance was needed with biodiesel, the strategy of good tank cleaning and flushing was mentioned a few times. This possibly could lead to more tank cleaning efforts when switching regularly between biodiesel and regular diesel. Other ship owners experienced no additional maintenance at all and referred to the FAME blends as a very clean fuel with good lubricity. There was one mention about the importance of the right settings for fuel tank temperature and the viscosity controller with biofuel, because of the higher pour point.

Performance with biodiesel
With respect to questions about the influence on performance and fuel consumption: five ship owners mentioned some increase in fuel consumption and in two cases a (slight) loss of power was mentioned. This loss of power did however not come up as an operational issue. There was one mention of 7%-10% increase in fuel consumption. It should be noted, that FAME has about 14% lower combustion value than MGO (per kg fuel). Consequently when using FAME blends from 30% to 100%, an increase of fuel consumption from about 4% to 14% Is to be expected. One participant explicitly mentioned their ships with electronic engine control were able to handle FAME up to 100% very well.

Questions and comments regarding biodiesel
A general comment coming back from the interview participants is the lack in transparency of the feedstock and origins of the biodiesel. It is difficult to know what is being burned, especially for the vessel crews operating on biodiesel this also results in concerns for possible health effects. Furthermore, although the use of FAME biodiesel in general proved successful, several participants mentioned to always keep a backup of regular fuel onboard as long-term effects of FAME are still largely unknown.

2.3.3 Feedback engine manufacturers

The feedback of the engine manufacturers on the use of biodiesel fluctuates. A clear distinction is made between FAME type biodiesel and HVO, and also between Tier III engines (with aftertreatment) and older engines. A regularly heard feedback is that the FAME quality can vary (depending on the feedstock and production aspects). Often HVO, up to 100% blend (HVO100) can be used in engines.

The recommendation per engine manufacturer are as follows:

- Caterpillar: All engines HVO100 compatible. Very few issues with (low blend) FAME.
- Mitsubishi: Normal compatibility is up to B7. For higher blends, up to B30, and for HVO, a special coating for fuel injection plungers and injectors is recommended to avoid increased wear. Also thorough tank cleaning before switching is recommended, along with a centrifugal filter (generally already present).
- Volvo: max B10 for Tier III engines, generally max B30 for older engines. All engines HVO100 compatible. High-speed engines are generally derived from road vehicle or mobile machine engines, which are developed and durability tested with the high-quality road vehicle diesel fuels (EN590). Earlier manufacturers feedback indicated that FAME type biodiesel causes an additional durability risk for engine and aftertreatment system.
- Wartsila:
  Positive about the use of biodiesel in general, and confirms that there engines and fuel systems are compatible with any biofuel that meets established standards. Wärtsilä also mentions the need for tank cleaning before switching to biodiesel. They ask to check the use of high blend FAME for each specific ship or engine installation with Wärtsilä.

The feedback and main recommendations of the engine manufacturers are summarised in the table below.

Table 2-4: Recommendations for the use of FAME blends for the Dutch reference vessels.

Nb	Vessel type	Engine type	FAME biodiesel recommendation	General recommendation
1	General Cargo	Medium Speed	Up to B100 often possible	Check higher than B10 blends with engine supplier. Centrifugal filter and day tank are generally already installed.
5	Dredging			
2	TUG	High Speed	Limit FAME blend to B10 or B20 In some cases higher blends are supported by engine supplier	Install centrifugal filter and day tank for fuel circulation. Check higher than B10 blends with engine supplier.
3	Offshore supply			
4	Crew Tender			
6	Super yacht			

2.4 Conclusions

With respect, to practical application of FAME type biodiesel, the following conclusions can be made:

- General positive feedback was received from ship owners, about the use of B30 to B100 (30% to 100%FAME) blends.
- Engine manufacturers are cautious. High-Speed engine manufacturers often recommend to limit FAME blends to B20. There were no directs blend limits for Medium-Speed engines, although manufacturers ask to check with them on a case by case basis. The precise reasons for the FAME blend limitation with high-speed engines are not clear. Possibly, the uncertain influence of FAME on the aftertreatment lifetime or specific wear risks on some engine components play a role. Medium and slow speed engines are developed to accommodate different fuel types, which may make manufacturers less hesitant towards biofuels.
- FAME quality used for blends should comply with the normal standards like EN14214 or ASTM D6751
- The need for tank cleaning when switching to a FAME blend is often mentioned by ship owners and engine manufacturers. This may limit the flexibility in periodic switching between Fuel Oil and FAME blends, with limited availability in all ports of call. The tank cleaning is likely needed for the risk of dissolving of tank residues in FAME fuel.
- The impact to operational aspects are limited to bunkering a slightly increased fuel quantity (plus ≈ 10% by volume). Additionally, measures, like more frequent inspections and cleaning of fuel tanks and filter system, limit or eliminate most potential risks.
- In general there are no limitations to the use of synthetic biodiesel such as HVO or FT biodiesel, provided that these fuels fulfil the requirements of the fuel standards.

3 Environmental impact

3.1 Validation approach

The validation of the Environmental impact of GoodFuels' MDF1 and other biodiesel options are based on literature study and on specific measurements of a general cargo vessels running on several blends with GoodFuels' MDF1 (section 3.2.2).
This section is split in section 3.2 which concerns the validation of the Tank-To-wake pollutant emissions and section 3.3 which contains the Well-To-Wake GHG emissions validation.

3.2 Tank to Wake emission

3.2.1 Literature on pollutants

A short description about a number of relevant literature sources is given in Appendix A.
Up to 2005 quite a lot of measurement results were published with conventional truck engines (without specific NO_x aftertreatment or EGR) to different FAME blends. A lot of measurements were collected and summarized in the Dutch BOLK project. The response of the pollutant emissions can be summarized as follows:
NOx: Up to B20: no clear influence. Above B20: increase in NO_x proportional to the blend percentage: average increase of 12% with B100, although for different measurements, it range from no influence up to 30% increase. Refer to figure below.
PM emissions: Strong reduction of PM emissions proportional with FAME blend percentage. At B100, the average reduction is 57%, although also a range in the measurements can be seen from 20% reduction to some 80% reduction.
(unburned) hydrocarbon emissions show a similar strong reduction as PM with increasing FAME blend percentage. On average there is a 44% reduction for B100.
CO emissions also show a reduction proportional with the FAME blend percentage. At B100 the average reduction is 19%.

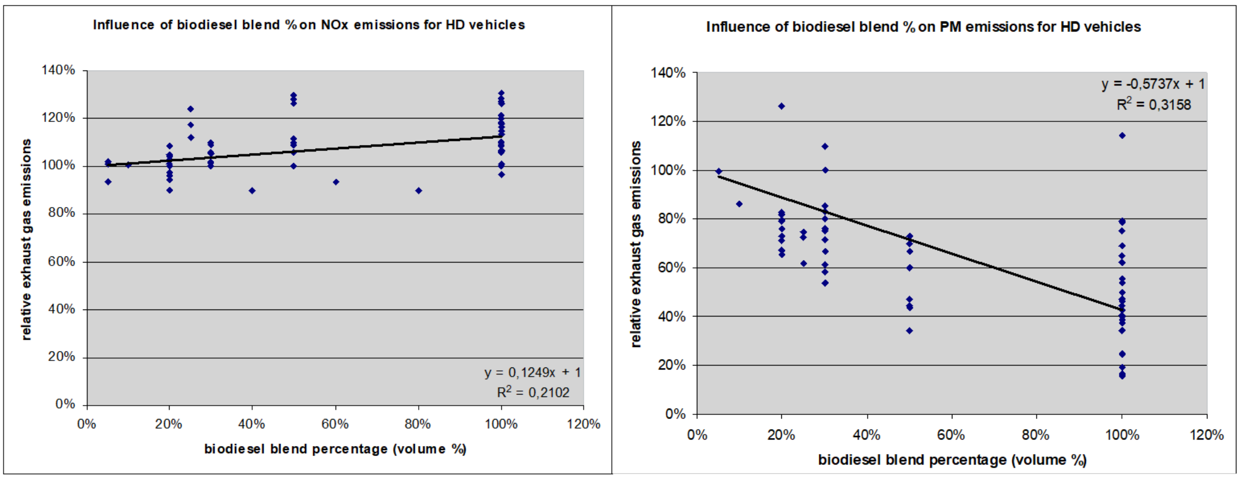

Figure 3-1. Influence of biodiesel-FAME blends emissions of HD engines (road transport).
Left: NO_x emissions Right: PM emissions

For sea ships, the fuel quality can vary apart from the influence of a biodiesel-FAME blend. As shown in section 2.1, different types of fuel can be used such as a Distillate Marine (DM) fuel type or a Residual Marine (RM) fuel type. And within those two there are large differences in Fuel Sulphur Content (FSC), primarily dependent on the sailing region and on whether or not a SOx scrubber is used (refer to section 2.2). The type approval of ship engines is generally done on the high quality fuel distillate marine fuel. It is generally known that a residual fuel (RM) leads to somewhat higher NO_x emissions. The particulate matter (PM) emissions are in practice proportional to the FSC. This is because a certain (small) percentage of sulphur oxide emissions is converted to sulphate which condensates on the soot particles (along with heavier hydrocarbons and some water) of the diesel engine.

Several sources report on the influence of the diesel fuel type and biofuel blends, for example (Aakko-Saksa et al., 2017, sponsored by Finnish Tekes and industrial partners; MAN, 2022).

MAN, (2022), reports on the NO_x emissions of using FAME and HVO type biodiesel blends for Low Speed engines. It compares the influence of FAME to DM and RM fuel grades based on a not specified number of emission measurements.

They come to the following conclusions for FAME type biodiesel:
- DM fuel and B30-B80 FAME blends have similar NO_x emissions
- B100 has similar emissions than residual marine (RM) fuel.
- For HVO type biodiesel, they conclude that the NOx emissions will be very similar to DM fuel, since the HVO fuel quality is similar to DM.

Evaluated the presented graph (see figure below), it can also be concluded that the emissions with RM and B100 are some 15% higher than with DM fuel. And at the 25% and 50% engine load points, B100 can lead to up to some 30% higher NO_x emissions. Engine producer Wartsila makes a general statement on NOx emissions with biodiesel, namely 10% to 20% increase of NO_x (Wärtsilä Marine Power, 2023).

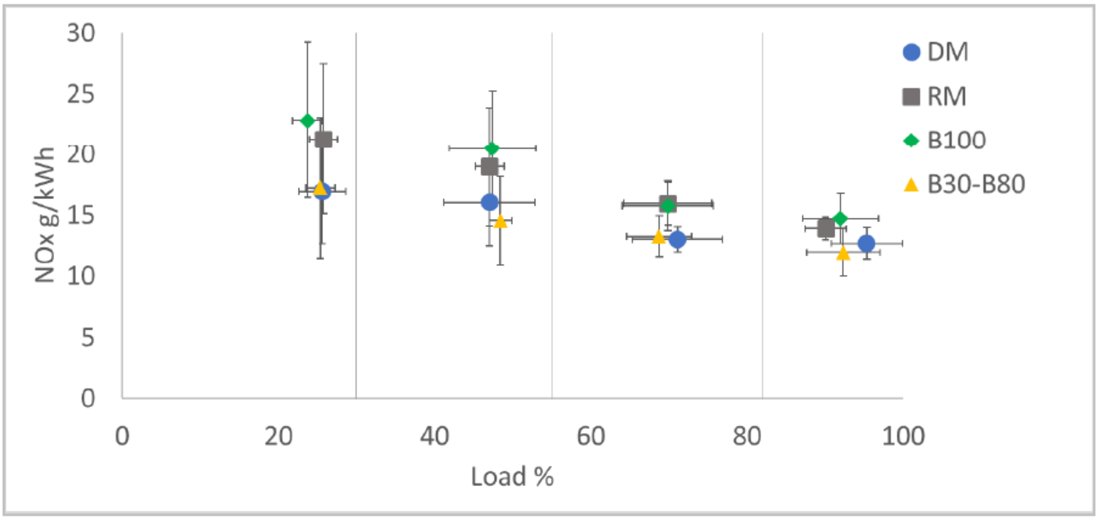

Figure 3-2: NO_x emissions of Low Speed engines with distillate marine (DM) fuel, residual marine (RM) fuel and FAME blends (B30-B80) or neat FAME (B100) (MAN, 2022).

Aakko-Saksa et al., (2017) is mostly focused on particulate matter (PM) and Black Carbon (BC) emissions, since it was focused on the investigation of BC emissions in artic regions.

This publication gives a thorough insight on the influence of fuel properties on engine behaviour, measurement principles and engine emissions including NO_x. It also states that the NO_x increase with FAME is assumed to be related to “its high density, high distillation temperature, high oxygen content and number of double bonds”. It also states that the “reduction of PM emission with FAME is believed to be due to presence of oxygen”.

Very extensive measurement results are reported for a Medium Speed Wartsila engine, with four fuel: two marine diesel oils (MDO) with 0.1% and 0,5% FSC, HFO with 3.5% FSC and Bio30, a 30% FAME blend with MDO.

When comparing MDO with ‘Bio30’ (30% FAME), the following is concluded:

- Bio30 leads to a small NO_x rise of 1%-3% depending on the load point.
- Particulate Matter (PM), is reduced by some 15% to 30% depending on the measurement technique.
- Black Carbon (BC) emissions are reduced by some 30% to 50% depending on the load point.

The PM and BC emissions are shown in the figure below, both in terms of mass concentration in the exhaust gas as well as in gram per kg diesel fuel equivalent. The figure clearly shows the very large influence of the FSC on both PM and BC emissions.
Remarkable also for this publication is that the HFO (3.5% FSC) did not lead to a NO_x rise. On the contrary, it led to small reduction of 1% to 5% depending on the load point.

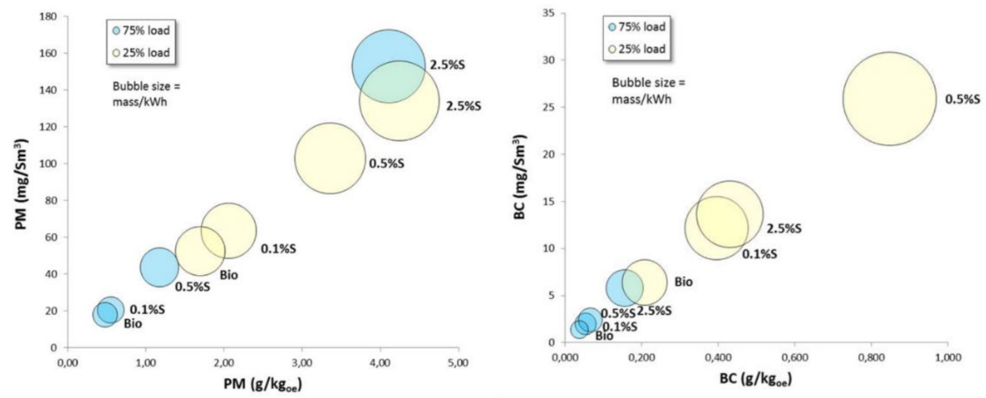

Figure 3-3: PM emissions (Left) and BC emissions (right) with 4 different fuels and a MS engine (Aakko-Saksa et al., 2017).

3.2.2 Measurements with GoodFuels MDF1

Measurement procedure

Extensive emissions measurement with the GoodFuels MDF1 FAME blends were carried out on a general cargo ship. The ship was constructed in 2008 and sails under the Dutch flag. Relevant characteristics of the ship and the ship driveline are noted in Table 3.1.
The measurements included NO_x, PN and PM emissions of the ship.

Table 3-1: Relevant ship properties general cargo vessel.

IMO number	********[3]
DWCC (summer)	3600 ton
Length	88.6 m
Breadth	12.5 m
Draught	5.42 m
Main engine	MAK 8M20C
Main engine power	1520 kW at 1000RPM
Driveline	Constant speed with variable pitch propeller
Main engine class	Tier 1

Measurements aboard the ship are performed with three MDF1 FAME blends and the MGO reference fuel. MGO, B70 and B100 were measured during normal operation. The measurements with B50 were limited and with the ship along the kay. This resulted in the measurements on this blend to be discarded for final analysis due to not enough measurement points being attainable. Samples of the test fuels were taken for fuel analysis. The main parameters such as FAME content and Lower Heating Value (LHV) are summarized in the table below.

Table 3-2: Fuel analysis of fuels used during measurements onboard test vessel.

Properties	MGO[4]	B50	B70	B100
FAME content [%V]	0.05%	29.3%[5]	64.3%	98.4%
LHV [MJ/kg]	43.28[6]	41.05	39.23	37.17
Density at 15°C [kg/m3]	851.2	851.5	861.3	880.1
FSC ppm[7] m/m	853	(606)[8]	(311)[8]	9.6

The power setpoints for the measurements are defined by the official marine engine test cycle. 82% power is used as additional setpoint, since this is the maximum attainable power during normal operation. The 75% setpoint is most frequently used during normal operation. For constant speed engine operation with a controllable pitch propeller, the official test cycle as described in the NO_x technical code 2008 is the E2 cycle. This cycle is defined with the power and speed settings as shown in Table 3-3.

[3] Left out for privacy reasons
[4] Taken from the bunker note corresponding to the fuel used during the measurements.
[5] FAME content of the 50% biofuel blend seems excessively low. A sampling error seems the most appropriate explanation of this low measurement.
[6] Derived from higher heating value by subtracting condensation heat water vapor.
[7] According to fuel suppliers Shell and GoodFuels
[8] By interpolation

Table 3-3: E2 test cycle.

Speed	100%	100%	100%	100%
Power	100%	75%	50%	25%
Weighting Factor	0.2	0.5	0.15	0.15

As power or torque measurements are not available aboard the ship, engine setpoints were determined using the fuel rack position of the fuel pump (unless specified otherwise). The actual output power is calculated afterwards from fuel flow and brake specific fuel consumption. A constant fuel rack position ensures an equal fuel flow to the engine between the different measurements on the same load setting. Note that differences in energy content of the fuel will therefore result in slightly different engine power. The propellor pitch setting was noted on each measurement as an additional reference for engine power.

Not all setpoints are attainable during normal operation, as such the test cycle is adapted according to the technical code guidelines as shown in Table 3.4. The adapted E2 cycle setpoints are used for both the gaseous and particulate matter emission measurements. Note that the 25% setpoint could not be tested during the voyage.

Table 3-4: Adapted E2 setpoints and E2 cycle weighting factors for onboard testing[9].

Speed	100%	100%	100%
Used for:	E2 cycle	E2 cycle	Max load during normal operation
Power IMO	50%	75%	82%
Original weighting factor	0.15	0.5	-
New weighting factor	0.23	0.77	-

NOx emissions
The specific NO_x emissions for the reference fuel MGO and the two FAME blends B70 and B100 are shown in the figure below. The load points consists of two E2 cycle points and the maximum attainable power setpoint during normal operation (82% engine power).
The figures shows that the NO_x increases by about 0.5 to almost 2 g/kWh with the use of the FAME blends compared to MGO. This is a quite normal response with FAME blends.

[9] According to the technical code. The E2 or E3 cycle can be measured by a minimum of two load points from which the 75% power point is mandatory.

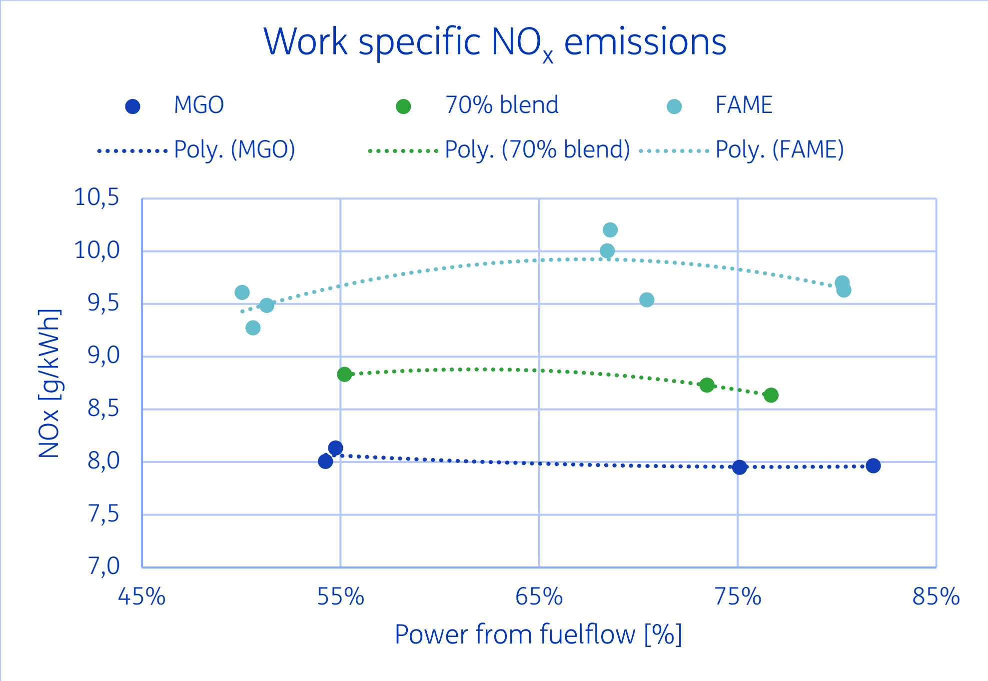

Figure 3-4: Work specific NO_x emissions with humidity correction.

The weighted average NO_x emissions during the E2 cycle are shown in Table 3-5. The table shows an average NO_x increase with B70 and B100 of respectively about 10% and 24%. The table also shows, that with B70 and B100, the NO_x emissions are still well below the Tier I limit value.

Table 3-5: Weighted average NOx[10] emissions E2 cycle with humidity correction.

	Date	NO_x	NOx increase	NO_x Tier I limit value
	dd-mm-yy	g/kWh	%	g/kWh
MGO	04-10-22	7.97	-	11.30[11]
B70	01-10-22	8.75	9.8%	
B100	02-10-22	9.84	23.5%	

Particulate Matter emissions

It should be noted that particulate emissions for maritime engines are not regulated, In Aakko-Saksa et al., (2017), it was shown that the PM mass emissions were quite dependent on for example the setting of the dilution ratio of the exhaust gas.. Furthermore, for the B100 measurements, high water content in the sample gasflow was noticed. This can make filter weighing less reliable. Particle matter mass emissions are shown in Figure 3-5.

[10] NO_x humidity correction factor included.
[11] Based on a Tier I constant speed engine operating at 1000 RPM.

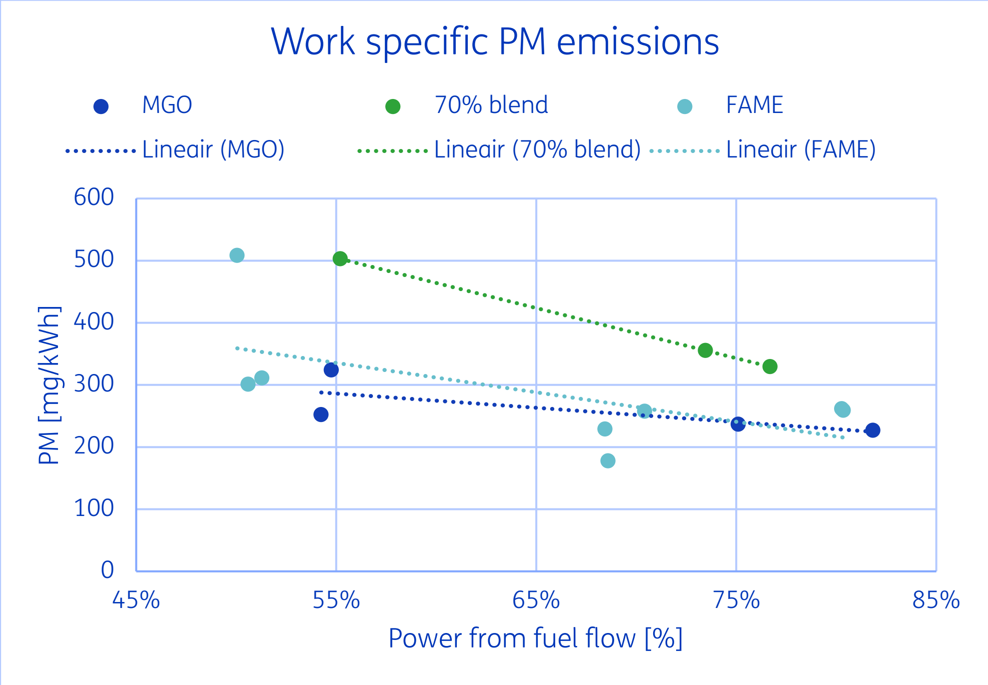

Figure 3-5: Work specific PM emissions.

The PM emissions of the B100 fuel are quite similar to the PM emissions of the MGO fuel, taking into account the measurement uncertainties. The majority of B100 measurements falls within 10% of the MGO results. Only at low load the B100 fuel has a single measurement showing a 57% increase of particulate mass. In contrast with the B100 measurement results, the B70 measurements show an increase of PM emissions compared to the MGO results. These deviating results might be explained by the engine not having reached a steady state yet during these measurements despite the temperature gauges of the engine showing stable conditions.

Black Smoke emissions
Black Smoke engine emissions are especially important for ships sailing across artic routes. BS causes a black coating on snow and ice leads to more heat adsorption from the atmosphere and consequently melting of the snow and ice. Additionally BS emissions are a reasonable indication for the level of Black Carbon (BC) emissions, however the relation between the two can be fuel type and engine type dependent. BC emission is also a direct greenhouse gas which contributes to the atmospheric temperature rise.
BS in the exhaust is an indicator of Elemental Carbon (EC) within the particulate matter. Black smoke is generally measured via the Filter Smoke Number (FSN). In this case the AVL 415S is used. The higher this number the higher the blackness of the exhaust gases. The BS measurement results with B100 are shown in the table below. It shows that the BS emissions with B100 are about 80% lower than with MGO. Also with B50 and B70 a strong reduction of BS was seen, proportional to the FAME content. For B70, the average reduction was 65%.

Table 3-6: Black smoke measurement with B100 and MGO.

B100	Black smoke – B100		Black smoke - MGO	
Rack – estimated power	FSN	mg/m^3	FSN	mg/m^3
50% load	0.053	0.66	0.317	4.37
75% load	0.042	0.52	0.206	2.72
82% load	0.045	0.56	0.234	3.13

Particle Number (PN) emissions
Particle number gives an indication of the amount of particles per volume of exhaust gas. It can also be transferred to a number emission per kWh of engine work. The PN emission is measured with TSI NPET measuring equipment. Volatile (hydrocarbon) particles are removed before the measurement, but the particle counter does not look at the particle size of the particles.
The table shows a significant increase in PN emissions with B100 compared to MGO. The increase with B100 is about a factor five. Apparently with B100 smaller particulates are emitted, since the total PM mass emissions are very similar to the emissions from MGO. For the B50 and B70 blends, the PN emissions are generally very similar to those of MGO.

It should be noted that particle number emissions are generally plotted on a logarithmic scale and differences below a factor 10 are not seen as (very) large differences.

Table 3-7: Particle number measurements on B100 on MAK 8M20C.

B100	PN B100 [#/cm^3]	PN MGO [#/cm^3]
50% load	51.9 * 106	8.4 * 106
75% load	46.6 * 106	8.6 * 106
82% load	54.3 * 106	10.7 * 106

3.2.3 Other measurement reports

A number of emissions measurements reports were made available by the Dutch inspection ILenT. This included a LR report summarising some 6 engine tests with different FAME blends and also with different fossil fuel types (particularly ULSFO and VLSFO and in one case HSFO). Additionally about 4 reports of individual ship measurements were provided. For several measurements no reference measurements were done with standard fossil diesel fuel. The results were than compared with the Tier I or II limit value.

In the figure below the average cycle results for in total 10 engines with different FAME blends (B30 to B100) and often different diesel fuel types are given. In general the figure shows some NOx increase proportion with the FAME blend percentage. It also shows that the NOx for VLSFO can be somewhat higher than for ULSFO.

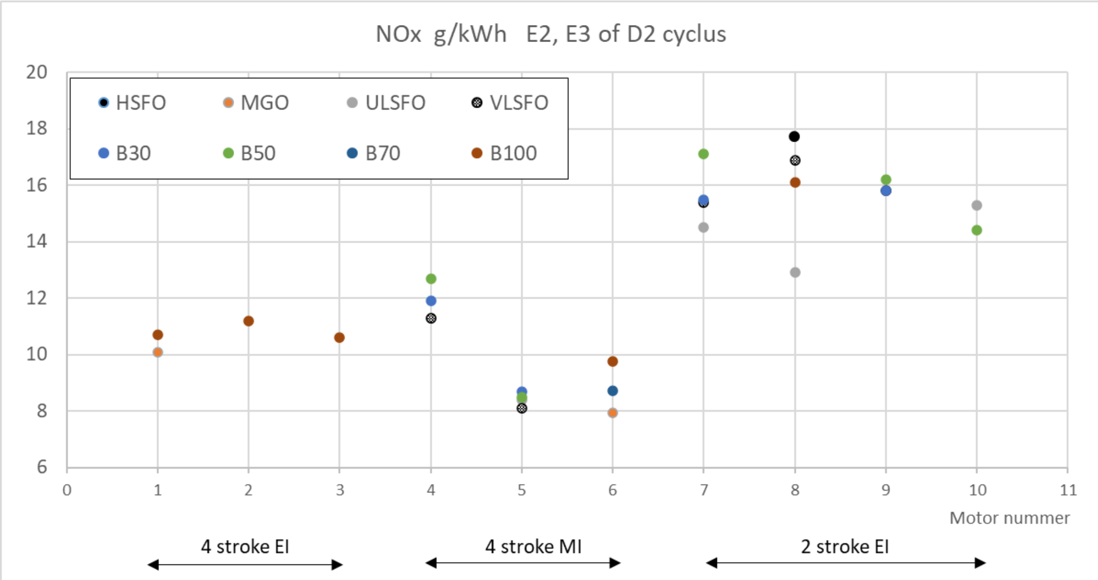

Figure 3-6: Influence of FAME biodiesel blends on NO_x emissions of marine engines

The average NO_x increase and variations per FAME blend (B30 -B100) is given in the table below. This shows for example that with B100 (100% FAME), the average NO_x increase of the data set is 12%. The variation is however considerable, namely it varies from 6% to 25%.

Table 3-8: Average NO_x increase with FAME blends compared to ULSFO or MGO

Fuel type	B30	B50	B70	B100
Average increase %	3%	5%	10%	12%
Variation	0 toto 7%	-6% to 18%	-	6% to 25%

3.2.4 Conclusions

The emissions measurements with the GoodFuels MDF1 FAME blends; B50, B70 and B100 on the general cargo vessel, lead to the following conclusions:

- For all FAME blends tested, NO_x emissions of the main propulsion engine are significantly below the applicable NO_x limit.
- The NOx emissions during the E2 cycle with B100 were approximately 23% higher than the baseline result with MGO. The NOx emissions at the generally used 75% load point were a little under 25% higher with B100. The NOx increase was shown to be proportional to the blend ratio. Note that the limited amount of measurement points induces a high measurement uncertainty (see Section 3.3.3), as such the above-named percentages should be taken as guidelines and not as exact numbers.
- The Black Smoke (BS) emissions are up to 80% lower with B100 compared to MGO. Also for B70 a large BS emission reduction compared to MGO is observed.
- The Particle Number (PN) emissions seem to increase with FAME, especially at higher load and at high FAME blends. However, the Filter Smoke Number (Black Smoke, blackness) decreases, and the particle emissions of the biofuel (blends) most likely exist of smaller particles compared to MGO.
- It should be noted that the water content of the biofuel (blends) was observed to be much higher compared to the MGO fuel for the sample analysed. When not properly addressed, this can in the long run result in oxidation issues.

The results from other measurement reports and literature are in line with the measurement results with GoodFuels MDF1. On average, the NOx increase with pure FAME (B100) compared to ULSFO or MGO is 12%, but with a bandwidth of 6% to 25%. It can also be concluded that both different types of fossil marine fuels and FAME lead to NO_x emissions variations. NO_x also tends to be significant higher with residual marine fuels compared to distillate marine fuels. Using pure FAME (B100) leads to NO_x emissions in the top of the range of the NO_x emissions bandwidth. The results also shown that the NO_x emission generally stay below the Tier limit value. It can however not be excluded, that for certain engines the NO_x limit value will be exceeded especially with B100. If that happens a lower max blend percentage may be considered to stay within the limit value.

3.3 Well to Wake GHG emission

For the validation process, not sufficient supply chain input data was provided by GoodFuels. However, the relevant feedstocks for biofuel production under GoodFuels operations are mainly brown grease, and Used Cooking Oil (UCO) and Tallow to a lower extent (Ferrari, 2022). Given the lack of data, GHG emissions for (advanced) biofuels are presented and retrieved from the Renewable Energy Directive Recast (REDII) standard values (European Commission, 2018b).

In the EU, REDII provides the standards to calculate the GHG emissions from the production and use of biofuels and bioliquids, among other renewable energy sources. For (advanced) biofuels to be rolled into the market, the overall GHG emissions should provide savings compared to their fossil fuel reference counterpart as follows (European Commission, 2018b):

- At least 50 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations in operation on or before 5 October 2015
- At least 60 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 6 October 2015 until 31 December 2020
- At least 65 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 1 January 2021

According to REDII, GHG emissions from (advanced) biofuels are calculated following Equation 1 (European Commission, 2018b).

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}, \qquad \text{Equation 1}$$

Where:
E: total emissions from the use of the fuel, g CO_2eq/MJ
E_{ec}: emissions from the extraction or cultivation of raw materials, g CO_2eq/MJ
e_l: annualised emissions from carbon stock changes caused by land-use change, g CO_2eq/MJ
e_p: emissions from processing, g CO_2eq/MJ
e_{td}: emissions from transport and distribution, g CO_2eq/MJ
e_u: emissions from the fuel in use, g CO_2eq/MJ
e_{sca}: emission savings from soil carbon accumulation via improved agricultural management, g CO_2eq/MJ
e_{ccs}: emission savings from CO_2 capture and geological storage, g CO_2eq/MJ
e_{ccr}: emission savings from CO_2 capture and replacement, g CO_2eq/MJ

Under REDII definition, for biofuels that use a feedstock classified as residue or waste (e.g., brown grease, and agricultural residues) GHG emissions start counting from the point of collection. The feedstocks used for biofuel production under GoodFuels operations are currently categorized as residues/waste. Therefore, GHG emissions from the extraction or cultivation of raw materials and annualised emissions from carbon stock changes caused by land-use change are considered zero. This is also particularly important as a large part of the feedstocks in annex IX part-a are residues or waste. GHG emissions of the fuel in use are zero for biofuels, in line with the REDII calculation rules in ANNEX V.

Figure 3-7 shows the GHG emissions of the different (advanced) biofuel pathways according to REDII standard values. All advanced biofuel pathways report low GHG emissions compared to conventional fossil fuel counterparts and comply with REDII 65% GHG emissions savings criterion. These production routes are largely energy self-sufficient. For example, biofuels that use a gasification process to produce methanol and Dimethyl Ether (DME) are energy self-sufficient, given that off-gases from the reactor can be used internally as energy fuel. In addition, small amounts of additional/auxiliary raw materials are required for the conversion process. Similarly, this occurs for feedstock (straw) fermentation for 2nd generation ethanol production. However, fermentation requires more additional/auxiliary raw materials than other routes. The main GHG emissions for this advanced biofuel pathway are related to transport and distribution. 2nd generation ethanol also shows slightly higher GHG emissions than other advance biofuels, given the conversion efficiency. The feedstock (biomass) to ethanol conversion efficiency is the lowest of all advanced biofuel pathways. To illustrate, 3.5 $MJ_{straw}/MJ_{ethanol}$ is the efficiency for 2nd generation ethanol compared to 2.1 MJ_{woody} biomass/MJFT-diesel or 1.96 for MJ_{woody} biomass/$MJ_{methanol}$ (European Commission, 2018b). The range of GHG emissions shown for each advanced biofuel pathway in Figure 3-7 corresponds to the different feedstock used in the process. The lower range corresponds to biomass residues (no GHG emissions allocated upstream from collection), while the upper range corresponds to short rotation coppice (including the GHG emissions from the cultivation process). Table 8-2 in the appendix includes the conversion routes.

For FAME and HVO, only the pathways that use waste as feedstock (e.g., cooking oil, animal fats) can comply with REDII GHG emissions savings criteria, lower range of GHG emissions shown in Figure 3-7. The GHG emissions from these conversion process pathways are higher than conversion processes from all advanced biofuel pathways. FAME and HVO conversion processes are not energy self-sufficient and require higher energy inputs. Nevertheless, the GHG emissions from FAME and HVO conversion processes are relatively low when compared to the overall supply chain emissions. When first-generation feedstocks such as soybean and palm oil are used, the REDII GHG emissions criteria are not met (upper range in Figure 3-7). Cultivation GHG emissions from these feedstock types are considerably high. In addition, according to the Dutch ordinance (see Chapter 6), these feedstocks are not allowed for FAME and HVO production. However, the difficulty in the traceability of waste feedstock types for FAME and HVO supply chains, in combination with advantageous market benefits (e.g., high prices of used cooking oil), has led to uncertainty about the origin of such feedstock and potential displacement effects (Van Grinsven et al., 2020). Therefore, the overall savings from waste-based FAME and HVO could potentially be lower, as shown in Figure 3-7.

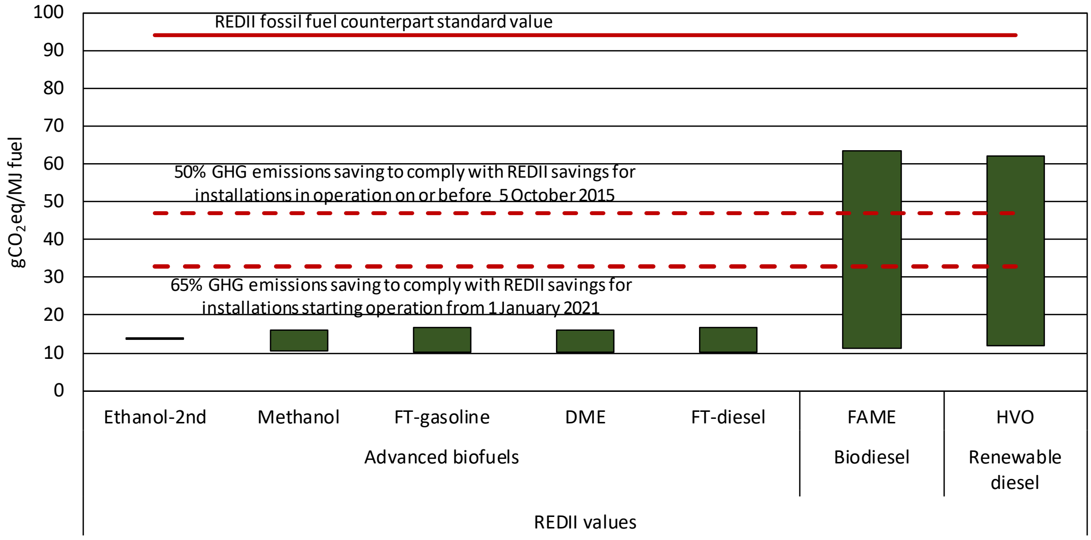

Figure 3-7: GHG emissions according to REDII standard values from different biofuels routes (European Commission, 2018b). See Table 8-2 for feedstock to fuel information

The conversion processes are relatively efficient (given the role of biogenic CO_2) for all (advanced) biofuel pathways, leading to low GHG emissions from feedstock to biofuel conversion. Therefore, the overall performance of these pathways will rely considerably on the following:

- Whether residues/wastes are used as feedstock given that GHG emissions are accounted for from the point of collection.
- Whether feedstocks different from residues/wastes are used, for example, lignocellulosic energy crops such as short rotation coppice given that cultivation (e_{ec}, Equation 1) and land use related carbon stock changes (e_l) GHG emissions are accounted.
- Accountability of biogenic CO_2.
- The efficiency of transport, distribution and logistics (e_{td}).

There are still concerns about the significant variation in GHG emissions performance for (advanced) biofuel logistics (Mussatto, 2017). Delivering feedstock to conversion sites can be challenging as many new inter and intra-EU supply chains will have to be developed from scratch to meet the advanced biofuel demand. These logistics are particularly important to mobilize the required feedstock from annex IX part-a, which cannot be easily accessible in supply nodes and they can be costly. For non-residues/waste feedstocks, the overall GHG emission performance can be strongly driven by carbon stock changes between land uses. This is the case for lignocellulosic energy crops, which are expected to play an important role in advanced biofuel production (Daioglou et al., 2019). For example, Vera et al., 2021 showed that despite meeting REDII land use sustainability criteria, there are several locations in the EU 27 + UK in which the carbon stock changes between prior land use and lignocellulosic energy crop production for advanced biofuels results in high GHG emissions leading to a potential non-compliance supply chain for the REDII 65% GHG emissions savings criteria. Note that carbon stock changes are determined by a wide variation of biophysical conditions such as climate and soil type that are heterogenous over space.

The variables mentioned above, in combination with future fuel demand and proposed legislation, will determine the potential GHG emissions savings across the maritime sector.

However, these savings are uncertain. (advanced) Biofuels are expected to cover a large share of the future fuel mix in the maritime sector (Prussi et al., 2021).
However, this fuel mix is largely determined by costs, technology improvements, ship modifications, upscaling markets, logistics, and the readiness of fuels to meet the demand. There is still no bullet-proof pathway for the maritime sector and several alternatives for advanced fuel types (see Chapter 5) are currently being explored, in addition to other sources of renewable energy. The penetration of such fuels in the maritime sector will drive GHG emissions reduction. Nevertheless, in the short term, with the implementation of FuelEU maritime (see Chapter 6), ships can shift to fossil-based fuels that provide a lower GHG emissions intensity and later introduce higher shares of renewable energy sources. In addition, REDIII proposal is currently negotiated and the targets and sub-targets will also drive the achievable GHG emissions savings once the scope is expanded to include the maritime sector.

3.3.1 Conclusions

GoodFuels did not provide specific information on the production of MDF1. Therefore REDII standard GHG emissions values were used as a proxy indicator. Note that REDII GHG emissions values are based on specific types of feedstock, standard production locations and transport distances. Economic operators can either use default GHG intensity values provided in REDII or calculate actual values for their pathway; these actual values may be different and even lower than the default values.

- Almost all production routes are able to comply with REDII GHG emission savings criterion, except FAME and HVO, when they use first-generation feedstocks.
- Overall supply chain GHG emissions can be driven more by cultivation and land use carbon stock changes when the used feedstock is not a residue/waste. For residues and waste, logistics efficiency can drive supply chain GHG emissions more. GHG emissions from conversion processes are low over the entire supply chain. The role of biogenic CO_2 is vital for low GHG emissions (advanced) biofuels supply chains
- Currently, GoodFuels MDF1 is made from residual streams, mainly brown grease, but can also be derived from UCO and Tallow. The standard GHG emissions savings according to REDII for these routes are (European Commission, 2018b):
  - 88% UCO to FAME
  - 84% animal fats to FAME
  - 87% UCO to HVO
  - 83% animal fats to HVO
- The GoodFuels claim (85%-90% GHG reduction for MDF1) aligns with the REDII standard values savings. However, additional data is required for an accurate validation process.
- Given the current uncertainty about future fuel demand and proposed regulations FuelEU Maritime and REDIII, estimating the development of specific renewable energy sources and their GHG emissions savings across the whole sector is challenging. In addition, economic parameters will play a pivotal role in the penetration (and scale-up) of different renewable energy sources in the transport sector. Consequently, GHG emissions savings can also be driven by economic developments.

4 Scalability

The scalability is determined by the possible use of FAME blends by the typical Dutch shipping fleet, represented by reference vessels.

4.1 Dutch fleet categories

An overview of the Dutch reference vessels is presented in the table below. This shows that four of the six reference vessels are equipped with High Speed (HS) engines. In section 2, it was concluded that ships with high-speed engines are often restricted to relatively low FAME blend percentages of 10% to 20% (B10 to B100). Part of the reason is that most of these engines were developed for landbased application where generally only distillate fuels are used. Ships equipped with these engines are designed to use only distillate fuel as MGO or EN590. Because of that they are often not equipped with extensive fuel treatment, such as a centrifugal fuel filter (and water separator) and/or fuel tank temperature control.

Table 4-1: Reference vessels in the context of Green Deal Maritime, inland shipping and ports. Source MARIN-TNO 2020.

Nb	Vessel type	Length (m)	DWT	Total max power (kW)	Engine type	Main fuel type
1	General Cargo	112	9200	4290	MS	MGO
2	TUG	32	285	5000	HS	Diesel ULSFO
3	Offshore supply	82	2900	6000	HS	MGO
4	Crew Tender	25	20	2100	HS	Diesel ULSFO
5	Dredging	125	21000	12000	MS	MGO
6	Super yacht	100	460	13000	HS	Diesel ULSFO

The general recommendations with respect to the FAME blends are summarised in the table below. For the ships with Medium Speed engines it is generally possible to use high blends of FAME up to B100.

Table 4-2: Recommendations for the use of FAME blends for the Dutch reference vessels (sequence changed compared to table above).

Nb	Vessel type	Engine type	FAME biodiesel recommendation	General recommendation
1	General Cargo	Medium Speed	Up to B100 often possible	Check higher than B10 blends with engine supplier. Centrifugal filter and day tank are generally already installed.
5	Dredging			
2	TUG	High Speed	Limit FAME blend to B10 or B20 In some cases higher blends are supported by engine supplier	Install centrifugal filter and day tank for fuel circulation. Check higher than B10 blends with engine supplier.
3	Offshore supply			
4	Crew Tender			
6	Super yacht			

It is generally recommended to check the use of higher than B10 with the engine supplier. He will probably give recommendations with respect to inspections and maintenance, and also with respect to the fuel treatment and other hardware or engine setting adaptations. This may for example include more frequent oil changes, tank cleaning, use of additives or disinfectants, engine lubricant inspections, etc.

A ship equipped with Medium Speed main engines, is generally equipped with high-speed auxiliary engines. It will often be possible to run the main engines on a higher FAME blend than the auxiliary engines, because of the presence of several bunker tanks. In the case that this is not possible, the auxiliary engines also determine the maximum FAME blend for the main engine(s).

4.2 Operational aspects

The influence of the use of FAME biodiesel blends on the operational aspects are very limited. The energy content of pure FAME (B100) on a mass or volume basis are respectively 14% and 10% lower. This means that for a B100 blend, 14% more tonnes or 10% more volume should be bunkered for the same sailing distance. Such a margin is generally available within the bunker tank volumes. And of course with lower blends, the influence it proportionally lower.

Another limited influence on the operational aspects are the maintenance aspects. More frequent fuel filter and bunker tank inspections and cleaning are generally recommended. Additionally more frequent oil changes may be needed.

The influence of HVO type biodiesel on operational aspects is even lower than for FAME. The energy content on a mass basis is about equal to MGO. On a volume basis the energy content is about 8% lower. There is generally no additional maintenance required for HVO type biodiesel.

4.3 Conclusions

With respect, to scalability, the following conclusions can be made:

- FAME blends can generally be used for all Dutch shipping categories. For Medium Speed engines FAME blends up to B100 can often be used. For high-speed engines, it is recommended to limit the FAME blend percentage to 20% (B20) and in some cases to B10.
- It is always recommended to check specific cases with the engine manufacturer, also because they can give advice with respect to the fuel system configuration and maintenance aspects.
- The impact to operational aspects are limited to a slightly increase bunker quantity (+ ≈10%) and additional maintenance, such as more frequent fuel systems inspections and cleaning.

5 Economic aspects

GoodFuels did not provide information on costs or prices of their FAME type MDF1 biodiesel because of marketing reasons. Moreover, pricing would significantly depend on supply and demand options and possible compensation from instruments like the Renewable Energy Directive (RED) (e.g., the value of renewable fuel units - HBE), ETS or CII (refer to section 6.1). For that reason, the economic aspects are evaluated based on the literature.

When considering the economic aspects of biofuels, a distinction should be made between several cost types, such as fuel productions costs, distribution costs and costs (or price) for end-user:

- Fuel production costs:
  - Feedstock costs
  - Transportation of feedstock to production location
  - Production capital and operational costs
- Distribution costs:
  - Transportation to tank storage
  - Tank storage
- Costs to end-user:
  - Ship bunkering costs
  - Margins
  - Possible discounts because of 'HBE' value

The economic margins are actually present in each step of the fuel chain. The margins can vary significantly depending on supply and demand curves and the costs of alternative options such as fossil fuel costs and the costs of other alternative fuels. Regular fossil marine fuels have shown large price variations in the past, even by a factor of three. For biofuels, similar price variations can be expected.

5.1 Current biodiesel costs

Biodiesel and marine diesel fuel prices vary significantly depending on supply, demand, and geopolitical aspects. Figure 5-1 shows the price variation of Used Cooking Oil Methyl Ester (UCOME) in the period between January 2017 to February 2022. UCOME is a FAME type biodiesel based on Used Cooking Oil. Note that this is currently the most used biodiesel type for road transport. There was a relatively normal market situation during this period, except for the COVID period starting in early 2020, leading to a significant decrease in UCOME prices which slowly recovered during 2021.

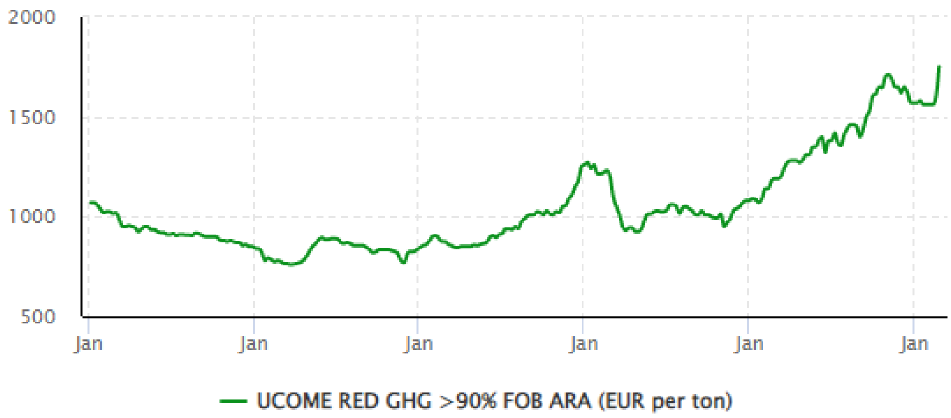

Figure 5-1: UCOME price development from January 2017 to February 2022 (Greenea, 2023).

Table 5-1 compares UCOME and Marine gasoil (MGO) prices. Prices in April 2020 are low for both fuel types compared to February 2022. It is shown that the UCOME price increased from 25 to about 47 €/GJ (1068 to 2020 €/TOE). The MGO price increased from 4.2 to 19.5 €/GJ (181 to 831 €/TOE). De price ratio between UCOME and MGO strongly decreased from a factor 5.9 (April 2020) to a factor 2.4 (February 2022).

Table 5-1: Comparison in market price development between FAME type biodiesel and MGO during 2020 to February 2022.

	FAME - UCOME		MGO	
Date	April 2020	February 2022	April 2020	February 2022
EUR/ton	925	1750	181	831
GJ/ton	37	37	42.7	42.7
EUR/GJ	25	47.3	4.2	19.5
EUR/MWh	90	170	15	70
EUR/TOE	1068	2020	181	831

UCOME was also the main biodiesel type supplied to the marine sector in the Netherlands up to 2022. UCOME was popular because it could be booked in for the RED obligation for road transport, according to the so-called ‘opt-in’ arrangement. In this way, the majority of the extra costs of biodiesel compared to fossil diesel are absorbed by road transport (to which the obligation applies). Therefore, the maritime sector has not paid the biodiesel prices shown in Table 5-1. However, this situation will change in the future with the formal implementation of FuelEU Maritime Regulation, and the ‘opt-in’ arrangement will end by 1 January 2025. Thus, if FuelEU Maritime enters into force, the maritime sector will fully pay the additional costs of biodiesel compared to fossil diesel. To give an example for 2030

A simple projection of the increased fuel costs due to FuelEU Maritime in 2030 can be made based on the prices in February 2022. The GHG intensity of maritime fuels for 2030 needs to be reduced by 6% compared to 2020. Assuming an 80% GHG reduction for biofuel, a total share of 7.5% biodiesel is needed.

Based on a price difference of 1179 €/TOE between biodiesel and MGO (February 2022), the additional fuel costs of a 7.5% biodiesel share will be 88 €/TOE, so the fuel price of 831 €/TOE will rise to 919 €/TOE, which is a fuel costs rise of almost 11%.

For the costs of GoodFuels MDF1 FAME type biodiesel, the market situation will likely be similar to UCOME, but with some differences. Generally, prices of different types of biodiesel and FAME are linked to each other. The main differences are caused by the RED sustainability criteria, the possible application of double counting and the compatibility with the formal diesel fuel specification. GoodFuels MDF1is primarily made from 'brown grease', a waste product similar to UCO. On the other hand, MDF1does not exactly fulfil the EN14214 requirements. Thus, it is not suitable for road transport.

5.2 Future biofuel costs

In the IEA study 'Task 41' (Brown et al., 2020) an extensive analysis is done on expected cost levels for biofuels based while considering different production processes, feedstocks and feedstock costs. The IEA study evaluates three cost scenarios: 1) current costs, 2) costs after technical improvements and 3) costs with lower financing costs. This study addresses the conventional and future types of biodiesel and other biofuels such as bio-ethanol, bio-methanol and bio-methane. The study considers different types of feedstock, with a split between biomass and (biomass) waste stream. In the latter case, the biomass is for free or has a negative value (so the user gets paid for using it). We consider free biomass less realistic since waste streams are often more expensive than new biomass in the current situation. Also, significant costs are associated with collecting and transporting waste streams to a production location. So as input for this study, we use the costs projection with biomass feedstock and assume that waste (if used) has a very similar price.

Table 5-2 provides an overview of the future biofuel costs for the middle scenario 2 ("after improvements"). The third scenario with lower financing costs[12] may probably only become realistic after 2045, when production volumes are high, and business cases are very stable. For feedstock, biomass is taken (excluding residual biomass). FAME and HVO, currently the only biofuels produced on a large scale, are also included in Table 5-2. For those, it is likely, that the costs will stay at a constant level. FAME and HVO are made from pure plant oil PPO and Used Cooking Oil (UCO).

Fossil diesel fuel prices tend to vary greatly depending on supply and demand issues of crude oil and the geopolitical situation. Over the last years, between April 2020 and February 2022, a price variation between 15 and 70 €/MWh has been seen. In the future, CO2 tax is also expected to influence marine diesel costs significantly.

[12] When technologies mature, the technical risks diminish. This will usually lead to lower financing costs. In this case it was reduced from 10% over 15 years to 8% over 20 years. This results in an annual financing costs reduction from 13.1% to 10.2% (interest + depreciation).

Table 5-2: Fuel production costs after improvements (2040) in €/MWh and €/GJ. Based on (Brown et al., 2020)

	Year	Feedstock	Costs €/MWh	Costs €/GJ	Average €/GJ	Average € / TOE
Fossil diesel	2040	Fossil	80-110	22-31	26	1110
FAME	2020-2040	PPO	67 - 100	19 - 28	23	980
HVO	2020-2040	PPO	75 – 122	21 - 34	27	1150
Bio-ethanol	2040	Cellulosic	76 – 122	21 – 34	27	1150
Bio-methanol and bio-LNG	2040	Biomass	48 – 100	13 – 28	20	850
FT liquids	2040	Biomass	64 – 125	18 - 35	28	1200
Bio-oil	2040	Biomass	75 - 132	21 - 37	28	1200

The International Energy Agency has developed scenarios based on assumptions on both carbon prices and oil prices developments (Brown et al., 2020). Figure 5-2 presents the expected cost levels for fossil diesel in these scenarios, including carbon prices (ranging from €17 to €122 per ton CO_2), for 2040. Overall, a fossil fuel price between €80 and €110 per MWh (€22 - €31 per GJ) is expected. In all scenarios, fossil fuel prices are expected to rise significantly compared to current fossil fuel costs.

The broad range of fuel prices (excluding the carbon price) is in line with a forecast of the US Energy Information Administration (EIA, 2019). For 2040, they project a maximum price of about $170[13] per barrel and a minimum price of about $45 per barrel.

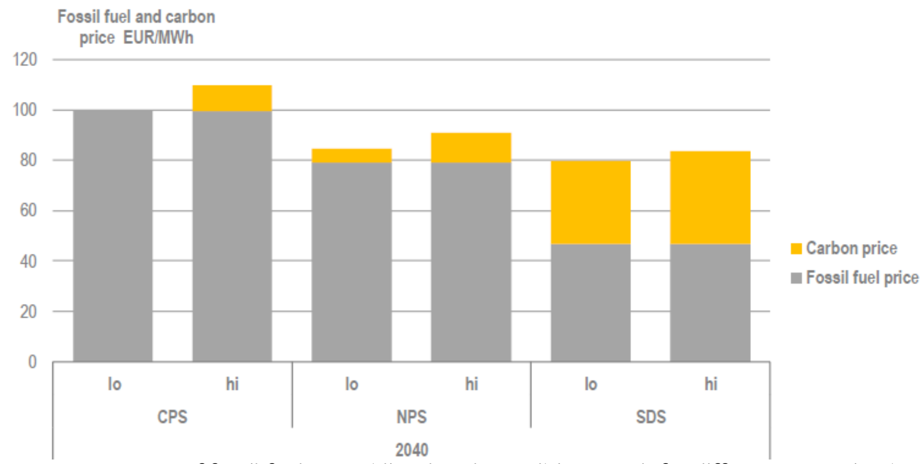

Figure 5-2: Forecast of fossil fuel costs (diesel and petrol) in €/MWh for different scenarios (CPS = Current Policies Scenario; NPS = New Policies Scenario; SDS = Sustainable Development Scenario) (Brown et al., 2020).

[13] $170 per barrel converts to €25 per GJ. Current difference between diesel fuel and oil price is about €4.4 per GJ. So, $170 per barrel would lead to a diesel fuel price of about €29 per GJ. Equivalent: $45 per barrel would lead to a diesel fuel costs of about €11 per GJ (€40 per MWh).

Table 5-2 shows that wide, and overlapping cost ranges are given for most advanced biofuels. The difference between the low and high end of the range can be up to a factor of two. On average, it is suggested that bio-methanol or bio-methane have the lowest cost projection of 20 €/GJ, followed by FAME with 23 €/GJ. Cellulosic ethanol, FT diesel and bio-oil are more expensive, with a projected average cost figure of approximately 27-28 €/GJ.

The wide range in cost projections for advanced biofuels is as expected since most advanced biofuel production options are still in an early development phase, such as 'prototyping' or early 'demonstration' (see Figure 5-3). Only lignocellulosic ethanol and methanol via gasification are in an early commercialization stage.

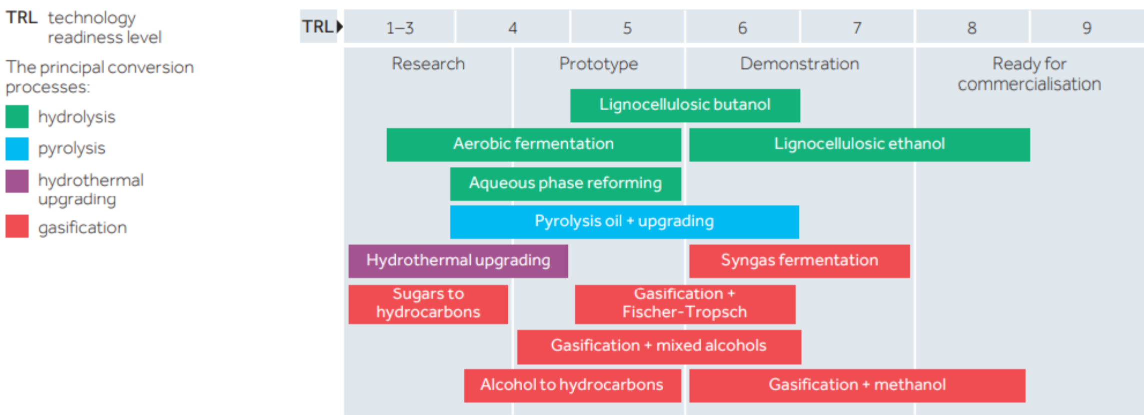

Figure 5-3: Commercial status of advanced fuel conversion technologies (Clean, 2019).

5.3 Conclusions

Economic aspects of biodiesel

- The market prices of biodiesel and fossil diesel fuel vary significantly. In the period from April 2020 to February 2022, the current biodiesel price almost doubled and the MGO price increased by more than a factor of four. In February 2022, the biodiesel price was a factor 2.4 or 1179 €/TOE higher than the price of MGO (831 €/TOE).
- The FAME type biofuel production cost from fresh vegetable oil can vary between 800 and 1200 €/MTOE. This is a lot lower than the UCOME market price in February 2020, which was about 2020 €/TOE. The 'double counting' category within the RED of UCOME probably plays a large role in this relatively high price.
- The biodiesel supply for the maritime market in 2030 and later will likely need to be a combination of FAME type and 'advanced' biodiesel such as FT diesel or bio-oil. The future cost of advanced biodiesel production is expected to range between 800 and 1600 €/TOE (excluding profit margin and bunkering costs).
- FAME type biodiesel such as GoodFuels MDF1 will likely be lower priced in the long term than the 'advanced' category biodiesel.

Comparison biodiesel with other biofuel types

- The future of biodiesel is also dependent on future production costs, market prices, sustainability criteria and production scale-up options compared to other sustainable fuels like methanol.

- Advanced biodiesel can use the same feedstock as other biofuels like methanol and bio-methane, so there are no evident differences concerning sustainability criteria and/or feedstock availability.
- The production costs of advanced biodiesel is expected to be around 10%-20% higher than that of bio-methanol, but the cost ranges overlap. Market mechanisms and differences in bunkering costs will determine the price for the end-user, which is hard to predict at this stage.
- Bio-methanol and bio-ethanol probably have better production scale-up options than advanced biodiesel since they are more ready for commercialisation
- Biodiesel will likely remain one of the most important and also economic fuel options for existing vessels and new vessels to reduce the GHG emissions of sea ships within the time frame up to 2030 and beyond.

6 Future proofness biodiesel

By 2050, the International Maritime Organization (IMO) aims to reduce shipping GHG emissions by 50% compared to 2008 levels (IMO, 2018). Currently, biofuels are the main renewable fuel used in this sector and where most of the GHG emission savings occur. However, compared to the total maritime bunker fuels, the share of biofuel supply is minimal. In 2020 it was estimated that globally, 99.9% of the maritime industry's fuels were fossil-based (European Maritime Safety Agency, 2022). A recent review of the decarbonization of the EU transport sector concluded that biofuels and mainly advanced biofuels are paramount to achieving EU climate targets by 2050 (Chiaramonti et al., 2021). Therefore, policy implementation is one of the key drivers to increase the penetration of biofuels in the sector for the upcoming years and support meeting decarbonization targets.

6.1 EU policy framework

The European Commission has adopted the 'Fit for 55' package to deliver the European Green Deal and reduce its net GHG emissions by at least 55% by 2030, compared to 1990 levels. This package has adopted several strategies to address the climate impact in all sectors of the economy.

Within the maritime sector, the 'Fit for 55' package includes proposals targeted to reduce GHG emissions and overcome development barriers, among which the following stand out:

- The revision of the recast renewable energy directive 2018/2001/EU (REDII, 2018) to increase the current EU target of renewable energy sources in the overall energy mix to at least 40% by 2030, thus boosting sectors (e.g. maritime) with slow progress of renewable energy sources.
- The introduction of the FuelEU maritime regulation (REF EC) that aims to specifically increase the use of sustainable (alternative) fuels in European shipping by addressing market barriers and technology uncertainties.
- The potential inclusion of maritime emissions in the EU Emissions Trading System (ETS)
- The revision of the energy taxation directive (ETD) to potentially tax marine fuels.

6.1.1 Renewable energy directive 2009/28/EC – RED and Dutch fuel suppliers' obligations

The Renewable Energy Directive (RED) and the amending renewable energy directive (Directive 2009/28/EC and Directive 2015/1513) introduced a renewable energy target for the transport sector. By 2020, renewable energy sources should meet at least 10% of the energy consumed in road and rail transport. This target was translated into annual obligations for fuel suppliers in the Netherlands. Companies that deliver more than 500,000 litres of petrol and diesel to certain destinations must provide an increasing annual share of renewable energy.

The annual obligation refers to petrol and diesel delivered to:

- Road and railway vehicles
- Non-road mobile machinery
- Agricultural tractors and forestry machines
- Pleasure craft when not at sea

While the obligation was not set on bunkering, the Dutch implementation of RED included the opt-in option from 2018 onwards (with the entry into force of the update of title 9.7 of the Environmental Act). Fuel suppliers to road transport with an annual obligation were given the option to use renewable energy in maritime shipping, to obtain so-called renewable fuel units (hereinafter: HBEs[14]), or to buy these HBEs via the trading system. This opportunity was created to increase the acceptance of biofuels in maritime transport. Furthermore, it was also set to gain experience in an international context on future agreements concerning maritime transport sustainability. As a result, biofuel deliveries to the shipping sector increased significantly in 2020. According to NEa (2021), nearly 30% of the HBEs created in 2020 were from biofuels delivered to maritime shipping. In the existing legislation and regulations, biofuels produced from the list in annex IX of the Directive 2015/1513, can be counted double. Despite this positive development for the maritime sector, these biofuels could not count towards the European transport target obligation of 10% in 2020 and the CO2 reduction needed within the Fuel Quality Directive (FQD, 2009) because of the difference in sector coverage, as the maritime sector was not included. Thus, the large contribution of biofuels to maritime shipping was at the expense of their use in road transport. In order to prevent a disproportionate use of biofuels in the Dutch maritime sector and to comply with the annual fuel suppliers' obligations for the calendar year 2021 and beyond it was agreed[15] to only book deliveries of biofuels produced from feedstocks listed in annex IX part-a (advance biofuels) to maritime shipping. This is in line with the legal situation of REDII (Ministerie van Infrastructuur en Waterstaat, 2021), which entered into force in 2022. Therefore, between 2022-2025 only advanced biofuels) and renewable energy can be booked in maritime and counted towards national targets. Beyond 2025, the expectation is that there will be sector-specific legislation.

6.1.1.1 Recast renewable energy directive 2018/2001/EU - REDII

REDII was issued in 2018 (European Commission, 2018b). This directive set, among other things, the framework for the use of renewable transport fuels in the EU for the period 2021-2030. In the context of this Directive's implementation and the Climate Agreement, the Dutch government issued an ordinance in December 2021 (Ministerie van Infrastructuur en Waterstaat, 2021) to establish the Netherlands' renewable energy obligations up to 2030. In July 2021, as part of the 'Fit for 55' package, the recast (REDII) revision started and proposed to introduce several changes in the transport sector. This proposal (REDIII) has been extensively discussed between the European Commission, the Parliament and the EU member states. Once the final version of the REDIII is officially adopted, the Dutch government will start the procedures to transpose this to the national law and legislation. The main differences relevant to the maritime sector between the Dutch ordinance and REDII can be summarised as follows, and a comparison between the Dutch ordinance, REDII and REDIII can be found in Table 6-1 . However, note that these are not final changes and the comparison is made based on the publicly available documents by the commission on the revision of REDII.

[14] ne gigajoule of energy content of renewable energy represents one HBE.
[15] See stcrt-2020-65200.pdf (officielebekendmakingen.nl)

Comparison target

The Dutch Ordinance sets a mandatory share of renewable energy, gradually increasing to 28.0% in 2030. This is more strict as compared to 14% of the share in renewable energy sources in the transport sector by 2030 (REDII). However, both targets include double counting for some renewable energy sources. REDIII has a 13% GHG intensity reduction target for transport by 2030, equivalent to an energy-based target of 28% using the methodology in the current directive REDII. By setting a GHG intensity reduction target, REDIII eliminates almost all of the multipliers associated with renewable fuels and renewable electricity used in transport. The 1.2x multiplier for aviation and maritime fuels remains in REDIII, and it only covers advanced biofuels from annex IX part-a feedstock and Renewable Fuels of Non-Biological Origin (RFNBO).

Comparison sector coverage

The Dutch ordinance covers diesel, petrol and heavy fuel oil supplied to road and rail transport, non-road machinery and recreational boating (when not on sea). It excludes fuels supplied to maritime and aviation bunkering. REDIII, proposes to expand the size of the fuel pool and cover all types of fuels and energy from the transport sectors, including aviation and maritime. This means that both the GHG intensity reduction target and the sub-targets on some renewable fuels introduced in REDIII will likely be larger than the targets set in the Dutch ordinance. The transport sector, according to Eurostat refers to five main transport modes: air, inland waterways, rail, road and maritime (sea).

Sub-target for advanced biofuels from annex IX part-a

The Dutch ordinance sets the advanced biofuel sub-target to 7% in 2030 (including double counting). Therefore, the physical contribution should be 3.5% of the energy content of fuels delivered to road and rail, non-road machinery, and recreational boating. REDIII proposes the advanced biofuels target to be 2.2% of the energy supplied to all transport modes and removes the double counting.

A cap to biofuels produced from feedstocks in annex IX part-b

The Dutch ordinance caps the biofuels produced from feedstocks listed in annex IX, part-b. The use of biofuels is limited to the 2020 levels, which was 5% of national transport without double counting and 10% with double counting. These shares apply to the energy content of the fuel deliveries coming under the scope of the Dutch annual obligation for final consumption. REDIII does not change the cap which is 1.7% of the energy supplied to the transport sector in 2030. However, recent discussions suggested that the cap might increase if new feedstocks are added to annex IX part-b

A cap to biofuels produced from food or feed crops

The Dutch Ordinance caps the food or feed biofuels to the 2020 level, which is 1.4% of the total diesel and gasoline consumed in the transport sector. REDII and REDIII limit to no more than 1% point higher than 2020 share in road and rail transport, with a maximum of 7%. Member States may set a lower limit and may distinguish between different biofuels from food or feed crop.

Sub-target for RFNBOs

Neither REDII nor the Dutch Ordinance includes a sub-target for RFNBO. REDIII introduced a minimum of 2.6% sub-target for these fuels by 2030. For the calculation of the share of RFNBO, member states can also include RFNBO when they are used as intermediate products to produce conventional fuels.

Table 6-1: Comparison between REDII, Dutch ordinance and REDII proposed changes

	REDII	Dutch ordinance	REDIII
End users subject to the obligation	Total energy used in road and rail transport	Diesel EN590, gasoline, and heavy fuel oil supplied to: Road and rail transport Non-road mobile machinery, Agricultural tractors and forest machines, Recreational boating (when not at sea).	Total energy used in all transport modes: Road and rail transport Inland shipping Aviation and maritime sector
Type and level of target	Overall Renewable energy Sources (RES) target (energy content) - at least 14 % by 2030 (including multiple counting)	Overall RES target (energy content) at least 17.9% RES in 2022, increasing to 28% in 2030 (including multiple counting)	Overall GHG emissions intensity reduction target 13% reduction by 2030, compared to the baseline calculated (no multiple counting) Equivalent to an energy-based target of 28% using the methodology in the current directive REDII
Limit to biofuels from food and feed crops	-No more than 1% point higher than 2020 share in road and rail transport, with a maximum of 7%. -Member States may set a lower limit and may distinguish between different biofuels from food or feed crops	Limited to the 2020 levels -This corresponds to 1.4% of the total diesel and gasoline consumed in transport. - Palm and soy oil as feedstock is not allowed due to indirect land use change (iLUC) risk	Limit is same as REDII. -If a Member State decides to limit the share further, that Member State may reduce the greenhouse gas intensity reduction target.
Sub-target for advanced biofuels from annex IX part-a feedstocks	At least 0.2% in 2022, 1% in 2025 and 3.5% in 2030 (including double counting).	Linear growth from 1.8% in 2022 to 7% in 2030. -These include double counting.	At least 0.2% in 2022, 0.5% in 2025 and 2.2% in 2030. -No double counting
Limit to biofuels from annex IX part-b feedstocks	Limited to 1.7 % of the energy content of transport fuels in 2030 (including double counting).	Limited to the 2020 levels of the national fulfilling, which is 5% without double counting and 10% with double counting.	Same as REDII, with the difference that transport sector is expanded to cover also aviation and maritime --No double counting
Sub-target for RFNBOs	No sub-target	No sub-target	At least 2.6% in 2030. It includes both direct use, and/or use as intermediate product for the production of conventional fuels.

	REDII	Dutch ordinance	REDIII
Multiple counting	Biofuels and biogas from annex IX- A and B can be double counted Renewable electricity can be 4 times counted when supplied to road vehicles and 1.5 times when supplied to rail transport Advanced biofuels and other renewable fuels in aviation and maritime can be counted 1.2 times their energy content	Biofuels and biogas from annex IX list- A and B can be double counted Renewable electricity in road transport counted 4 times its energy content. Renewable electricity in rail transport is not counted. RFNBO counted 2.5 times to the overall target Advanced biofuels and renewable energy to aviation and shipping can be counted towards the (road transport) target up to 1 January 2025.	No multiple counting. Only 1.2 times counting for RES(annex IX A, and RFNBO) when used for aviation and maritime
GHG emission saving threshold	At least 65% for installations producing biofuels from 1 January 2021 onwards at least 70% for installations producing RFNBO	Same as REDII	Same as REDII
Renewability of electricity	The average share of renewable electricity as measured two years before the year in question	Same as REDII	The average share of renewable electricity in the two previous years.
Renewability RFNBO	The average share of electricity from renewable sources, as measured two years before the year in question, shall be used to determine the share of renewable energy	Same as REDII	Same as REDII
Other biofuels	Not mentioned	Liquid biofuels from crops that do not entail a risk of agricultural land expansion (i.e., catch and cover crops) can be counted towards the target	Not mentioned

6.1.2 FuelEU Maritime

In 2021, the European Commission published the regulation proposal on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC (FuelEU) (European Commission, 2021c). This proposal is part of the Fit for 55 package in line with the EU Green Deal and directly aims to reduce GHG emissions in the maritime transport sector. In this implementation context, the FuelEU Maritime regulation proposal lays down rules to limit the GHG intensity of energy used on-board for all ships above 5000 gross tonnes (regardless of their flag) when arriving, staying and traveling from and to within the EU.

It also promotes the use of on-shore power supply or zero-emission technology in EU ports and the uptake of renewable and low-carbon fuels (RLF) in the maritime sector. This proposal details specific obligations for the maritime transport sector to contribute to the European ambition of climate neutrality by 2050, which the key elements are summarized below:

- Requirements to improve the yearly average well-to-wake GHG intensity (considering 2020 as a baseline) of the energy used by a ship during a reporting period as follows and shoed in Figure 6-1:
    - -2% from 1 January 2025
    - -6% from 1 January 2030
    - -13% from 1 January 2035
    - -26% from 1 January 2040
    - -59% from 1 January 2045
    - -75% from 1 January 2050

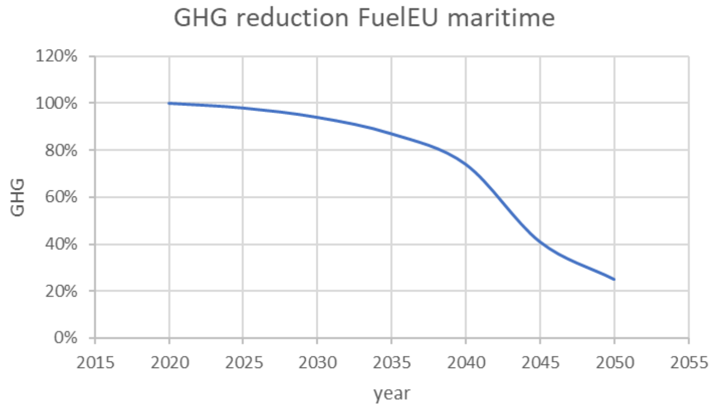

Figure 6-1: EU GHG reduction target under Fit for 55 FuelEU Maritime.
From 1 January 2030, it introduces additional requirements for ships at berth with an obligation of zero-emission of on-shore energy supply

- From 1 January 2030, it introduces additional requirements for ships at berth with an obligation of zero-emission of on-shore energy supply

- By 31 August 2024, companies shall submit to the verifiers a monitoring plan for each of their ships regarding the amount, type and emission factor of energy (well-to-wake, WtW emissions factors for each type of fuel used at berth and at sea) used on-board to evidence compliance with the GHG reduction targets set out above. There are penalties for non-compliance.

The FuelEU provides a standard method to estimate the GHG intensity limit of the energy used on-board a ship. The GHG emissions intensity reduction targets are on a well-to-wake basis (g CO2eq/ MJenergy used on-board). The well-to-wake emissions factor covers all impacts across the supply chain of energy production, including use on board and during combustion, thus assuring consistency with REDII. It is worth highlighting that the methodology introduced in the FuelEU regulation proposal and fossil fuel emission factors should be addressed using FuelEU Maritime's default emission factors (Table 6-2, and full table in Appendix C), while the emission intensity of biofuels, biogas, RFNBOs and recycled carbon fuels will still follow REDII methods. This proposal introduces the GHG intensity of different fuels used in maritime shipping, whereas REDIII baseline calculations refer to a single emission factor, 94 g CO_2eq/MJ. Therefore, in REDII only renewable fuels can contribute to the GHG intensity reduction target.

In contrast, in the FuelEU Maritime regulation proposal, fossil fuels with a better GHG emissions performance are also eligible to achieve the GHG intensity reduction. Table 6-3 compares the FuelEU Maritime Regulation proposal with the REDIII directive proposal.

Table 6-2: FuelEU fossil fuel default emission factors for CO_2 emissions. For a complete table including CH_4 and N_2O refer to Appendix B

	Lower com-bustion value [MJ/kg]	Fuel carbon content [kg/kg fuel]	Specific CO_2 emissions [kg /kg fuel]	Note
Diesel, gasoil, VLSFO, MDO	42.7	0.8774	3.206	ISO 8217 grades DMX through DMB
HFO, LSFO, ULSFO	40.5	0.9493	3.114	ISO 8217 grades RME through RMK
LFO	41	0.8594	3.151	ISO 8217 grades RMA through RMD
LNG	49.1	0.750	2.755*	Pure methane
Methanol	19.9	0.375	1.375	Pure methanol

6.1.2.1 Reporting requirements under the RefuelEU Maritime regulation

The regulation proposal introduces an extensive monitoring, reporting and verification plan. The shipping companies will be responsible for monitoring the type and amount of energy used in operating and at berth. They will have to submit to verifiers a standardised emissions monitoring plan for each of their vessels by 31 August 2024. These should include the method chosen to monitor and report the amount, type and emission factor of energy used on-board by ships and other relevant information. At the end of April each year, shipping companies will need to submit their data, fulfilling that already reported for MRV regulation, to the compliance database that the Commission will develop. The verifiers will issue a document of compliance. This document must be kept on board all ships calling at an EU port until the end of the reporting period. Independent verifiers shall calculate the following and inform the company:

- The yearly average GHG intensity of energy used on-board by the ship,
- The ship's compliance balance.
- Number of non-compliance port calls in the previous reporting period.
- Amount of penalties in case of non-compliance.

This regulation proposal includes some flexibility for the ship operators. Any surplus on average GHG intensity limit of energy reduction can be shifted to the following year. A company can borrow a surplus from the next year and it is called advance compliance. In the following year's balance, the borrowed amount will be multiplied by 1.1 and reduced from the overall balance. The advance compliance surplus borrow is limited to a maximum of 2% of the GHG limit. Borrowing is also limited to two consecutive years.

Next to that, two or more ships, verified by the same verifier, may be pooled to fulfil the requirements together. Similar to the REDIII proposal, the European Parliament and the European Council have adopted the proposal and are currently under negotiations.

Table 6-3: Comparison of REDIII and the FuelEU Maritime regulation proposal

	REDIII	FuelEU Maritime
Document type	Directive proposal	Regulation proposal
Coverage	All energy supplied to all transport modes, including maritime and aviation	Maritime shipping[16]: -The energy used during their stay within a port in the Member States (MS) -Voyages within EU MS jurisdiction are accounted fully (100%) and by half (50%) if the voyage's start or end is outside of the MS jurisdiction.
Obliged parties	Fuel suppliers to the transport sector	The shipping company that has the responsibility for the operation of the ship - All ships above a gross tonnage of 5 000, regardless of their flag.
Type of compliance	Reduce greenhouse gas intensity of transport fuels by 13% by 2030 (equivalent to an energy-based target of 28% using the methodology in the current directive REDII)	The yearly average GHG Intensity limit of energy used on-board by a ship in comparison to a EU 2020 refence value[17]. - Additionally, zero-emission requirements of energy used at berth from 2030 onwards (Article 5).
Type of fuels eligible	Only renewable energy carriers (biofuels, direct use of renewable electricity and RFNBO, including H2)	Renewable energy carries and low-carbon fossil fuels
Certification of biofuels, RFNBO and RCF	GHG emission saving threshold of at least 65% for installations producing biofuels and biogas from 1 January 2021 onwards. They should comply with the GHG criteria set out in Directive (EU)2018/2001 For RFNBO and RCF at least 70% GHG threshold.	
Potential entry into force date	First quarter 2023	January 2025

6.1.3 EU European Emission Trading System

The revision of the European Emission Trading System (ETS) (European Commission, 2021b) includes maritime shipping to the EU's carbon market, and pricing the carbon emissions from this sector. Like the Fuel EU Maritime regulation proposal, this revision applies to all vessels exceeding 5000 gross tonnes and would cover 100% of intra-European Economic Community (EEC) shipping emissions and 50% of extra-EEC emissions.

[16] Warships, naval auxiliaries, fish-catching or fish-processing ships, wooden ships of a primitive build, ships not propelled by mechanical means, or government ships used for non-commercial purposes are excluded.
[17] Reference value will correspond to the fleet average GHG intensity of energy used on board in 2020 derived from the reported data to the EU Monitoring, Reporting, and Verification (MRV) database.

The revision includes a phase-in period between 2023-2026. During this period, the emissions will partially be included:
- 20% in 2023
- 45% in 2024
- 70% in 2025
- 100% in 2026.

After that, all verified maritime shipping emissions will be included in the EU ETS. While the Fuel EU Maritime regulation proposal targets the life cycle emission (well-to-wake), the EU ETS focuses on direct tank-to-wake emissions.

6.1.4 The European energy taxation directive (EU ETD)

The revision of the EU ETD (European Commission, 2021a) proposes a gradually increasing minimum tax rate for various fuels, including maritime fuels. The proposal includes a new structure for minimum tax rates based on the real energy content and environmental performance of fuels. Minimum rates will be based on the energy content of each product. Heavy oil used in the maritime industry will no longer be fully exempt from energy taxation for intra-EU voyages in the EU and over ten years, the minimum tax rates for these fuels will gradually increase. In contrast, sustainable fuels, including biofuels and biogas, low-carbon fuels, RFNBO and electricity, will benefit from a minimum rate of zero for a transitional period of 10 years to promote their uptake.

The proposed minimum tax rates are:
- Conventional fossil fuels and non-sustainable fuels such as gas oil and petrol: €10.75/GJ.
- Fossil-based fuels supportive of decarbonisation in the short term, such as natural gas and liquified petroleum gas (LPG): for a transitional period of 10 years, a minimum rate of €7.17/GJ.
- Sustainable but no advanced biofuels such as food-derived biofuels: €5.38/GJ.
- Advanced sustainable biofuels and biogas, electricity and RFNBOs such as hydrogen: €0.15/GJ.

6.2 FAME and HVO production and use

EU-27 and Netherlands

Currently, 72% of the renewable energy used in the EU-27 transport sector corresponds to FAME (including HVO and "other liquid biofuels”) (EurObserv’ER, 2022). In 2021, the EU-27 produced 15,590 million litres of FAME (441.9 PJ), 3,604 million litres of HVO (123.7 PJ), imported 3100[18] million litres, and exported 1,059[19] million litres (USDA, 2022). The overall EU-27 consumption was 17,611 million litres of FAME and HVO, with 93% used in road transport (USDA, 2022). This is approximately 571.2 PJ (including other liquid biofuels) (EurObserv’ER, 2022). The main feedstocks used for FAME and HVO production were rapeseed oil (40%), followed by UCO (22%), palm oil (17%) and animal fats (8%) (USDA, 2022).

The Netherlands continues to be the main EU-27 producer of HVO with 1,218 million litres (41.8 PJ) and the 5th of FAME with 1,136 million litres (32,2 PJ), with UCO being the primary feedstock (NEA, 2022; USDA, 2022). A summary of the current use and projection of drop-in biofuel is summarized in Table 6-4.

[18] FAME + HVO.
[19] FAME + HVO.

Table 6-4: Current use and projections for drop-in biofuels
(Chiaramonti et al., 2021; EurObserv'ER, 2022; Eurostat, 2022; Prussi et al., 2021; USDA, 2022)

	EU-27		Netherlands	
	PJ	MTOE	PJ	MTOE
Current FAME and HVO use road (maritime)	571.2 (8.4)	13.6 (0.2)	15.2	0.36
Indication Maritime drop-in biofuel demand 2030	105 – 217	2.5 – 5.2	24 - 50	0.57 – 1.2

Currently, the use of biofuels in the EU-27 maritime sector is minimal. Following current trends and legislation, by 2030, the EU maritime biofuel demand (drop-in fuels) is expected to be between 105 to 217 PJ/year (Chiaramonti et al., 2021; Prussi et al., 2022). This demand can even be higher with the potential changes that REDIII might bring. The expected demand is considerably higher than the current use of biofuels in the maritime industry. In 2020 approximately 8.4 PJ of drop-in biofuels was used in this sector (Hamelinck et al., 2021).

FAME and HVO can help to meet the biofuels demand and reduce GHG emissions in the maritime industry. These biofuels are potentially suitable for diesel engines without or with minor modifications. Therefore, they present a technologically suitable alternative to conventional fossil-based fuels for ship engines. Most FAME and HVO are produced from specific feedstocks such as vegetable oils, UCO, and animal fats (annex IX part-b feedstocks as mentioned in section 6.3.1) through either a hydrotreating or transesterification processes (European Commission, 2018b). However, with the current legislation trends and to meet future biofuel demand in the maritime sector, the use of annex IX part-a feedstocks (see section 6.3.2) is expected to ramp up and assure a shift between feedstock types if biofuels stay as one of the main alternatives for the maritime sector (see section 6.3).

As shown in Figure 6-2 , there are several routes for producing drop-in fuels. The main routes for annex IX part-a feedstock are pyrolysis and gasification (agricultural residues, forest residues, non-food energy crops). The main difference between these two processes is that gasification is carried out at a slightly higher temperature with the presence of oxygen. For both routes, an upgrade is required to obtain a drop-in fuel as the end product. The gasification process produces syngas which will provide a range of end products with different applications not only limited to biofuel production. This is particularly relevant given the high degree of uncertainty about future fuel use in the maritime sector. To illustrate, syngas can be upgraded to drop-in fuels but also to methanol or hydrogen. For example, methanol can be used as a fuel (with modifications for engines or new engines) but also in other sectors such as olefins production.

Biomass-integrated processes with gasification and Fischer-Tropsch (FT) synthesis are recognized as a promising technology for producing FT-diesel. Furthermore, FT-diesel is expected to contribute to the decarbonization of the maritime industry (Douvartzides et al., 2019) and is highly compatible with the current fleet.
Therefore, it can be relevant to understand the potential of annex IX part-a feedstock in the EU that can be dedicated to this fuel production route, particularly biomass, as it shows the highest potential (Daioglou et al., 2019). However, note that these conversion routes are still in the demonstration phase. This assessment is covered in section 6.3.2

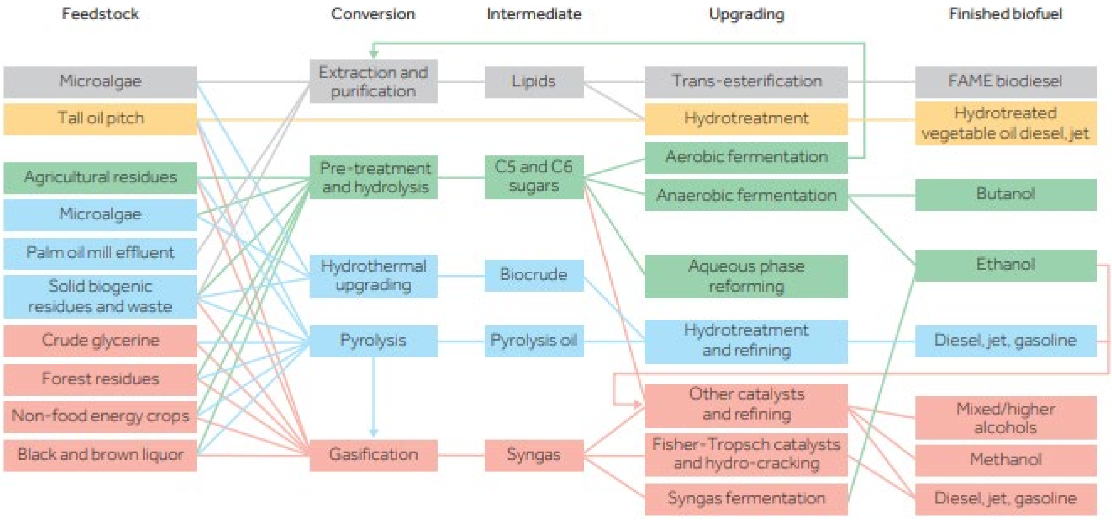

Figure 6-2: Advanced biofuels pathways (Concawe, 2019)

6.3 Current trends and availability of feedstock and drop-in biofuels

Current uses of drop-in biofuels in the maritime sector are minimal compared to road. However, it is expected that these biofuels will ramp up in the upcoming years to meet the demand that will be set by sector-specific legislation. Drop-in biofuels use in the maritime industry will increase by 12 to 24 folds (as shown in Table 6-4) and their market development will also depend on the whole transport sector fuel pool. Therefore, It is adequate to evaluate the current trends in biofuel consumption and how these are related to current legislative obligations in the transport sector to understand the potential effects in the maritime sector.

In 2021 the share of renewable energy sources in the EU-27 transport sector was 9.1%, from which the main sources were food and feed biofuels (3.8%) and REDII annex IX biofuels (3.4% - double counted) (Eurostat, 2022). Note that renewable energy sources in the transport sector calculation currently exclude maritime and aviation from the total fuel pools. The total share had a reduction compared to 2020 (10.3%), mainly driven by the entrance into force of REDII, which limited the contribution of biofuels to the total final energy consumption. According to REDII (mentioned in section 6.1) food and feed biofuels must not exceed 7% of final energy consumption in transport in 2030 and may be no more than one percentage point higher than their 2020 rate and limit annex IX part-b biofuels to 1.7 % of the final energy consumption. These caps resulted that for some member states, such as the Netherlands, a part of the biofuel shares consumed in the transport sector could not contribute as part of their renewable energy sources contributions.

To illustrate, in 2021, the Netherlands' biofuels use in the transport sector corresponded to 26.3 PJ, composed of food and feed biofuels 5.2 PJ, annex IX part-a biofuels 6.1 PJ (single counted) and annex IX part-b biofuels 15 PJ (single counted) (Eurostat, 2022).

As most of the biofuels used in the Dutch transport sector come from annex IX part-b, this decreased the renewable energy sources to be counted to the national target from 12.6% to 9%. This is increasingly relevant for the Dutch maritime sector as with the current uses and fuel pool, the annex IX part-b REDII cap is already met.

As mentioned in section 6.1, REDIII proposes expanding the fuel pool's size and covering all types of fuels and energy from the transport sectors, including aviation and maritime. In addition, it eliminates all the multiple counting except for annex part-a biofuels and RFNBOs (1.2) when used in aviation and maritime. REDIII also introduces sub-targets for the aforementioned energy sources. Under these considerations, the demand for annex IX part-a biofuels is expected to increase. In addition, some projections expect a shift of biofuels from annex IX part-b to the aviation sector resulting in a significant share of the cap spent for that sector (Uslu, 2022). Therefore, besides other renewable energy sources, annex IX part-a biofuels will play an important role in the decarbonization of the EU transport and maritime sector.

6.3.1 Conventional and annex IX part-b feedstocks

In the EU-27, FAME and HVO are mainly produced from virgin vegetable oils, UCO, palm oil and animal fats (see section 6.2). The use of feedstocks related to conventional biofuel pathways, virgin vegetable oils and palm oil are capped and discouraged in efforts to incentive a transition towards advanced biofuels and minimize potential negative environmental effects (e.g. direct and indirect land use change). Furthermore, in some countries, such as the Netherlands, palm and soy oil are not allowed for biofuel production (De Staatssecretaris van Infrastructuur en Waterstaat, 2020). UCO and animal fat fall under a waste feedstock category in REDII, are listed in part-b of annex IX, and are also not considered as advanced biofuels (see section 6.2).

For the Netherlands, UCO (mainly used frying oil) is the main feedstock used to produce FAME and HVO. In 2021, 62% and 58% of the Dutch FAME and HVO production were UCO based and most of the feedstock was sourced overseas, mainly from China and other Asian countries (NEA, 2022). The high UCO demand and policy incentives to double count UCO-based fuel for suppliers made UCO market prices significantly higher than those of virgin oil. This setting resulted in a potential incentive for illegal practices to convert virgin oil into UCO, mix virgin oil with UCO, or increase the production of UCO and suspected fraud in the Netherlands and other EU countries (Van Grinsven et al., 2020). However, UCO's adulterations are not easy to detect, and current regulations can lead to non-transparent certification with a high volume of feedstock sources overseas. Stronger regulation and tracing mechanisms are required and currently discussed as the EU demand for FAME and HVO is expected to increase[20] if their contribution is included as renewable fuels in the transport sector in 2030 (Van Grinsven et al., 2020). Currently, REDIII proposes to add the following feedstocks to part b of the annex IX list:

- Bakery and confectionary residues and waste not fit for use in the food and feed chain
- Drink production residues and waste not fit for use in the food and feed chain;
- Fruit and vegetable residues and waste not fit for use in the food and feed chain, excluding tails, leaves, stalks and husks
- Starchy effluents with less than 20% starch content not fit for use in the food and feed chain
- Brewers' Spent Grain not fit for use in the food and feed chain

[20] According to REDII 1.7 % of the energy content of transport fuels in 2030 by each member state cap.

- Liquid whey permeate
- Deoiled olive pomace
- Damaged crops that are not fit for use in the food or feed chain, excluding substances that have been intentionally modified or contaminated in order to meet this definition
- Municipal wastewater and derivatives other than sewage sludge
- Brown grease
- Cyanobacteria
- Vinasse excluding thin stillage and sugar beet vinasse
- Dextrose ultrafiltration retentate from sugar refining
- Intermediate crops, such as catch crops and cover crops that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land and provided the soil organic matter content is maintained."

It is uncertain how the addition of new feedstocks will impact biofuel use when considering the several changes that REDIII can bring (sector expansion to include maritime and aviation). Expansion of the list to other types of feedstocks while maintaining the current cap can result in undesirable effects. In addition, many of the feedstock included in the new list are low-cost and a cap will undermine their future role. To illustrate, in 2021, 14% of the entire biodiesel production in the Netherlands was based on pit greases and flotation sludge (brown grease) (Nederlandse Emissieautoriteit, 2022). For 2021, the use of brown grease-based biodiesel counted towards the renewable energy targets. However, with the potential inclusion of brown grease on annex IX part-b, brown grease-based biodiesel would fall under the 1.7% annex IX part-b cap. Under current circumstances, it would not count towards renewable energy targets as the cap is already met as of 2020.

6.3.2 Annex IX part-a feedstock Advance biofuels

Advanced biofuels are defined in REDII as those produced from the feedstock listed in Part A of Annex IX (European Commission, 2018b). These feedstocks generally fall within the definition of waste and residues and are listed in the directive as follows:

- Algae if cultivated on land in ponds or photobioreactors
- Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC
- Biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate B collection as defined in point (11) of Article 3 of that Directive
- Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex
- Straw
- Animal manure and sewage sludge
- Palm oil mill effluent and empty palm fruit bunches
- Tall oil pitch
- Crude glycerin
- Bagasse
- Grape marcs and wine lees
- Nut shells
- Husks Cobs cleaned of kernels of corn

- Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, pre-commercial thinnings, leaves, needles, treetops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil
- Other non-food cellulosic material
- Other ligno-cellulosic material except saw logs and veneer logs

The REDIII proposes to add the following feedstocks to Part A of Annex IX.

- Alcoholic distillery residues and wastes (fossil oils) not fit for use in the food or feed chain
- Raw methanol from kraft pulping stemming from the production of wood pulp
- Non-food crops grown on severely degraded land, not suitable for food and feed crops

Figure 6-3 shows the range of the main EU biomass potentials (annex IX part-a) found in literature when converted to FT-diesel potentials. There is a large variation in FT-diesel potentials given the difference in geographic scope, methods, demand and supply scenarios, biomass types and assumptions for biomass potentials. The following paragraphs describe the results for each feedstock type.

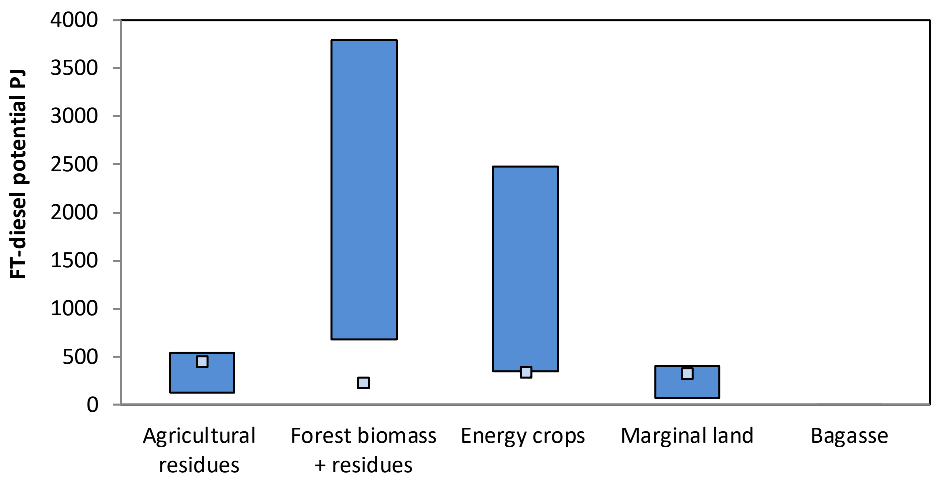

Figure 6-3: Range of FT-diesel potential based on the main EU biomass potentials found in the literature (Hoefnagels & Germer, 2018). The box marker represents the S2biom high sustainability constraints scenario value for agricultural residues, forest biomass + residues and energy crops (lignocellulosic energy crios) (Dees et al., 2017). The box marker for marginal lands represent the amount of lignocellulosic crops that can be rolled into the market under REDII GHG emissions criteria (Vera et al., 2021). Conversion factors between FT diesel and biomass were retrieved from (dos Santos et al., 2023; European Commission et al., 2019; Okeke et al., 2020; Petersen et al., 2015)

Agricultural residues

Agricultural residues, mainly straw, are considered as relevant biomass sources. The large variation in agricultural residue potentials depends on the scenario, scope and assumptions, such as excluding biomass that is required to maintain Soil Organic Carbon (SOC) levels, removal rates, and demand for competing uses (e.g. animal bedding). An extensive review of agricultural residues while considering ecological constraints showed 1978 to 3182 PJ/year available in the EU by 2030 (Kluts et al., 2017). A recent study estimated 2185 PJ/year (based on a lower heating value of 17.2 MJ/kg) of agricultural residues in the EU by 2030 while considering competing uses (Scarlat et al., 2019).

One of the most extensive supply potentials for biomass is provided by the S2Biom project at the country and NUTS3 level (Dees et al., 2017). In their sustainability scenario, by 2030, agricultural residues (cereals straw, oil seed rape straw, maize stover, sunflower straw) can reach 2328 PJ/year for EU 27. This scenario contains a high degree of sustainability criteria, such as leaving in the field enough residues to maintain soil characteristics. This biomass potential can be translated to 447[21] PJ/year of advanced FT-diesel, as shown in Figure 6-3 – box marker.

For the Netherlands, the domestic supply of straw and other feedstocks listed in annex IX part-a to meet the advanced fuel targets in the Dutch ordinance (Panoutsou et al., 2016) is limited. To illustrate, the contribution of FT-diesel[22] from agricultural residues by 2030 can reach 1.81 PJ/year. Thus, the Netherlands will rely on intra-EU and extra-EU imports to develop its advanced fuels sector and meet the demand. However, recent developments, such as the war between Russia and Ukraine, have shown that supply chains can be easily disrupted, especially for agricultural commodities. Note that (pre-war) Ukraine was one of the main producers and exporters of cereals worldwide (directly related to agricultural residue production) (Hellegers, 2022). By 2030, Ukraine showed a FT-diesel potential of 123 PJ/year[23] from agricultural residues (Dees et al., 2017) and this country was identified as a key export region for solid biomass (Mai-Moulin et al., 2019). Therefore, with current and future developments, it is uncertain how intra-EU and extra-EU supply chains will be affected and to what extent these disruptions will limit meeting advanced biofuel demand and renewable energy targets.

Forest biomass

Forest biomass covers many feedstock types ranging from stemwood up to primary and secondary forest residues. Furthermore, several studies also consider the residues available from forestry-related activities such as sawdust from sawmill facilities. In literature, results of forest resources biomass potentials available for energy purposes generally considered stemwood in their assessments. This assumption results in considerably high biomass potentials, as shown in Figure 6-3. To illustrate, approximately 60% of the forestry biomass potential in S2biom forest biomass potentials corresponds to stemwood (Dees et al., 2017). In FIGURE 6-box marker, results are shown for EU-27 without considering stemwood. Under a high level of sustainability constraints (Dees et al., 2017), by 2030, there is 231PJ/year[24] FT-diesel potential available from forest residues for EU-27. Note that stemwood is not defined under forestry residues in annex IX part-a. Therefore, results are shown without stemwood to avoid potential misinterpretations of forest resources availability and avoid confusion over forest resources competition with other sectors different than energy.

[21] Considering a conversion ratio between straw and diesel of 0.192 MJfuel/MJ feedstock (dos Santos et al., 2023).
[22] Considering a conversion ratio between straw and diesel of 0.192 MJfuel/MJ feedstock (dos Santos et al., 2023).
[23] Considering a conversion ratio between straw and diesel of 0.192 MJfuel/MJ feedstock (dos Santos et al., 2023).
[24] conceding a conversion ratio between woody feedstock and diesel of 0.38 MJfuel/MJ feedstock (European Commission et al., 2019).

Energy crops

Despite the current small share of lignocellulosic energy crop production in the EU, these crops are expected to grow in importance in the upcoming decades to meet advanced biofuels and renewable energy targets and reduce GHG emissions in line with policy objectives (Cintas et al., 2021). Lignocellulosic energy crops provide a good alternative in terms of availability, costs and associated emissions (Daioglou et al., 2019). Several studies have projected the potential of lignocellulosic energy crop production for Europe under different sustainability criteria (Allen et al., 2014; Creutzig et al., 2015; Dees et al., 2017; Ruiz et al., 2015). One of the most comprehensive reviews on biomass potentials shows that the EU domestic availability of lignocellulosic energy crops reported in different studies for the EU ranges between 2240 PJ and 12880 PJ by 2030 (Hoefnagels & Germer, 2018). The differences in scope, parameters and methods drive the wide range of projections between studies. Furthermore, this limits the translation into advanced biofuels potentials. However, Dees et al., 2017, under a high sustainability constrain scenario, estimated 1643 PJ of ligno-cellulosic energy crops for EU-28 by 2030. This is equivalent to 336[25] PJ of FT-diesel by 2030 (Figure 6-3).

Sugarcane bagasse

Some feedstocks listed in part-a of annex IX are unavailable locally in the EU. Therefore, using them for advanced biofuel production and use in the EU maritime industry will rely on extra-EU imports. This is the potential case of sugarcane bagasse. Currently, Brazil is the lead producer of sugarcane in the world (more than twice compared to the second producer, India) and, consequently, presents the highest potential for sugarcane bagasse use (or export). For Brazil, the sustainable bagasse potential when considering local competing uses and following current development trends is 0,8 PJ/year by 2030 (Mai-Moulin et al., 2019). This bagasse potential is equivalent to 0.18 PJ/year[26] of FT-diesel production (Figure 6-3). Note that most of the bagasse is currently used (even the bagasse surplus after meeting the energy requirements) in the sugarcane mills for energy production. Thus, along the sugar-derived sugarcane value chain, these practices would have to be adapted to release feedstocks for export or the local production and export of final commodities such as advanced biofuel.

Marginal and degraded lands

The proposal in REDII to add explicitly non-food crops grown (energy crops) on severely degraded land, not suitable for food and feed crops, is of particular importance. In REDII, using land for biomass production was constrained by the sustainability criteria for biofuels, bioliquids and biomass fuels laid down in article 29. Despite that, the use of degraded land was encouraged for biomass production by granting a bonus of 29 g CO2eq/MJ biofuel if biomass originates from restored degraded land under the conditions that the land was not in use for agriculture or any other activity in and after January 2008; and is severely degraded land (including land that was formerly in agricultural use) (European Commission, 2018b). With the potential explicit addition of this feedstock type, the use of degraded land for biomass production and advanced fuels can be encouraged. Particularly, the use of lignocellulosic energy crops such as perennial grasses (e.g. Miscanthus) and short rotation coppice (e.g. Willow), which can deliver high yields in less suitable conditions.
In addition, these feedstocks can contribute to carbon sequestration, land restoration and limit soil erosion (Næss et al., 2023; Richter et al., 2015).

[25] Considering a conversion ratio between herbaceous lignocellulosic energy crop and diesel of 0.193 Mjfuel/Mj feedstock (Okeke et al., 2020) and a conversion ratio between woody lignocellulosic energy crop and diesel of 0.38 Mjfuel/Mj feedstock (European Commission et al., 2019).

[26] Considering a conversion ratio between bagasse and diesel of 0.22 Mjfuel/Mj feedstock (Petersen et al., 2015).

A recent study showed that by 2030, approximately 1951 PJ/year of lignocellulosic energy crops that meet REDII land-related sustainability criteria could be produced in EU-28 (including UK) marginal lands (Vera et al., 2021). Note that marginal lands can be categorized as degraded lands following REDII definitions. This potential is equivalent to 400[27] PJ/year of FT-diesel by 2030 (Figure 6-3). Despite the high potential, approximately 20% could not be rolled out into the market as several production routes fail to meet REDII GHG savings criteria, leaving 320PJ/year available (Figure 6-box marker). For several locations, the production of lignocellulosic energy crops results in high LUC GHG emissions that overpass REDII thresholds. Note that no bonuses, as mentioned in REDII for land restoration, were granted under the mentioned assessment. Note that the biomass potentials estimated by Vera et al., 2021 are potentially lower given that relevant criteria such as economic and non-economics barriers were not considered.

Biomass potentials challenges

The contribution of FT-diesel from agricultural residues, forestry residues and lignocellulosic energy crops can provide enough locally sourced biomass for conversion to FT-diesel to meet the EU 2030 maritime demand for renewable and biodiesel. Similar results are provided in other studies, such as (Prussi et al., 2022). However, supplying different feedstock alternatives, mainly biomass, for producing advanced biofuel to meet the EU's current and future demand in the maritime sector is challenging. Besides energy carriers, biomass is a key resource for other industries and their decarbonization pathways. For example, biomass use for biochemicals is expected to ramp up in the upcoming years and, thus, provide an alternative to conventional fossil-based chemicals (Nong et al., 2020). It is suggested that achieving net zero GHG emissions by 2050 for the plastics sector can rely considerably on biomass use in combination with other technologies such as Carbon Capture and Utilization (CCU) (Meys et al., 2021). These conditions can steer the future market in the function of end-uses, cost and competitiveness, leading to additional stresses for biomass production and availability. This competitive market configuration is particularly important for the maritime sector as biomass use for producing advanced biofuels is one of the main decarbonization strategies given the few alternatives (European Commission, 2018a) .

Other challenges can limit feedstock availability for the EU's advanced biofuel production. For example, the promotion of using degraded land or marginal land for biomass production can bring additional benefits in terms of GHG emissions and other ecosystem services. However, marginal lands are generally located in remote regions, and supplying biomass from these locations to conversion facilities without adequate infrastructure can be logistically challenging, resulting in high costs. In addition, there is still a lack of trials on producing large volumes of biomass in such conditions (Hoefnagels & Germer, 2018). Furthermore, scaling up biomass production in remote locations and the entire advanced biofuels value chain can take years, leading to a mismatch between demand and readily available supply. These logistics barriers, lack of experience and production scale-up can lead to unappealing opportunities for biomass production without the right incentives for farmers and other stakeholders, thus, constraining the overall potential of using degraded or marginal land for biomass production in the EU.

Most projections show that for the maritime sector, the use of biofuels and advanced biofuels in 2030 is low when compared to the current volumes consumed and trends in other transport (sub) sectors (EurObserv'ER, 2022).

[27] Considering a conversion ratio between herbaceous lignocellulosic energy crip and diesel of 0.193 MJfuel/MJ feedstock (Okeke et al., 2020) and a conversion ratio between woody lignocellulosic energy crip and diesel of 0.38 MJfuel/MJ feedstock (European Commission et al., 2019).

To illustrate, under a high-demand scenario, the total maritime demand for biofuels in 2030 can reach 217 PJ/year, while for road transport is 1842 PJ/year (Chiaramonti et al., 2021). However, scaling up the production of advanced biofuels from current volumes used in the maritime sector to meet the potential demand will be challenging, especially when considering the competition for different feedstock types that can arise from road transport and aviation under potential legislation developments. In addition, the demand for biofuels, advanced biofuels and other renewable energy sources is expected to increase considerably after 2030 towards 2050 in all transport modes (IEA, 2022).

6.4 Conclusions

FAME and HVO for maritime use will stay relevant due to the introduction of instruments REDIII, FuelEU Maritime, CII and EU-ETS and the slow development of other renewable energy sources into the market (e.g., advanced biofuels). It should be noted that there is still uncertainty about the precise requirements for the EU maritime sector. However, FuelEU Maritime will enter into force in 2025.

FAME and HVO

- FAME and HVO produced from annex IX part b and conventional feedstock are the only large-scale commercially proven conversion pathways. Therefore, they will likely remain important for many years ahead.
- The current proposed legislation aims to cap the use of conventional and annex IX part-b biofuels and shift to advanced biofuels (produced from feedstocks listed in annex IX part-a) and other renewable energy sources. This may limit the ultimate growth of biodiesel like GoodFuels MDF1.

Feedstock additions

- The potential addition of new feedstock to annex IX part-b without cap modifications, might have undesirable effects on some conversion routes already in place, for example, biodiesel production and use of brown grease (e.g., GoodFuels MDF1) in the Netherlands

Advanced biofuels (FT diesel) potential.

- According to the available literature, the EU can source sufficient sustainable feedstock from agricultural residues, forestry residues and energy crops to produce advanced biofuels (drop-in biofuels) for maritime shipping (and other transport sectors).
- There are already established logistics for FAME and HVO and the fleet compatibility enables a faster shift to other renewable fuel types like advanced biofuels. In addition, due to the long lifetime of ships and engines, there will be a long-term need for sustainable drop-in biofuels.
- Ramping up production capacity for ‘advanced’ biodiesel will be challenging. It lacks investors, possibly because of technical and economic risks and ultimate uncertainty about demand and European instruments. Also, mobilisation of large quantities of sustainable biomass will be challenging to meet the projected advanced biofuels demand
- The production of advanced biofuels (feedstock annex IX part-a) is not yet commercial.

7 Conclusions

TNO has investigated the GoodFuels MDF1 FAME type biodiesel and biodiesel in general in the context of the Green Deal validation program.

The validation include the following:
- Environmental impact
- Practical application and scalability
- Economic aspects
- Future proofness

The conclusions with respect to the validation aspects and GoodFuels claims are summarised in the sections below. Apart from the assessment of the FAME type biodiesel MDF1, the scope has been broadened to include the 'advanced' type of biodiesel such FT diesel.

Environmental impact
The main conclusions with respect to the claims of GoodFuels for MDF1 are summarised in the table below.

GoodFuels claim MDF1	Validation result
WTW GHG emission reduction of 84% - 95%	No specific MDF1 chain analysis performed. FAME produced from residue flows has a GHG reduction of 84%-88% based on default numbers
SO_x emission reduction	Up to 50 times lower SO_x emission level due to the very low FSC of MDF1 compared to MGO or ULSFO with 0.1% FSC
No NO_x emission reduction	For Tier I and Tier II engines: a NO_x increase is expected of about 3% with B30 to about 12% with B100, compared to ULSFO or MGO. In most cases, NOx emissions with B30 – B100 will continue to comply with Tier I and Tier II limit values, for engines developed for a range of fuels. For Tier III engines urea dosage for SCR system can be adapted such that NOx emissions will remain the same. For engines with closed loop control this will be done automatically
BC reduction but no PM mass emission reduction	Not sufficient results to predict general influence on PM mass emissions (in g/kWh). Strong (3 to 5 times) reduction of Black Carbon (BC) emissions proportional to the blend percentage

Practical application and scalability
With respect, to practical application and scalability of FAME type biodiesel, the following conclusions can be made:
- General positive feedback was received from ship owners, about the use of B30 to B100 (30% to 100%FAME) blends.
- Engine manufacturers are cautious. High-Speed engine manufacturers often recommend to limit FAME blends to B20. There were no directs blend limits for Medium-Speed engines, although manufacturers ask to check with them on a case by case basis.

- FAME quality used for blends should comply with the normal standards like EN14214 or ASTM D6751.
- The recommendations for the use of FAME blends for the Dutch shipping categories are as follows:
  - o For ships with medium speed engines (general cargo and dredging vessels) of up to B100 can be used, but it is highly recommended to check each engine installation with the engine supplier.
  - o For ships with high-speed engines (TUG, offshore supply, crew tender and super yacht), Engine manufacturers often recommended to limit the FAME blend to B10 or B20.
- The impact to operational aspects are limited to bunkering a slightly increased fuel quantity (plus ≈ 10%). Additionally, relatively simple measures, like more frequent inspections and cleaning of fuel tanks and filter system, limit or eliminate most potential risks.
- In general there are no limitations to the use of synthetic biodiesel such as HVO or FT biodiesel, provided that these fuels fulfil the requirements of the fuel standards EN15940.

Economic impact

Regarding the economic aspects of FAME biodiesel, the following conclusions are made:

- The market prices of biodiesel and fossil diesel fuel vary a lot. In the period from April 2020 to February 2022, the biodiesel price almost doubled and the MGO price increased by more than a factor of four. In February 2022, the FAME biodiesel price was a factor 2.4 or 1179 €/TOE higher than the price of MGO (831 €/TOE).
- The FAME type biofuel production cost from fresh vegetable oil can vary between 800 and 1200 €/TOE. This is a lot lower than the UCOME[28] market price in February 2022 which was about 2020 €/TOE. The 'double counting' category within the RED of UCOME probably plays a large role in this relatively high price.
- FAME type biodiesel such as GoodFuels MDF1 will likely be lower priced in the long term than the 'advanced' category biodiesel.

Regarding 'advanced' (Annex IXA feedstock) biodiesel (e.g. FT biodiesel):

- The biodiesel supply for the maritime market in 2030 and later will likely need to be a combination of FAME type and 'advanced' biodiesel. The future cost of the advanced biodiesel production is expected to range between 800 and 1600 €/TOE (excluding profit margin and bunkering costs). There are large concerns about production ramp up and availability of advanced biodiesel up to 2030 and later.
- The future price of advanced biodiesel is also dependent on precise sustainability criteria, minimum volume requirements, production scale up options and market prices of other advanced sustainable fuels like methanol.
- Both FAME type and advanced biodiesel will likely remain one of the most important and also economic fuel options for existing vessels and new vessels to reduce the GHG emissions.

Future proofness

Future proofness is influenced by fuel production and economic aspects, as well as by the fit in the RED and maritime instruments for GHG reduction (both in comparison with other sustainable fuels).

[28] UCOME: Used Cooking Oil Methyl Esther, a FAME type.

In particular, the following conclusions with respect to future proofness of FAME type biodiesel are made:

- The use of FAME blends in the maritime sector has been very popular during the past years especially due to ‘opt-in’ possibility of the RED. In 2021, about 10 PJ or 270.000 ton FAME was supplied as bunker fuel blend in the Netherlands (≈2% of the total Dutch bunker quantity).
- For 2023 it has become impossible for FAME to comply with the Dutch feedstock (particularly the Annex IXA) requirements for the opt-in arrangement. This will severely disrupt the economic aspects of using FAME type biodiesel.
- From 2025 onwards, maritime GHG instruments such as FuelEU Maritime, ETS can IMO CII are likely to stimulate the use of FAME and ‘advanced’ biodiesel in maritime shipping. The feedstock types for FAME are generally categorised in Annex IXB, which is limited in volume[29] and also already used by road transport. This may limit the use of FAME biodiesel. On the other hands other types of ‘advanced’ (Annex IXA) biofuels such as FT diesel, methanol or ethanol are not likely to be available in sufficient volume and most ships cannot use methanol or ethanol. So alternatives for FAME are very limited, which may positively influence the acceptability of FAME (category Annex IXB) such as MDF1.
- The current biodiesel production in Europe (primarily for road transport) is much larger than the quantity needed for maritime transport in 2030 (according to FuelEU Maritime).
- HVO, Hydrotreatment Vegetable Oil, biodiesel has the same advantages and limitations with respect to future proofness, since it is generally produced from the same feedstocks as FAME.

[29] The volume of REDII Annex IXB (Part B) is limited to 1.7% of the total fuel demand.

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IMO Resolution MEPC 259(68), 2015 Guidelines for Exhaust Gas Cleaning systems. Annex 1. 15 May 2015.

Relevant references with respect to biofuel and IMO MARPOL standards:
MARPOL Annex VI Regulation 18.3
Marine Vessels Rules 4-2-1
MEPC.1/Circ.795/Rev.6
MEPC.1/Circ.878
ISO 8217:2017
ABS, 2022: ABS regulatory news No.6/2022: MARPOL Annex VI – biofuels as marine fuels

Relevant fuel standards for biodiesel
EN14214: liquid petroleum product - Methylesters van vetzuren (FAME) for diesel engines and furnaces.
EN15940: Paraffine diesel fuel produced via a synthetic process or via hydrogenation
EN16734: B10 dieselbrandstofmengsels – Eisen en beproevingsmethoden
EN16709: diesel fuel with high FAME content (B20-B30)
CEN/TR 13567-1, Petroleum products - Guidelines for good housekeeping

Signature

The Hague, 2 November 2023

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Appendix A

Appendix A – Literature biodiesel use in ships

Some existing literature on various aspects described in Chapters 2 and 3 is presented below with a short summary of the results in these studies.

Black carbon emissions from a ship engine in laboratory (Aakko-Saksa, et al., 2017):

This study investigates the black carbon emissions from a ship engine in laboratory conditions on a B30 biodiesel blend. PM in the engine exhaust is shown to consists typically of carbonaceous compounds. The study finds that PM concentrations and emissions are very dependent on the sulphur content in the fuel. Biofuels often have a lower sulphur content, as such, higher biofuel content fuels show a decreasing PM concentration in the engine exhausts. However, as the oxygen content in biofuels is higher, higher biofuel blends tend to increase NOx emissions compared to non-oxygenated fuels.

The use of biodiesel fuels in the U.S. Marine Industry (Nayyar, 2010):

In Europe, the most common biodiesel is derived from rapeseed oil, and is referred to as Rapeseed Methyl Ester (RME). Animal fat-based biodiesel has different properties than vegetable oil-based biodiesel and normally have poor cold flow and stability properties. Cold flow properties of biofuel blends can be a problem as the fuel starts to gel at higher temperatures compared to conventional diesel. As the biofuel begins to gel, the viscosity starts to rise, which causes increased stress on fuel pumps and fuel injection systems. Therefore, engine manufacturers will not warranty equipment produced prior to 2006 for biodiesel blends over 5%. Also, biodiesel may soften and degrade certain types of rubber compounds in hoses and gaskets, causing leakages and crumbling of the rubber material.

The high oxygen content of B100 (11%) provides a more complete combustion and a reduction in most emissions compared to pure diesel. However, this also increases the oxidation of the fuel, which causes a higher degradation and problems regarding long-term storage. The effect of biodiesel fuel on the various corrosion preventive coatings or cathodic protection systems used in marine fuel tank applications has yet to be determined.

Projected impact of biodiesel on road transport emissions up to 2030 – background report (Kadijk, et al., 2014):

There are uncertainties regarding the health impact of biofuel blends due to the changes in elemental composition within these blends. This study focusses on the impact of B7 FAME blends on light duty vehicles with diesel. The results show that for road traffic, NO_x emissions can go up by 10% with FAME. There is a decrease in particle number emissions. However, particle size distribution is not significantly affected. Health related emissions include benzene, toluene and xylene (BTX), which are emitted from unburned molecules. There is however no real trend found between BTX emissions and biofuel use.

Biofuels in ships (Opdal & Hojem, 2007):

Biodiesel can act as a solvent which causes softening and degradation of certain rubber and elastomer compounds used in older engines. These issues could be resolved by switching to system components with synthetic hoses and seals that are biodiesel resistant. The study also notes that new engines are often biodiesel compatible but that the OEM should be consulted before use of biofuels. Another concern noted in the report is that biodiesel could potentially clean deposits left in the fuel system by petroleum diesel which could then clog filters. Filters should thus be checked and cleaned. Low blends of biodiesel up to B20 are shown to not result in any fuel system degradation.

Impact assessment biobrandstoffen voor de binnenvaart (Verbeek, Karaarslan, Quispel, & Tachi, 2020)

This study focusses on the impact of biofuels for inland shipping. Usually, the technical risks within the engine system increase with increasing blend percentage. Engines in inland ships are usually well resistant to FAME blends. B7 (7% FAME) can be used in almost all inland engines. CCRII engines are often well resistant to B20 and B30 blends. Older engine types seem to be less sensitive to the fuel type, on the other hand gaskets and rubber hoses are not always sufficiently resistant to biodiesel. Biofuel blends are shown to have better lubrication properties compared to conventional fuels, hence reducing wear of the engine.

Technical issues are often associated with low quality feedstock for FAME production. Clotted filters, corrosion of tanks and bacteria growth are found to be the main related complications. Good maintenance practice of the engine systems is required to mitigate these issues, including frequent inspections and cleaning of the fuel systems and frequent replacement of the fuel filters. Shelf life of FAME is also shorter compared to fossil fuels (1 year versus 5 years) with multiple factors influencing this shelf life such as temperature, water content and rest products in the fuel tank.

Impact of Biofuel on the Environmental and Economic Performance of Marine Diesel Engines (Sagin, et al., 2023)

This research was performed on Yanmar 6N165LW marine medium-speed diesel engines in a laboratory with operating loads of 50 to 80% and a fuel mixture between B80 and B95 RMA10/FAME. The study focuses on the impact of FAME blends on environmental and economic efficiency. For the assessment of environmental efficiency, general CO and NOx emissions are studied. They are seen to be reduced by 8.7-23.4% and 3.1-24% respectively with higher biofuel blends. Economic efficiency criteria were based on fuel consumption efficiency. Higher biofuel blends resulted in higher fuel consumption (0.5-9.3%.) and therefore lower economic efficiency.

Biofuels for the marine shipping sector (Hsieh & Felby, 2017).

Biodiesel can be used to replace MDO and MGO in low or medium speed diesel engines like tugboats, small carriers and cargo ships. FAME as a fuel has good ignition and lubricity properties. It is theoretically possible to run diesel vehicles on 100% FAME, but this requires adjustments to the ships engines as well as approval from the engine manufacturers. FAME blends up to 20% can however be used in diesel engines with little or no engine modifications.

FAME blends used for automotive diesel engines have shown to reduce the emissions of sulphur oxides, carbon monoxide, and unburned particulate matter (PM). Higher acidity of FAME can however cause damage to the engine components like fuel pumps, injectors and piston rings.

Lower NO_x but higher particle and black carbon emissions from renewable diesel compared to ultra low sulfur diesel in at-sea operations of a research vessel (Betha, et al., 2017).

In this study, gas and particle emissions were measured from a research ocean-going vessel with hydrogenation derived renewable diesel (HDRD) with different engine speeds. CO and NO_x emissions were respectively 20% and 13% lower for HRDR compared to conventional diesel at low speeds (700 rpm). At higher speeds (1600 rpm) the emissions from the different fuels were indistinguishable. Particulate matter emissions were much higher for the HDRD fuel compared to conventional diesel at almost all engine speeds.

The potential of liquid biofuels in reducing ship emissions (Zhou, Pavlenko, Rutherford, Osipova, & Comer, 2020)

This study explores the potential contribution from different biofuel pathways in achieving the emission reduction targets set by IMO by looking at the well-to-wake emission cycle for different liquid biofuels including FAME. Due to the low sulfur content of FAME biodiesel, SO_x emissions have been reported to be 90% lower compared to conventional diesel. There is no clear correlation of NO_x emission reduction and the use of FAME biofuel blends discovered yet. PM emissions can reduce up to 30% compared with conventional marine fuels.
Blends containing up to 20% of FAME are not expected to require marine engine modifications. Higher blends would require engine and fuel system modifications and more frequent maintenance and filter check-ups.

Information from engine manufacturers

Wartsila

Wartsila is positive about the application of FAME type biodiesel in blends up to 100%. They state ‘minor differences’ in physical and chemical properties when compared to fossil distillate fuel. They have experience with the application since the 1990s. Future Fuels Biodiesel - Wärtsilä (wartsila.com) (Wartsila 2023)
Apart from the GHG emissions reduction, they summarise the following pros and cons

Pros:
- Virtually no sulphur emissions
- Low particulate (PM) emissions
- Can be burned in existing engines without the need for modifications
- Blends well with fossil diesel
- Good lubrication properties

Cons:
- Increased NO_x emissions (~10–20%)
- Contains ~10% less energy than fossil diesel
- Reduction of water content with separator more challenging than with fossil diesel
- Can foster heightened microbial activity
- Long-term storage potential limited by oxidation

In terms of maintenance, Wartsila emphasises the need to clean tanks before switching to FAME. This is because FAME would dissolve deposits or sludge in the tank, which can clog fuel filters They also recommend to check gaskets, seals, rubbers and metals for potential degradations with FAME. Wartsila emphasises that their engines and fuel supply systems are compatible with any biofuel that meets established standards.

Volvo Penta
Volvo Penta only offers high speed engines. For maritime applications.
Volvo recommends the use of synthetic biodiesel HVO. This can be used in 100% blend (HVO100) for all their engine types, including Tier III engines. HVO100 does not affect the SCR system operation.
Top 5 tips using HVO 100 fossil-free fuel instead of diesel | Volvo Penta

The Volvo Penta engines are generally also compatible for FAME blends up to 20% or 30% (B20 – B30).

Appendix B

Appendix B – GHG emissions maritime fuels

Table 8-1: FuelEU Maritime fossil fuel default emission factors

		WtT		TtW				
Class / Feedstock	Pathway name	LCV $\left[\frac{MJ}{g}\right]$	$CO_{2eq\,WtT}$ $\left[\frac{gCO2eq}{MJ}\right]$	Energy Converter Class	$C_{f\,CO_2}$ $\left[\frac{gCO2}{gFuel}\right]$	$C_{f\,CH_4}$ $\left[\frac{gCH_4}{gFuel}\right]$	$C_{f\,N_2O}$ $\left[\frac{gN_2O}{gFuel}\right]$	C_{slip} As % of the mass of the fuel used by the engine
Fossil	HFO ISO 8217 Grades RME to RMK	0,0405	13,5	ALL ICEs	3,114 MEPC245 (66) Regulation (EU) 2015/757	0,00005	0,00018	-
				Gas Turbine				
				Steam Turbines and Boilers				
				Aux Engines				
	LSFO	0,0405	13,2, crude 13,7 blend	ALL ICEs	3,114	0,00005	0,00018	-
				Gas Turbine				
				Steam Turbines and Boilers				
				Aux Engines				
	ULSFO	0,0405	13,2	ALL ICEs	3,114	0,00005	0,00018	-
	VLSFO	0,041	13,2	ALL ICEs	3,206 MEPC245 (66) MRV Regulation	0,00005	0,00018	-
	LFO ISO 8217 Grades RMA to RMD	0,041	13,2	ALL ICEs	3,151 MEPC245 (66) Regulation (EU) 2015/757	0,00005	0,00018	-
	MDO MGO ISO 8217 Grades DMX to DMB	0,0427	14,4	ALL ICEs	3,206 MEPC245 (66) Regulation (EU) 2015/757	0,00005	0,00018	-
	LNG	0,0491	18,5	LNG Otto (dual fuel medium speed)	2,755 MEPC245 (66) Regulation (EU) 2015/757	0	0,00011	3,1
				LNG Otto (dual fuel slow speed)				1,7
				LNG Diesel (dual fuel slow speed)				0.2
				LBSI				N/A
	LPG	0,046	7,8	All ICEs	3,03 Buthane 3,00 Propane MEPC245 (66) Regulation (EU) 2015/757	TBM	TBM	
	H2 (natural gas)	0,12	132	Fuel Cells	0	0	-	-
				ICE	0	0	TBM	
	NH3 (natural gas)	0,0186	121	No engine	0	0	TBM	-
	Methanol (natural gas)	0,0199	31,3	All ICEs	1,375 MEPC245 (66) Regulation (EU) 2015/757	TBM	TBM	-

Appendix C

Appendix C - REDII conversion routes

Table 8-2: REDII conversion routes (European Commission, 2018b)

REDII conversion route
Straw (agricultural residues) to 2nd generation ethanol
Forest residues to Methanol
Short rotation coppice to Methanol
Forest residues to FT-gasoline
Short rotation coppice to FT-gasoline
Forest residues to DME
Short rotation coppice to DME
Forest residues to FT-diesel
Short rotation coppice to FT-diesel
Rapeseed to FAME
Sunflower seed to FAME
Soybean to FAME
Palm oil, open effluent pond to FAME
Palm oil, methane captured to FAME
UCO to FAME
Animal fats to FAME
Rapeseed to HVO
Sunflower seed to HVO
Soybean to HVO
Palm oil, open effluent pond to HVO
Palm oil, methane captured to HVO
UCO to HVO
Animal fats to HVO

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