European Maritime Safety Agency

SAFE BUNKERING OF BIOFUELS

BUNKERING OF BIOFUELS IN MARITIME: CHARACTERISTICS, REGULATORY LANDSCAPE, AND SAFETY ASSESSMENT

Rev.1.0

Date: 15/12/2023

EMSA

About this study:

This report was commissioned by the European Maritime Safety Agency (EMSA) under Contract 2023/EMSA/OP/11/2023.

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Recommended citation:

European Maritime Safety Agency (2023), *Safe Bunkering of Biofuels*, EMSA, Lisbon

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Document History

Version	Date	Changes	Prepared	Approved
1.0	15/12/2023	First issue	Henriksen, Per Einar	Hoem, Åsa Snilstveit

Executive summary

The maritime industry confronts substantial challenges propelled by increasingly stringent air emissions and climate legislation. In the pursuit of viable solutions, the industry is presented with a diverse array of new technologies and alternative fuels. Various biofuels are emerging as viable options with the potential to swiftly entering the market. Positioned as one of the limited choices for decarbonizing the deep-sea sector of the global fleet, biofuels necessitate a thorough understanding of their potential risks and hazards prior to a more widespread adoption.

Despite the current bunkering of both neat biofuels and biofuel blends in shipping, there is a notable gap in widespread knowledge concerning these fuels and their associated safety implications. This report aims to address the safe bunkering of a selection of biofuels identified through a recent EMSA study as the most promising for maritime applications, including bio-methanol, bio-FT-diesel, bio-DME, HVO and FAME and relevant blends. The study focuses on characterizing the selected fuels by identifying and reviewing their hazardous properties. It also examines practices in other industries that may be applicable to the maritime sector and reviews the status of development of regulations for maritime use, specifically considering conventional bunkering arrangements.

Based on the identified characteristics, it is evident that bio-FT-diesel, HVO, and to a certain extent FAME share similarities with conventional marine distillates concerning hazardous properties relevant for bunkering. Consequently, it is rational to compare these with fossil marine diesels when identifying the risks. Bio-methanol, being chemically identical to fossil methanol, can leverage existing practices and regulations, as methanol is currently utilized as a marine fuel. Bio-DME, being gaseous under normal conditions, exhibits similarities with LPG fuels, enabling the utilization of LPG infrastructure, and opens the possibility of drawing inspiration from or aligning with established guidelines and regulations developed for LPG.

The chosen biofuels are distinct when it comes to regulatory coverage and industry best practices for their safe bunkering, with bio-methanol standing out as the most mature. The industry has more experience with methanol used as a marine fuel and by extension its bunkering, which led to the development of specific procedures, technical requirements, and a regulatory framework. Thus, best practices regarding the safe bunkering of bio-methanol are more mature compared to the other biofuels due to its identicalness with fossil-based methanol. An example of this being the comprehensive best practice laid out by the Port of Gothenburg on methanol bunkering, in addition to the CEN's Specification for Bunkering of Methanol Fuelled Vessels. For HVO, FAME and bio-DME there are no specific best practices or guidelines regarding its safe bunkering, although those fuels are clearly defined regulatory-wise. The Port of Singapore aims to facilitate the bunkering of these fuels by providing its own framework as outlined in its Port Marine Circular No. 21 of 2022, highlighting the role Port Administrations play in interpreting IMO regulations for use in practice. FT-diesel has the least regulatory coverage among the selected biofuels. A risk-based approach for the safe bunkering of biofuels seems the most appropriate until their use matures.

The study reviewed incidents and accidents in land-based industries dealing with the biofuels, looking for incidents related to the bunkering of the selected biofuels. The scope excluded accidents rooted in manufacturing processes or equipment specific to biofuel production and other industrial uses. Similarly, transportation accidents where biofuel cargo had no impact on the root cause were deemed irrelevant. A recurring issue involves hot work around fuel infrastructure leading to ignition and explosions, along with general equipment failure which may in part be attributed to inadequate maintenance procedures. Some accidents also occur during maintenance activities, suggesting that the maintenance procedures themselves may not be sufficiently robust.

The appropriate level of Personal Protective Equipment depends on the particular situation and the preceding risk assessment performed before fuel handling. Both the exposure risk and the classification of the substance to be bunkered play a role in determining the appropriate PPE for each crew member. Recurring PPE for all biofuels includes safety glasses, chemical-resistant gloves, as well as body- and respiratory protection based on the exposure risk. It is imperative to strictly adhere to the PPE guidelines outlined in the respective Safety Data Sheets.

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List of Abbreviations and Definitions

Terms	Definition
ARIA	Analysis, Research and Information on Accidents
Biodiesel	Generic term describing a bio-based fuel with properties similar to diesel or diesel containing bio-blends. "Biodiesel" is often used to describe fuels containing FAME, but it is not exclusively for FAME fuels (ISO, 2023).
Biofuel	Generic term for bio-based liquid fuel, and biofuel-fossil fuel blends (ISO, 2023)
Biomass	Solid plant or animal matter, including micro-organisms such as algae. May also refer to plant/animal matter which has been altered to some solid end products.
BtL	Biomass to Liquid
CAIRS	The Computerized Accident/Incident Reporting System. A database used to collect and analyse injuries, illnesses and other accidents that occur during the operations of the United States Department of Energy
Cold flow properties	The cold flow properties of fuels refer to their behaviour and performance under low-temperature conditions. Important cold temperature metrics for marine distillate fuels are cloud point (CP), pour point (PP) and cold filter plugging point (CFPP).
CSB	United States Chemical Safety Board
CTIF	The International Association of Fire and Rescue Services
CtL	Coal to Liquid
DM	Distillate marine fuel grades
DME	Dimethyl Ether
ECHA	European Chemicals Agency
ECS	European Committee for Standardisation
EPA	United States Environmental Protection Agency
FACTS	The Failure and Accident Technical Information System (FACTS) database, operated by the Unified Industrial & Harbour Fire Department in Rotterdam-Rozenburg (the Netherlands)
FAME	Fatty Acid Methyl Ester (often referred to as biodiesel)
FOGs	Fats, Oils and Grease (feedstock for biofuel production)
FT diesel	Fischer-Tropsch diesel
GHG	Greenhouse gas
GtL	Gas to Liquid
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil (sometimes referred to as paraffinic diesel)
IChemE	The Institution of Chemical Engineers
IDLH	Immediately Dangerous to Life or Health
IBC Code	International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk
IGC Code	The International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels

IMO	International Maritime Organization
ISGOTT	International Safety Guide for Oil Tankers and Terminals
JST	by the Japan Science and Technology Agency
LEL	Lower Explosive Limit
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSA	Life-saving appliances
MARPOL	The International Convention for the Prevention of Pollution from Ships
MGO	Marine gas oils
MHIDAS	The Major Hazard Incident Data Service, by the UK Health and Safety Executive
Natech	Natural Hazards Triggering Technological Accidents
NTSB	National Transportation Safety Board (For the US)
NCR	The United States National Response Centre
OSHA	United States Occupational Safety and Health Administration
PPE	Personal Protective Equipment
ppm	Parts per million (commonly used unit for very small concentrations of a solution)
PSM	Process Safety Management
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SAF	Sustainable Aviation Fuels
SDS	Safety Data Sheet
UEL	Upper Explosive Limit
ZEMA	The German Central Reporting and Evaluation Office for Major Accidents in Process Engineering Facilities
% v/v	Percent concentration by volume (volume/volume)

1. Introduction

1.1 Background

In recent years, the maritime industry has turned its gaze towards biofuels as a viable solution for reducing carbon impact, driven by the imperative to decarbonize the global fleet. Positioned as one of the limited choices for decarbonizing the deep-sea sector of the global fleet, biofuels necessitate a thorough understanding of their potential risks and hazards prior to a widespread adoption.

As traditional fuels like heavy fuel oils and marine diesel oils progressively give way to other energy carriers such as biofuels, the maritime industry may face a profound transformation in the design and operation of ships and their fuel supply chains. This transition not only introduces novel safety concerns but also underscores the urgency of addressing the associated challenges in a cohesive and standardized manner.

Ensuring the safe deployment of these new fuels is imperative to prevent additional threats to human life, health, and the environment, as well as to safeguard the integrity of assets. The selection of biofuels for this study, identified through a recent EMSA assessment, are limited to bio-methanol, bio-FT-diesel, bio-DME, HVO and FAME, including relevant blends.

Despite the ongoing bunkering of some biofuels in shipping, there exists a notable gap in widespread knowledge concerning these fuels and their potential safety implications. This report aims to bridge this information void on a high level by focusing on the characterization of the selected biofuels as chemicals and fuels, as well as reviewing and identifying available rules, regulations, industry standards and best practices.

1.2 Scope and Objectives

This study is designed with a threefold objective. Firstly, it seeks to identify the hazardous properties of the selected biofuels and their commonly used blends. Secondly, it aims to identify prevailing best practices employed in other industries that may be applicable to the maritime sector, facilitating for a potential transfer of knowledge. Lastly, the study delves into the current regulatory landscape, specifically focusing on the development of regulations pertinent to the biofuels' use in the maritime industry. This review takes into account conventional bunkering arrangements and operational procedures, providing a holistic understanding of the regulatory framework surrounding fuel usage in maritime operations. Additionally, a preliminary framework for a guidance on bunkering is established.

The scope of this study concentrates on the characterisation of selected biofuels as chemicals and fuels, encompassing a review of applicable rules, regulations, industry standards, shipowners' and ports' best practices, and preliminary considerations for a guidance framework ensuring the safe bunkering of the selected biofuels. The scope is limited to assessing safety for individuals on board, third parties, and the ship, excluding environmental damage related to bunker spills. Additionally, insights from incidents and accidents in land-based chemical and processing industries dealing with selected fuels inform the assessment of associated risks and hazards. A review of suitable personal protection equipment (PPE) for handling these fuels has also been conducted. As an input to drafting a goal-based guidance framework for safe bunkering of biofuels, a preliminary table of contents has been established with associated preliminary goals and functional requirements.

2. Selected biofuels and their characteristics

The deviation in characteristics between biofuels and traditional marine fuels has the potential to introduce new hazards during handling and bunkering operations. For biofuels, the various fuel properties can, to a large extent, vary based on the type of feedstock, the production method and level of refining and upgrading. In the broader context of biofuel products, this underscores the relevance of assessing the fuel product to be bunkered to unveil potential risks and consequences.

This chapter focuses on the examination of the selected biofuels, both as chemical substances and as marine fuels. The analysis encompasses an exploration of its physical properties, chemical hazards, and the broader impact on vessel safety, bunkering infrastructure, and crew safety during bunkering operations.

Highlighting disparities in physical and potentially hazardous characteristics in comparison to fossil-based marine diesel, this chapter employs distillate marine fuel grade DMA, as specified in ISO 8217, as a baseline for comparison. Furthermore, a high-level review of critical conditions, grounded in the identified characteristics of each fuel, has been conducted in relation to the anticipated conditions during bunkering operations.

2.1 Definition of relevant fuel characteristics

Table 2-1 provide a description of key fuel characteristics covered in this chapter, that may have implications for biofuel bunkering operations. Each fuel characteristic has been categorized into those relating to *flammability* of a fuel and its *storage, handling, release, and dispersion*.

Table 2-1: Description of relevant characteristics of fuels. Each description has been adapted from (DNV, 2022) and other sources.

Category	Fuel characteristics	Description
Flammability	Flashpoint (°C) (Not applicable for gases and gas mixtures)	The flashpoint is used as a main indicator of the flammability of a liquid product. It is defined as the lowest temperature at which there will be enough vapour from the liquid to produce a flammable mixture with air that can be ignited.
	Lower & upper flammability limit[2] (LEL and UEL) (% vol. fraction)	Flammability limits refer to the range of gas or vapour concentrations in air which will burn or explode in the presence of an ignition source. Flammability limits are usually given as the percent by volume of the gas or vapour in air.
	Minimum ignition energy (mJ)	The minimum ignition energy (MIE) determines the ignition capability of fuel-air mixtures, where the fuel may be a combustible vapour or gas. It is defined as the minimum electrical energy stored in a capacitor, which, when discharged, is sufficient to ignite the most ignitable mixture of fuel and air under specified test conditions. The MIE value is used to assess the likelihood of ignition during processing and handling.
	Auto-ignition temperature (°C)	Also known as self-ignition temperature, the auto-ignition temperature of a substance indicates the lowest temperature at which it may spontaneously ignite without the presence of an ignition source such as a flame or spark. At the auto-ignition temperature, the temperature alone provides sufficient energy to induce combustion. The auto-ignition temperature depends on pressure and availability of oxygen and is typically given at standard pressure and temperature, with ideal oxygen concentration. Since the auto-ignition temperature is given at idealized conditions, higher temperatures would be needed for ignition in most realistic scenarios.

[2] Also known as lower and upper explosive limit

Category	Fuel characteristics	Description
	Laminar burning velocity (m/s)	Burning velocity is the speed at which a flame front propagates relative to the unburned gas. As such, the burning velocity indicates how fast a flame travels through a flammable air-fuel mixture. The laminar burning velocity is the speed at which a laminar (planar) combustion wave propagates relative to the unburned gas mixture ahead of it. For most hydrocarbons the laminar burning velocity is measured in cm/s. Indirectly, laminar burning velocity can indicate the severity of an explosion.
Storage, handling, release, and dispersion	Normal Boiling point (°C)	The boiling point of a liquid is the temperature at which its vapour pressure is equal to the surrounding pressure and the liquid changes into a vapour.
	Toxicity	Toxicity is a chemical substance's ability to damage an organism. Toxicity is dose-dependent; even harmless substances, such as water, can lead to intoxication if taken in too high dose, and very poisonous substances can be harmless if the dose is negligible.
	Odour threshold	Limit for air concentration for which the odour is detectable and unpleasant. This can imply stricter control for fuel slip and leakages than toxicity limit on ferries and crew areas.
	Specific gravity (or relative density) (Air/water:1)	Specific gravity for gases is defined as the ratio of the density of the gas to the density of air at a specified temperature and pressure. If a gas has lower specific gravity than air (<1), it is said to be "lighter" than air, and if it has a higher specific gravity it is said to be "heavier" than air (>1). Similarly, specific gravity for liquids is defined as the ratio of the density of the liquid to the density of water at a specified temperature and pressure.
	Corrosion	A process where metal deteriorates, due to chemical, electrochemical and other reactions of the exposed material surface with the surrounding environment.
	Kinematic viscosity (mm^2/s or cSt)	Kinematic viscosity measures a fluid's internal resistance to flow under gravitational forces. Commonly used to characterize flow behaviour of fuels at a given temperature.
	Density (kg/m^3)	The amount of mass in a specific volume.
	Vapour pressure (mbar)	The pressure exerted by the vapour present above a liquid. It is a measure of how readily a substance evaporates into vapour or gas at a given temperature. It indicates the substance's volatility; in practical terms, the higher the vapour pressure, the more easily the substance evaporates and turns into vapour at a given temperature. High vapour pressure at a specific temperature correlates with a lower boiling point.
	Cold flow properties	Cold flow properties indicate the low-temperature operational ability of a fuel during cold weather. For example while one fuel at very low temperatures may remain fluid, another of a similar grade may either stop flowing or result in the deposition of wax crystals at the filters.
	Cloud point (°C)	Related to a fuel's cold flow properties, indicating low-temperature operation ability. The cloud point (CP) is defined as the temperature of a liquid specimen when the smallest observable cluster of wax crystals first appears upon cooling under prescribed conditions.

Category	Fuel characteristics	Description
	Cold Filter Plugging Point (°C)	Related to a fuel's cold flow properties, indicating low-temperature operation ability. The Cold Filter Plugging Point (CFPP) is defined as the lowest temperature, at which a given volume of diesel type of fuel still passes through a standardized filtration device in a specified time when cooled under certain conditions.
	Water solubility (g/L)	Water solubility refers to the ability of a substance to dissolve in water. If a substance is water-soluble, it means that it can effectively mix with and dissolve in water, forming a homogeneous solution. High water solubility means easier dissolving in water.

2.2 Summary of fuel characteristics

In Table 2-2, an overview of fuel properties relevant for the five biofuels examined in this study is presented. The properties listed in the table lack footnotes, and specific conditions relevant to each characteristic may apply. For further details, refer to the respective sections for more information, including references. It should be noted that this summary is based on a selection of fuel products, and exclusively includes the neat biofuels and does not account for any blends.

Table 2-2: Summary of fuel characteristics as presented in section 2.4.1 to 2.8.1. For further details see the respective sections.

Fuel property	Unit	MGO	Bio-methanol	Bio-FT-diesel	Bio-DME	HVO	FAME
Flashpoint	°C	≥ 60	9.7	59	-41	61	≥120 - <180
LFL and UFL	% v/v	0.5-7.5	5.5-44	Not available	3.4 - 27	0.8 – 5.4	-
Minimum ignition energy	mJ	-	0.14	-	0.29	-	-
Auto-ignition temperature	°C	240-350	455	208	350	204	≥256 - ≤266
Laminar burning velocity	m/s	-	0.48	-	0.54 (max)	-	-
Normal Boiling point	°C	160-400	64.7	158-351	-24.8	180 – 390	≥302.5-≤570
Specific gravity (Air = 1)	-	> 1	1.11	>1	1.59 (G)	> 1 (V)	> 1 (V)
Specific gravity (Water = 1)	-	< 1	0.79-0.80 (20°C)	<1	0.61(L)	0.77– 0.79	0.87-0.89
Toxicity IDLH	ppm	-	6000	-	Not available	-	-
Odour threshold	ppm	0.11	3.1-5960	Not available	Not available	-	-
Vapour pressure	mbar	<0.4 (20°C)	169 (25°C)	Not available	5333 (20°C)	0.4 (20°C)	≥2 - ≤6
Density (15°C)	kg/m³	800-910 (15°C)	791 (25°C)	770 (15°C)	661 (20°C, L)	765 – 800	878-895
Kinematic viscosity (40°C)	mm²/s	≥ 1.4 (40°C)	0.54-0.59 (20°C)	<7	<1 (L)	2.6	3.8 – 5.0
Cloud point	°C	**	-	**	-	-10 – -34	**
CFPP	°C	**	-	**	-	-	**
Oxidation stability	[g/m³] or [h]	Max 25 g/m³	-	Not available	-	Max 25 g/m³	Min 8 h
Water solubility	g/liter	Negligible	1000 (20°C)	Non-soluble	24-353	Non-soluble	Negligible
Remarks: ** See ISO 8217 for specification. (All references are indicated in the respective tables in section 2.4.1 to 2.8.1).							
IDLH = Immediately Dangerous to Life or Health Concentrations specified by the United States National Institute for Occupational Safety and Health (NIOSH), **L** = liquid, **G** = gas, **V** = vapour							

2.3 Summary of critical conditions

This section presents a high-level overview of what can be identified as critical conditions and fuel properties for the selected biofuels in relation to the foreseen conditions during bunkering. These conditions can play a crucial role in ensuring safe and efficient bunkering operations, meeting regulatory requirements, and preserving the fuel's integrity during storage and transfer processes. The outlined conditions are based on the pure biofuel intended for maritime use, while blends, if applicable, typically exhibit characteristics falling between the pure biofuel and the fuel being blended.

Table 2-3: Summary of critical conditions and the most crucial fuel properties for the five biofuels, in consideration of the anticipated conditions during bunkering.

Fuel	Critical conditions
Bio-methanol	**Temperature** ■ Methanol has a lower flashpoint (9.7 °C) compared to traditional marine fuels (≥ 60 °C), requiring careful additional safeguards to mitigate the risk of fire and explosion hazards. ■ Methanol's normal boiling point is about 65 °C. This temperature is considered out of range for normal bunkering operations. **Material compatibility** ■ Methanol can be corrosive to some materials (e.g., aluminium, copper, titanium, and polyvinyl chloride). Corrosion is prevented through the selection of materials in contact with methanol, or application of appropriate coating. **Miscibility and contaminants** ■ Methanol has a high solubility in water. Even solutions of methanol containing up to 74% water may be flammable. **Toxicity** ■ The Immediately Dangerous to Life or Health concentration (IDLH) of methanol is 6000 ppm. Primary risks related to methanol toxicity is through ingestion of the substance in its liquid state, but vapour inhalation and contact/absorption through the skin can also have harmful impact.
Bio-FT-diesel	**Temperature** ■ Bio-FT-diesel may have a lower flashpoint than 60°C. As such, the IMO IGF Code could be mandatory, depending on the specified flashpoint of the bio-FT-diesel product.
Bio-DME	**Temperature** ■ DME is a flammable gas under normal ambient conditions necessitating additional safeguards to avoid the risk of fire or explosion. The presence of surfaces above the autoignition temperature of DME (350 °C) is not considered credible during bunkering operations. However, sources of ignition still pose a risk. ■ DME will liquefy if cooled (below boiling point at -24.8 °C at 1atm) or pressurized (above the vapour pressure at 5.3 bar at 20 °C). ■ The freezing point of DME (-141.5 °C) is considered out of range during bunkering operations. **Pressure** ■ If pressure drops below 5.3 bar at 20 °C, DME vaporizes, and due to the relative vapour density of DME (1.59) compared to air (1.0), becoming heavier than air and posing a risk of distant ignition or inhalation in confined spaces as it travels along the ground or water surface.
HVO	**Temperature** ■ HVO share the same flashpoint specification as distillate marine fuels (≥ 60 °C), requiring similar flammability precautions. ■ Some HVO fuels, without additional cold flow processing, may exhibit poorer cold flow properties than MGO.

Fuel	Critical conditions
FAME	**Temperature** ■ Cold temperatures can cause fuel degradation, clogging and reduced flow capabilities. Cold flow properties differ among biodiesels, with the cloud point for B100, for instance, ranging from -5 to 20°C. Typically lower tolerance to cold temperatures than MGO. ■ B100 flashpoint (≥ 101 °C) exceeds that of MGO (≥ 60 °C), signifying lower flammability. This temperature is not considered a credible risk during bunkering. **Contamination** ■ FAME is more contamination-sensitive than MGO. Prevent water, oxygen, dirt, and rust introduction to maintain fuel quality. Exposure to water can facilitate for microbial growth and/or hydrolysis which may cause corrosion and formation of sediments. **Material compatibility** ■ B100-compatible materials: carbon steel, aluminium, stainless steel, Teflon, Viton, Nylon, fluorocarbon, carbon filled acetal, fibreglass. ■ Not recommended materials (B100): copper, bronze, brass, zinc, lead, tin, galvanized metal, nitrile rubber, butadiene, Hypalon, natural rubber, neoprene, Polypropylene, Polyurethane, Polyethylene (CONCAWE, 2009) (McCormick & Moriarty, 2023).

2.4 Bio-methanol

Bio-methanol can be produced via gasification of biomass, followed by methanol synthesis. It is a liquid at normal conditions and can therefore be stored in tanks comparable to conventional fuel oil tanks. Since bio-methanol is chemically identical to methanol produced via fossil energy (fossil methanol) or via electricity (e-methanol), for the remainder of the report, bio-methanol will be referred to as methanol.

With a flashpoint of about 10°C, methanol is flammable and evaporates easily. Methanol is also toxic and poisonous to the central nervous system, and may cause blindness, coma, and death if ingested in small quantities. Methanol is presently in use as a marine fuel, and engine technology that can utilize methanol is already available on a commercial basis. According to DNV's Alternative Fuels Insight platform (AFI), 29 ships are in operation or to be delivered in 2023, utilizing methanol as the source of power.

2.4.1 Characteristics of bio-methanol and preliminary hazard identification

Table 2-4 presents some key properties of methanol, comparing them to those of marine gas oil (MGO).

Table 2-4: Summary table with key properties and characteristics of methanol compared to marine gas oil. Characteristics not easily quantified is not shown.

Category	Fuel property	Unit	MGO (ref.) [1]	Methanol [4]
Flammability	Flashpoint	°C	≥ 60	9.7
	Lower & upper flammability limit (LFL and UFL)*	% v/v	0.5 - 7.5	5.5-44
	Minimum ignition energy *	mJ	-	0.14
	Auto-ignition temperature*	°C	240 - 350	455
	Laminar burning velocity *	m/s	-	0.48[5]
Storage, handling, release, and dispersion	Normal Boiling point	°C	160 - 400	64.7
	Specific gravity (Air = 1)	-	> 1	1.11
	Specific gravity (Water = 1)	-	< 1	0.79-0.80 (20°C)
	Toxicity IDLH	ppm	-	6000[6]
	Odour threshold	ppm	0.11[2]	3.1-5960[7]
	Vapour pressure	mbar	<0.4 (20°C)	169 (25°C)
	Density	kg/m^3	800-910 (15°C)	791 (25°C)
	Kinematic viscosity	mm^2/s	≥ 1.4 (40°C)	0.54 - 0.59 (20°C)
	Cloud point	°C	**	-
	CFPP	°C	**	-
	Oxidation stability	g/m^3	Max 25[3]	-
	Water solubility	g/liter	Negligible	1000 (20°C)
Remarks:	* Ignition and combustion properties for air mixtures at 25°C and/or 101.3 kPa. ** See ISO 8217 for specification.			
IDLH = Immediately Dangerous to Life or Health Concentrations specified by the United States National Institute for Occupational Safety and Health (NIOSH), **L** = liquid, **G** = gas, **V** = vapour				
[1] Unless specified otherwise, source of data is Chevron, BP and Exxon Mobil Safety Data Sheet for distillate marine gas oil (DMA/DMZ) (Chevron, 2023) (ExxonMobil, 2018) (BP, 2021)				

[2] Applicable for dodecane, a constituent of MGO. Based on Chemical Safety Data Sheet MSDS/SDS (Chemicalbook, 2023)
[3] As specified in ISO/DIS 8217:2023 (ISO, 2023)
[4] Unless specified otherwise, source of data is Methanol Safety Data Sheet by Sigma-Aldrich (Sigma-Aldrich, 2023)
[5]ISO/TR 15916 Basic considerations for the safety of hydrogen systems (ISO, 2004)
[6]Center for Disease Control and Prevention (CDCP, 2023)
[7]Odour Thresholds for Chemicals with Established Health Standards, 2nd Edition (AIHA, 2013)

In the following sub-chapters, the key implications of bio-methanol's characteristics are described with respect to flammability, storage, handling, release and dispersion, and if relevant compared with MGO. Given its similarity to fossil methanol, bio-methanol is expected to pose the same risks and hazards.

2.4.1.1 Flammability

Methanol has a flashpoint of about 10 °C which is significantly lower than that of MGO (≥ 60 °C), creating ignitable vapours above this temperature. It is reasonable to assume that that the temperature at bunkering facilities (onboard or onshore) is normally above 10°C. This introduces fire and explosion hazards upon loss of containment and in tank ullage spaces. This means that methanol is highly flammable and constitutes a fire risk on open deck during bunkering operations. Accumulation of methanol vapours in confined spaces may lead to explosion if ignited. Hence, a methanol leakage will introduce fire and explosion hazards, and the methanol tank atmosphere will be explosive.

The flammable range of methanol vapour in air is 5.5-44%, compared to MGO (0.5-7.5%). However, the flammability range of MGO only applies to temperatures above its flashpoint (≥ 60 °C), whereas as for methanol it applies to all temperatures above its flashpoint of about 10°C. The minimum ignition energy of methanol is 0.14 mJ for air mixtures at 25°C and 101.3 kPa.

The auto-ignition temperature of methanol (455 °C) is higher than that of MGO (240-350 °C). Any high-temperature surfaces that may heat up methanol above its auto-ignition temperature should be insulated.

The laminar burning velocity of methanol is about 0.48 m/s. Methanol flames are particularly hazardous, as they burn at low temperatures with a flame that is nearly invisible in daylight with no smoke. A methanol flame often goes undetected until it has spread to adjacent materials that burn in a wider range of light. A methanol-water mixture of at least 74% water is still capable of burning, so special fire extinguishing practices need to be followed, including the use of alcohol-resistant foams.

2.4.1.2 Storage, handling, release, and dispersion

General
Methanol is a liquid at normal conditions and can therefore be stored in tanks comparable to conventional fuel oil tanks. The normal boiling point of methanol is about 65°C. Consequently, safety aspects of methanol boiling are not considered relevant for bunkering operations. Methanol will remain in liquid state after a spill. If the temperature is above its flashpoint (10°C), a toxic and flammable atmosphere will result, but there will not be any significant pressure increase.

With a relative density in air of 1.11, methanol vapour is practically neutrally buoyant in air. Like gases, the density of methanol vapours is sensitive to pressure and temperature differences. A methanol vapour cloud can be heavier than air if colder, or lighter than air if warmer than its surroundings. Safety measures such as ventilation arrangements, escape routes and fixed gas detection systems should be designed reflecting this.

Stability
Methanol produced from biomass is chemically stable under normal ambient temperatures. Same storage conditions apply, as for methanol produced from other sources (e.g., fossil feedstocks).

Cold flow properties
Flow performance during cold temperatures is not considered to be an issue for methanol. With a freezing point of about -98°C (Sigma-Aldrich, 2023), freezing will not be an issue during bunkering operations.

Material compatibility
Unlike MGO and other hydrocarbons, methanol is a polar molecule. As a result, it can be corrosive to some materials, including metals and alloys, as well as elastomers and polymers (IEA AMF, 2023). Examples of materials not suitable are aluminium, copper, titanium, and polyvinyl chloride. Corrosion is prevented through the selection of materials in contact with methanol and application of appropriate coating. A proper material and spare parts selection is then important while designing, operating, or maintaining related installation. Typically, methanol fuel tanks onboard ships are made of carbon steel with zinc coating systems.

Miscibility and contaminants
Methanol is completely miscible in water and easily absorbs water, unlike MGO (which has a negligible water solubility).

Safe handling and toxicity
Methanol exposure can occur by vapour inhalation, by contact and absorption through the skin, and by liquid ingestion. Methanol is not toxic itself but is metabolized after intake and becomes highly toxic. The primary risks related to methanol toxicity is through ingestion of the substance in its liquid state. However, harmful atmospheres can be generated, especially if methanol is released as a liquid spray (aerosols) or when entering enclosed spaces. Methanol, when introduced into the human body, undergoes oxidation to form formic acid and formaldehyde. Ingesting a minimum of 10 ml of pure methanol can result in the accumulation of hazardous levels of formic acid, leading to the destruction of optical nerves and causing symptoms such as blurred or indistinct vision, alterations in colour perception, and eventual blindness. Additional manifestations encompass headache, vertigo, weakness, nausea, vomiting, or inebriation, with fatal outcomes occurring upon overexposure, where the median lethal ingested dose is approximately 100 ml.

Methanol has poor warning properties, making it challenging to detect. Methanol vapour is invisible; methanol liquid is clear, colourless and easily mistaken for water; methanol flames are invisible in bright light; and the odour threshold of methanol vapour is high, meaning that the presence of methanol vapour may not be detectable below 5960 ppm. By the time a person detects the odour of methanol vapour, they may have already incurred an acute IDLH exposure. A final consideration is that acutely irreversible exposure can occur without symptoms beyond irritation of the nose, throat and airways, and a feeling of fatigue and disconnected discomfort similar to drunkenness.

The Lower Explosive Limit of methanol is about 6% by volume, which is 10 times the Immediately Dangerous to Life or Health concentration (IDLH). Since methanol vapour concentrations in the explosive range are toxic, keeping the air concentration safe for health also makes it safe from fire and explosion. However, keeping it safe from fire and explosion does not make it safe to breathe.

Occupational exposure limits (OELs) are regulatory values used in the EU which indicate levels of exposure that are considered to be safe for a chemical substance in the air of a workspace. The limits take into account available information on hazards of a substance with respect to carcinogenicity, mutagenicity, toxicity to reproduction and repeated dose toxicity, and effects from short-term exposure. The long-term exposure limit for methanol is set to 200 ppm (ECHA, 2023).

2.4.2 Methanol and bio-methanol used in land-based industries

Methanol as energy carrier
Methanol serves as a fundamental precursor for numerous indispensable chemical commodities integral to our daily existence, such as construction materials, plastic packaging, paints, and coatings. Historically, methanol was employed as a denaturant for ethanol or as an antifreeze agent; however, these applications have been prohibited in the United States and the European Union for several years due to safety and health concerns. Nevertheless, methanol serves dual roles as a transport fuel and as a hydrogen carrier for fuel cells. Given its combustibility at atmospheric conditions, methanol presents a viable alternative for conventional liquid fuel applications. Drawing from the extensive historical use of land-based methanol infrastructure, the chemical industry has amassed considerable expertise in the prevention and mitigation of methanol-related fires.

Owing to its density and lower heating value (19.5 MJ/kg), methanol exhibits a volumetric energy density approximately 2.5 times lower than that of HFO. The lower heating value (LHV) characteristic of methanol implies that, to store an equivalent energy amount, a methanol tank would need to be about double the size of a tank containing traditional diesel fuel. Nevertheless, the energy density of methanol is comparable to that of Liquefied Natural Gas (LNG).

Methanol proves to be a versatile fuel with applications in diverse modes, including direct use, integration as a blending component in fuels, and the generation of fuel components. Generally, the combustion of methanol yields reduced emissions of carbon monoxide, hydrocarbons, nitrogen oxides, and particulates. To guarantee stability and safety, particularly in instances of high blending ratios with gasoline, the incorporation of corrosion inhibitors, co-solvents, and materials compatible with alcohol is imperative in vehicles to resist phase separation. The subsequent sections outline methanol blending standards associated to the automotive sector in various countries:

- The Fuel Quality Directive (2009/30/EC) and CEN standard (EN 228) allow a maximum of 3 vol% of methanol to be blended with gasoline in EU.
- In China, methanol finds application in various blends, ranging from M5 (5 vol%) to M100 (100 vol%). Some markets also explore the viability of gasoline/ethanol/methanol blends (GEM).
- ASTM D 4814-10a limits the addition of methanol up to 0.3 vol% in the US. However, the limit can be extended to 2.75 vol% if an equal volume of butanol or higher molecular weight alcohol is added. Additionally, waivers granted by the U.S. EPA permit a higher methanol blend of up to 5, with a minimum of 2.5 vol% co-solvents.

Bio-methanol production pathways
Methanol can be derived from various feedstock resources, predominantly natural gas or coal, as well as renewable sources such as black liquor from pulp and paper mills, forest thinning or agricultural waste, and even directly from captured CO2 in power plants.

Traditionally, methanol is produced from non-renewable hydrocarbons, primarily natural gas, or coal. In the case of natural gas, a combination of steam reforming and partial oxidation is commonly employed, achieving an energy efficiency of approximately 70% (defined as the energy stored in methanol relative to the energy provided by natural gas). Methanol produced through coal gasification relies on a cost-effective and widely available resource, but its greenhouse gas (GHG) emissions are roughly double those from natural gas.

Bio-methanol shares identical chemical properties with conventional methanol derived from fossil fuels but is generated through three primary production pathways: gasification of biomass and Municipal Solid Waste (MSW), reformer-based (from biogas), and from the pulping cycle in pulp mills (Ajdari). The reduction in greenhouse gas emissions, in comparison to fossil methanol, can reach up to approximately 85%, depending on the chosen production pathway and the raw biomass feedstock implemented.

2.4.3 Existing laws, regulations and best practices related to toxicity and exposure limits for methanol and bio-methanol in land-based industries

Organizations engaged in the handling of methanol or other chemical and petroleum products are bound by various rules and standards that influence their operational procedures. Adherence to applicable laws and regulations is imperative, as is the attainment of prescribed minimum performance levels stated in codes and standards, often integral to local regulations such as National Fire Codes. Additionally, companies may choose to adopt external and internal standards, encompassing both recommended and obligatory practices, and it is compelling to ensure comprehensive organizational compliance with these standards.

Certain countries also have specialized regulations addressing process safety considerations.

2.4.3.1 International regulation and rules

For informational purposes, even if the emphasis is not on land-based industries, it is advisable to take into account the general recommendations and codes set forth by the International Maritime Organization (IMO) for bunkering operations. See Section 3.5.

In parallel, the OECD (Organization for Economic Cooperation and Development) provided some general advice to process safety management, into the OECD Guiding Principles for Chemical Accident Prevention, Preparedness, and Response.

2.4.3.2 European regulation

The Seveso III directive encompasses obligations for installation operators and stipulates measures to prevent and inform regarding major accidents involving hazardous substances. Notably, the directive excludes transport and temporary storage activities related to dangerous goods, including loading and unloading. Given the toxicity and flammability of methanol, the directive is applicable to onshore methanol installations.

All onshore facilities holding more than 500 tonnes of methanol are within the directive's scope and are required to formulate a major accident prevention policy. Furthermore, operators of high-tier establishments with more than 5000 tonnes of methanol must draft a safety report before commencing construction. This report should encompass the identification and assessment of major hazards, necessary preventive measures, a safety management system, and an emergency plan. The Seveso III directive is implemented through national legislation in each EU member state.

Table 2-5 displays EU directives, regulations, standards, and guidance applicable to methanol production, storage, packaging, distribution, or utilization, with a specific focus on regulations related to toxicity and exposure limits.

Table 2-5: European Union directives and legislation.

Seveso III directive (Directive 2012/18/EU)
Personal Protective Equipment Directive (Directive 89/686/EEC)
Directive on the introduction of measures to encourage improvements in the safety and health of workers at work (Directive 89/391/EEC)
Directive on Indicative Occupational Exposure Limit Values (DIR 2006/15/ EC) & Chemical Agents at Work Directive (DIR 98/24/EC)
Regulation (EC) No 1272/2008 - classification, labelling and packaging of substances and mixtures (CLP)
Directive on Pollutant Release and Transfer Register (EC/166/2006) amending Integrated Pollution Prevention and Control (IPPC Directive: 96/61/EC); Directive 2008/50/EC on ambient air quality and cleaner air for Europe
Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) (EC/2006/1907)
Accidental Marine Pollution (2850/2000/EC); Maritime Safety: Prevention of Pollution from Ships (2002/84/EC); Protection of Groundwater Against Pollution (2006/118/EC)
ATEX (Directive 2014/34/EU)

2.4.3.3 Example of existing National regulation for land-used methanol and bunkering application

United States

In the United States, two primary regulations address process safety management and are overseen by regulatory bodies, namely the Occupational Safety and Health Administration (OSHA) and the Environmental Protection Agency (EPA).

OSHA has a regulation called OSHA 29 CFR 1910.119 Process Safety Management (PSM) of Highly Hazardous Chemicals. This regulation tells companies how to find out if they must follow the regulation and what kind of PSM system they need to have.

EPA has a regulation called EPA 40 CFR 68 Chemical Accident Prevention Provisions (EPA, 2023). This regulation tells companies how to prevent and manage chemical accidents safely. Part of this regulation is the same as the OSHA PSM regulation, while other parts include rules for emergency response and risk management plans.

The main US Federal OSHA, EPA, and DOT regulations that apply to methanol production, storage, packaging, distribution, or use are shown in the table below. This table may not have all the relevant regulations and codes; state and local codes and regulations might apply to methanol facilities (Methanol Institute).

Table 2-6: U.S Regulations and codes (Methanol Institute).

Regulation/Code	Relevant Section or Part
Occupational Safety and Health, Code of Federal Regulations – 29 CFR	Part 1904 – Recordkeeping
	Section 1910.20 – Access to Exposure and Medical Records
	Section 1910.38 – Employee Emergency Plans and Fire Protection Plans
	Section 1910.119 – Process Safety Management of Highly Hazardous Chemicals
	Section 1910.120 – Hazardous Waste Operations and Emergency Response
	Section 1910.132 to 139 – Personal Protective Equipment
	Section 1910.146 – Confined Space Entry
	Section 1910.147 – Control of Hazardous Energy (Lockout/Tagout)
	Section 1910.151 – First Aid/Medical Service
	Section 1910.331 to 335 – Electrical Safety
	Section 1910.1000 – Air Contaminants (exposure limits)
	Section 1910.1200 – Hazard Communication
Environmental Regulations – 40 CFR	Part 61 – National Emissions Standards for Hazardous Air Pollutants
	Part 68 – Chemical Accident Prevention Provisions (Clean Air Act/Accidental Releases)
	Part 68 Subpart D – Program 3 Prevention Program (Process Safety Management requirements)
	Part 68 Subpart G – Risk Management Plan
	Part 141 – Safe Drinking Water
	Part 260 to 269 – Hazardous Waste Management System
	Parts 302 and 355 – Release of Hazardous Substances, Emergency Planning and Notification

Regulation/Code	Relevant Section or Part
	Parts 370 and 372 – Hazardous Chemicals Reporting: Community Right to Know
	Part 373 – SARA Title III Reporting
	Subchapter R, Parts 700 to 799 – Toxic Substances Control Act
Transportation Regulations – 49 CFR	Part 106 – Rulemaking Procedures
	Part 107 – Hazardous Materials Program Procedures
	Part 171 – General Information, Regulations, Definition
	Part 172 – Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, and Training Requirements
	Part 173 – Shippers, General Requirements for Shipments and Packaging
	Part 176 – Carriage by Vessel
	Part 178 – Specifications for Packaging
	Part 190 – Pipeline Safety Program Procedures
	Part 195 – Transportation of Hazardous Liquids by Pipeline
Navigable and Navigable Water Regulations - 33 CFR	Part 1 to 26, Subchapter A – General delegation of authority, rulemaking procedures and enforcement regulations
	Part 126 – Handling Explosives or Other Dangerous Cargoes within or Contiguous to Waterfront Facilities
	Part 130 – Financial Responsibility for Water Pollution
	Part 153 – Control of Pollution by Oil and Hazardous Substances; Discharge Removal
	Part 154 – Facilities Transferring Oil or Hazardous Materials in Bulk
	Part 155 – Oil or Hazardous Material Pollution Prevention Regulations for Vessels
	Part 156 – Oil and Hazardous Material Transfer Operations
	Parts 160 to 167, Subchapter P – Ports and Waterways Safety
Shipping Regulations – 46 CFR (Water Transportation)	Part 2 – Vessel Inspections
	Part 30 to 40, Subchapter D – Tank Vessels
	Part 151 – Barges Carrying Bulk Liquid Hazardous Materials Cargoes

Canada

In Canada, specific regulations for Process Safety Management (PSM) requirements are not in place. However, the Criminal Code of Canada underwent a change in 2004 through Law C-21, rendering organizations and individuals more accountable for chemical accidents. This legal amendment stipulates that both entities can face criminal charges if they fail to take reasonable measures to prevent accidents causing harm to workers or the public. In the event of an accident, Canadian regulators assess whether the organization or individual took adequate preventive measures, often utilizing the US OSHA 29 CFR 1910.119 as a benchmark for good practices. Failure to meet these standards may result in substantial fines and imprisonment (Methanol Institute).

United Kingdom

The Health and Safety Executive (HSE) serves as the regulatory authority responsible for enforcing all health and safety laws in the United Kingdom. These laws encompass both worker safety, addressing aspects such as Personal Protective Equipment (PPE), fall prevention, working at heights, and entering confined spaces, as well as process safety.

In the UK, process safety laws, notably the Control of Major Accident Hazards (COMAH) Regulations, are designed for industries with a heightened risk of causing major accidents that could pose harm to employees, the public, and the environment. These regulations are intended to prevent and mitigate the impact of such accidents at sites falling under COMAH jurisdiction.

Derived from European legislation, specifically developed in compliance with the EU Major Hazard regulation (Seveso III Directive), the COMAH Regulations underwent an update in 2015, now referred to as COMAH 2015. Further information can be accessed at Britain's national regulator for workplace health and safety, the "Health and Safety Executive" (HSE) webpage [3].

China

China has a national standard to identify and prevent major industrial accidents, called Identification of Major Hazard Installations (GB 18218 2009). It was first issued in 2000 and then revised in 2009. In 2010, China also issued its first Process Safety Management regulation, called AQ/T 3034-2010 Guidelines for Process Safety Management of Chemical Corporations. It became effective in 2011.

This regulation followed twelve of the fourteen OSHA PSM elements, except for Trade Secrets and Employee Participation. The regulation also referred to other regulations that supported its requirements.

In 2013, China published more detailed guidance to improve process safety management practices (SAWS III [2013] No. 88) (Methanol Institute).

[3] https://www.hse.gov.uk/comah/index.htm

2.4.3.4 Exposure control best practises[4]

There are accepted industry good practices that will act to prevent or limit exposure to methanol. The primary ones are listed below.

Engineering Controls: To minimize the risk of exposure, employ automatic pumps for the transfer of liquid methanol from drums or other storage containers to process containers. It is imperative to store methanol in closed systems, avoiding exposure to the atmosphere.

Monitoring: Methanol vapour levels can be assessed using gas detection tubes that undergo colour changes or electronic devices like portable gas monitors. Gas monitors offer continuous methanol level readings and can trigger alarms in the event of elevated levels.

Personal Protective Equipment (PPE): Utilize safety glasses with side shields or safety goggles, along with gloves appropriate for the task. Additional personal protective equipment may be necessary depending on the specific situation (refer to Chapter 5 for further details).

Respiratory Protection: Select respiratory protection measures based on identified hazards and potential exposure. Table 2-7 delineates instances requiring respiratory protection based on methanol air concentrations. Note that 200 ppm is the occupational exposure limit defined in the European Chemicals Agency (ECHA) REACH[5] system for long term exposure (ECHA , 2023). No exposure limit was identified for short term exposure.

Chemical resistant clothing: Wear clothing/materials that can resist chemicals if you expect to touch methanol often or for a long time.

Table 2-7: Air Concentration of Methanol and related respiratory protection (Methanol Institute).

AIR CONCENTRATION OF METHANOL	RESPIRATORY PROTECTION
< 200 ppm	No protection required. Skin and eye protection may still be needed.
200 ppm or greater	Protection required if the daily time-weighted- average (TWA) exposure is exceeded or if there are additional routes of exposure (skin, eyes, ingestion). A supplied air system must be used if protection is needed.
> 200 ppm sustained	A supplied air breathing apparatus (SCBA) system must be used (i.e., positive-pressure SBCA).

2.4.3.5 Safety precautions[4]

Exercise caution with methanol due to its toxicity and flammability. Methanol vapour can ignite from static electricity within the flammable range, emphasizing the importance of grounding and bonding all equipment in situations where static electricity is possible.

A enlarge process safety management strategy needs to be implemented to operate safely. Some selected precautions during transfer of methanol, regarding spill management, can be highlighted to be prepared to manage release properly:

- Limit the dispersion:
    - Bund around all significant inventories to prevent spread of liquid, so limiting evaporation.
    - Appropriate detection: liquid or vapour detection to identify methanol spill.
    - In case of possible domino effect, gas/vapour detection to allow quick response.

[4] Methanol Safe Handling Manual (Methanol Institute)
[5] The regulation concerning Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is the main EU law to protect human health and the environment from the risks that can be posed by chemicals.

- Ignition source prevention:
    - Prohibit smoking.
    - Restrict vehicle proximity.
    - If necessary, employ electrical equipment labelled as explosion-proof according to the national electrical code. ATEX (Equipment for potentially explosive atmospheres) refers to a set of European Union directives that outline the standards for equipment and protective systems intended for use in potentially explosive atmospheres.
    - Proper grounding.
    - Lightning protection.

- Protect people against vapour, i.e.:
    - Ensure adequate ventilation in buildings to maintain low vapour levels.
    - Positive pressure to exclude methanol from specific areas, such as control rooms, switch rooms etc.
    - Specific breathing protection and PPE for your intervention team.

- Firefighting and dispersion management:
    - Specific alcohol resistant AR-AFFF foam.
    - Portable dry chemical extinguishers readily available for small fires.
    - Install fire hydrants strategically, equipped with hoses that are both sizable and lengthy, featuring misting nozzles to catch the methanol in case of dispersion and radiation in case of fire.
    - Train, drill and test your firefighters' teams.

- Prevent escalation:
    - Appropriate segregation of flammable storage.
    - Verify that storage tank vents are sufficiently sized to release vapour in case of a fire.
    - Fixed protection (i.e., sprinkler and deluge).

These precautions need to be adapted and designed to each individual situation, depending on location, surrounding, volumes and process conditions, ideally based on a dedicated need-assessment.

2.5 Bio-FT-diesel

Bio-FT-diesel is produced by gasification of biomass, followed by the Fischer-Tropsch (FT) synthesis process which converts syngas into liquid hydrocarbons, including FT-diesel. Bio-FT-diesel is a subset of Biomass to Liquid (BtL) fuels, which otherwise encompass other liquid biofuels produced via gasification of biomass and conversion of syngas to fuel product. Production volumes of bio-FT-diesel is currently very limited with only one commercial large-scale production plant in operation (IEA Bioenergy, 2023). Besides biomass, FT-diesel can also be produced via other feedstocks such as natural gas, coal, and renewable electricity in combination with carbon. The resulting hydrocarbons in FT-diesel, whether originating from biomass or fossil sources, exhibit similar characteristics, and their physiochemical properties closely resemble those of conventional diesel fuels. For the remainder of this chapter, bio-FT-diesel is referred to as FT-diesel.

2.5.1 Characteristics of bio-FT-diesel and preliminary hazard identification

FT-diesel is considered a drop-in diesel fuel, fully compatible with existing diesel infrastructure and internal combustion engines, fuel storage, and fuel supply systems onboard ships (see e.g., (E4Tech, 2018) & (EMSA, 2022). Some FT-diesel products are stated to be in compliance with fuel standards for fossil diesel such as ASTM D975 D-2[6] (Emerging Fuels Technology, 2021) or for paraffinic diesel like EN 15940[7] (Shell, 2023).

Table 2-8 quantifies key properties of FT-diesel, comparing them to those of fossil MGO. The table exemplifies the typical characteristics by examining one specific FT-diesel product. For precise specification, refer to the relevant fuel standards, such as ISO 8217 and EN 15940.

Table 2-8: Summary table with key properties and characteristics of FT-diesel compared to marine gas oil. Characteristics not easily quantified is not shown.

Category	Fuel property	Unit	MGO (ref.)[1]	F-T diesel[4]
Flammability	Flashpoint	°C	≥ 60	59
	Lower & upper flammability limit (LFL and UFL)*	% v/v	0.5 - 7.5	Not available
	Minimum ignition energy *	mJ	-	-
	Auto-ignition temperature*	°C	240 - 350	208
	Laminar burning velocity *	m/s	-	-
Storage, handling, release, and dispersion	Normal Boiling point	°C	160 - 400	158-351
	Specific gravity (Air = 1)	-	> 1	>1
	Specific gravity (Water = 1)	-	< 1	<1
	Toxicity IDLH	ppm	-	-
	Odour threshold	ppm	0.11[2]	Not available
	Vapour pressure	mbar	<0.4 (20°C)	Not available
	Density (15°C)	kg/m^3	800 - 910	770
	Kinematic viscosity (40°C)	mm^2/s	≥ 1.4	<7
	Cloud point	°C	**	**
	CFPP	°C	**	**
	Oxidation stability	g/m^3	Max 25[3]	Not available
	Water solubility	g/liter	Negligible	Non-soluble
Remarks:	* Ignition and combustion properties for air mixtures at 25°C and/or 101.3 kPa.			

[6] Standard Specification for Diesel Fuel
[7] The European specification of automotive paraffinic fuel from synthesis or hydrotreatment

** See ISO 8217 for specification
IDLH = Immediately Dangerous to Life or Health Concentrations specified by the United States National Institute for Occupational Safety and Health (NIOSH), **L** = liquid, **G** = gas, **V** = vapour
[1] Unless specified otherwise, source of data is Chevron, BP and Exxon Mobil Safety Data Sheet for distillate marine gas oil (DMA/DMZ) (Chevron, 2023) (ExxonMobil, 2018) (BP, 2021) [2] Applicable for dodecane, a constituent of MGO. Based on Chemical Safety Data Sheet MSDS/SDS (Chemicalbook, 2023) [3] As specified in ISO/DIS 8217:2023 (ISO, 2023) [4] Unless specified otherwise, source of data is BP Distillates (Fischer-Tropsch), C8-26, branched and linear Safety Data Sheet (BP, 2023a)

In the following sub-chapters, the key implications of FT-diesel's characteristics are described with respect to flammability, storage, handling, release and dispersion, and if relevant compared with MGO. Given its substantial similarity to marine distillate fuels, FT-diesel is expected to pose similar risks and hazards to those fuels.

2.5.1.1 Flammability

The indicated flash point for the FT-diesel product in Table 2-8 is 59°C. This is close to the lower limit of 60°C specified for MGO. It is, however, reasonable to assume that any FT-diesel sold as fuel for ships, would as a minimum have a flashpoint of 60°C. SOLAS prohibits the use of fuels with flashpoint below 60°C. Ships using fuels with a lower flashpoint will have to comply with the IMO IGF Code[8]. This will, very significantly limit the number of vessels allowed to utilize FT-diesel with a flash point of 59°C. The ISO 8217 standard for marine distillate fuels which also covers BtL fuels including bio-FT-diesel, specifies a flash point above 60°C (ISO, 2023). As a consequence, FT-diesel used as ship fuel, is expected to have flashpoint of at least 60°C. A correspondence group in the IMO is currently working on development of guidelines, which includes the use biofuels with a flashpoint between 52°C and 60°C (IMO, 2022b). This could potentially lower the barriers for vessels trading internationally for using biodiesels with flashpoint lower than 60°C depending on the resulting design requirements.

LFL and UFL of the FT-diesel product from Table 2-8 are not available but are expected to be similar to those of MGO and fossil diesel.

The auto-ignition temperature of FT-diesel is given as 208 °C, compared to >250 °C for MGO. This must be considered wherever heated surfaces may be in contact with FT-diesel. Class rules for ship design typically use equipment surface temperatures of 220°C as a cut-off point for insulation requirements.

2.5.1.2 Storage, handling, release, and dispersion

General
FT-diesel is a high-quality fuel for diesel engines, with properties similar as fossil diesel. The normal boiling point range of FT-diesel (158-351°C) is comparable to that of MGO (160 – 400 °C). The density at 15°C can be somewhat lower for FT-diesel (770 kg/m^3), compared with 800-890 kg/m^3 for MGO.

Stability
FT-diesel is chemically stable and has a high oxidation stability, not needing anti-oxidant additives as is required by some FAME biodiesels (Bezergianni & Dimitriadis, 2013). In case of blending with other fuels, e.g., FAME, oxidation properties may change.

Cold flow properties
Several 100% FT-diesel products on the market, is said to be in compliance with EN 15940 or similar standards for fossil diesel such as ASTM D975, see e.g., (Shell, 2023) and (Emerging Fuels Technology, 2021). As such, requirements on cold flow properties stated in this fuel standard should also apply to FT-diesel, and cold flow properties are comparable to those of fossil diesel. This should, however, be verified with the fuel supplier.

[8] International Code of Safety for Ships Using Gases and Other Low-Flashpoint Fuels

Material compatibility
FT-diesel can be regarded as possessing materials compatibility equivalent with that of fossil MGO. It should be kept away from oxidising materials during handling and storage (BP, 2023a).

Miscibility and contaminants
FT-diesel is thought to exhibit similar properties as fossil diesel with respect to miscibility and contaminants. For example, as stated in Table 2-8, it is not soluble in water.

Safe handling and toxicity
FT-diesel is thought to exhibit similar properties as fossil diesel with respect to safe handling and toxicity. All ignition sources should be eliminated during handling and storage. Tank headspaces should be regarded as potentially flammable (BP, 2023a).

2.6 Bio-DME

Dimethyl ether (DME) with chemical formula CH_3OCH_3, is also known as methoxymethane, wood ether, dimethyl oxide, or methyl ether. It is gaseous at atmospheric pressure and room temperature and is usually liquefied during storage and transportation by slightly pressurizing the gas (approximately 0.5 MPa). Various production methods are available for DME, with the common approaches being either a one-step or a two-step process involving the production of methanol from syngas. The feedstocks utilized in these processes encompass a range of possible sources, including natural gas, coal, crude oil, biomass, and others. When DME is produced from biomass, such as forest products or animal waste, the resulting product is commonly referred to as bio-DME. However, since all DME is chemically identical, regardless of production pathway, we will refer to bio-DME as DME for the remainder of this report.

DME produced from natural gas is based on quite mature technology, while production based on biomass is associated with a more expensive technology currently under development. Industry feedback suggests lack of experience and limited interest in utilizing DME as a marine fuel. In terms of blend-in capabilities, blending with LPG may be an option due their relatively similar properties. LPG infrastructures are usually designed to accommodate properties similar to those of DME.

2.6.1 Characteristics of bio-DME and preliminary hazard identification

Table 2-9 quantifies key properties of bio-DME, comparing them to those of fossil MGO. There is no knowledge of established blends of DME; therefore, the table is based on pure DME. A possible fuel blending for maritime purposes could be with LPG.

Table 2-9 Summary table with key properties and characteristics of DME compared to marine gas oil. Characteristics not easily quantified is not shown.

Category	Fuel property	Unit	MGO (ref.) [1]	DME [4]
Flammability	Flashpoint	°C	≥ 60	-41
	Lower & upper flammability limit (LFL and UFL)*	% v/v	0.5 - 7.5	3.4 - 27
	Minimum ignition energy *	mJ	-	0.29 [5]
	Auto-ignition temperature*	°C	240 - 350	350 [6]
	Laminar burning velocity *	m/s	-	0.54 (max) [5]
Storage, handling, release, and dispersion	Normal Boiling point	°C	160 - 400	-24.8
	Specific gravity (Air = 1)	-	> 1	1.59 (G)
	Specific gravity (Water = 1)	-	< 1	0.61(L) [6]
	Toxicity IDLH	ppm	-	Not available
	Odour threshold	ppm	0.11 [2]	Not available
	Vapour pressure (20°C)	mbar	<0.4	5333 (20°C)
	Density	kg/m^3	800 – 910 (15°C)	661 (20°C, L)
	Kinematic viscosity	mm^2/s	≥ 1.4	<1 (L) [5]
	Cloud point	°C	**	-
	CFPP	°C	**	-
	Oxidation stability	g/m^3	Max 25 [3]	-
	Water solubility	g/liter	Negligible	24[6] - 353
Remarks:	* Ignition and combustion properties for air mixtures at 25°C and/or 101.3 kPa. ** See ISO 8217 for specification			

IDLH = Immediately Dangerous to Life or Health Concentrations specified by the United States National Institute for Occupational Safety and Health (NIOSH), **L** = liquid, **G** = gas, **V** = vapour
[1] Unless specified otherwise, source of data is Chevron, BP and Exxon Mobil Safety Data Sheet for distillate marine gas oil (DMA/DMZ) (Chevron, 2023) (ExxonMobil, 2018) (BP, 2021) [2] Applicable for dodecane, a constituent of MGO. Based on Chemical Safety Data Sheet MSDS/SDS (Chemicalbook, 2023) [3] As specified in ISO/DIS 8217:2023 (ISO, 2023) [4] Unless specified otherwise, source of data is Sigma-Aldrich Safety Data Sheet Dimethyl ether (Sigma-Aldrich, 2023) [5] Based on (IEA AMF, 2023) [6] Based on (ILO, 2023)

ISO 16861:2015 specifies characteristics of DME when used as fuel of which the main component is the dimethyl ether synthesized from any organic raw materials (ISO, 2015).

In the following sub-chapters, the key implications of bio-DME's characteristics are described with respect to flammability, storage, handling, release and dispersion, and if relevant compared with MGO and/or LPG.

2.6.1.1 Flammability

DME is categorized as an extremely flammable gas, necessitating precautions to avoid heat, hot surfaces, sparks, open flames, and other ignition sources. Contaminated clothing poses a fire hazard and should be handled accordingly. In the event of major fires, foam or water fog should be used for extinguishing, while dry chemical powder, carbon dioxide, or sand/earth are suitable for minor fires. Due to the vapour's heaviness, it may travel along the ground or water surface, posing a risk of distant ignition. Additionally, pressurized content can potentially explode when exposed to heat or other ignition sources (Shell, 2014).

The flammable range of DME in air is 3.4 – 27%, compared with 5.5 – 44% (methanol) and 0.5 – 7.5% (MGO). However, in the case of MGO, the temperature must be ≥ 60 °C in order for a flammable air-vapour mixture to form.

The minimum ignition energy for DME is about 0.29 mJ, which is twice as high as for methanol (ref. earlier section). Since DME is normally stored as a liquefied gas at pressure, in case of leakage, ignitable vapours will be created.

The maximum laminar burning velocity of DME is about 0.54 m/s. This is comparable to that of methanol (ref. Chapter 2.2).

The auto-ignition temperature of DME (350 °C) is typically higher than that of MGO (240 – 350 °C). This implies that hotter conditions are needed for DME to auto-ignite, compared to MGO. However, as a gas, DME could have a higher risk of being in contact with a hot surface.

2.6.1.2 Storage, handling, release, and dispersion

General
DME has a saturated vapour pressure of 5.3 bar (ISO, 2015) at 20 °C, allowing it to be stored in a liquid state when pressurized above this limit, given a temperature of 20 °C. The handling requirements for DME closely resemble those of propane; both require storage in pressurized tanks at ambient temperature.

DME has low kinematic viscosity (<1 mm^2/s) compared to MGO. This may lead to leakage problems within the fuel bunkering supply system (e.g., pumps).

Stability
No hazardous reactions are anticipated when the substance is handled and stored in accordance with established provisions. Additionally, there is no expectation of the formation of hazardous decomposition products during routine storage. The substance is considered chemically stable under normal use conditions (Shell, 2014).

Cold flow
Cold temperatures are not anticipated to be an issue during bunkering operations of DME (melting/freezing point typical value is 141.5°C (Shell, 2014)).

Material incompatibility
While DME is non-corrosive, certain elastomers may experience swelling upon contact. Its liquid state at moderate pressures (0.53 MPa or just above 5 atm) allows for handling similar to LPG, enabling the utilization of existing on- and off-shore LPG infrastructure for the transportation, storage, and distribution of DME with minimal modifications (f3 Innovation Cluster for Sustainable Biofuels, 2017).

The solvent properties of DME pose a risk of degrading rubber and elastomer seals, which may necessitate their replacement. For sealing materials both Teflon and PTFE (polytetrafluoroethylene) compounds are compatible (J. Patten & T. McWha, 2015). Other recommended materials are stainless steel and mild steel. Conversely, unsuitable materials comprise certain forms of cast iron, ABS, polyethylene (PE/HDPE), polypropylene (PP), PVC, natural rubber (NR), Nitrile (NBR), ethylene propylene rubber (EPDM), Butyl (IIR) and more (Shell, 2014).

Miscibility and contamination
The physical properties of DME closely resemble those of LPG, leading to similar requirements related to refueling and storage. Utilizing existing LPG infrastructure for the transport and distribution of DME is feasible with some potential adjustments to pumps, seals, and gaskets. Given its gaseous form under normal conditions, direct blending with diesel is not a feasible option. DME's polar nature makes it miscible with water.

Safe handling and toxicity
DME at 1 atm and 25°C have a specific gravity of 1.59 relative to air, or a density of 1.92 g/L (O'Neil, 2001). As such, the expansion ratio of DME from liquid form at 20°C to a gas at standard temperature and pressure is roughly 350. This poses a potential risk of overpressure in confined spaces if liquid DME is accidentally released without appropriate pressure relief measures in place.

Occupational exposure limits (OELs) are regulatory values used in the EU which indicate levels of exposure that are considered to be safe for a chemical substance in the air of a workspace. The limits take into account available information on hazards of a substance with respect to carcinogenicity, mutagenicity, toxicity to reproduction and repeated dose toxicity, and effects from short-term exposure. The long-term exposure limit for DME is set to 1000 ppm (ECHA, 2023).

In case of DME leakage, the gas can accumulate as a white vapour cloud near the ground at first, before dissipating and diffusing. Before dissipation however, fire and explosions hazards are the main risks (EMSA, 2022).

Infrared radiation is absorbed by DME, but since commercial use of DME is not very extensive, few if any commercial detectors exist (EMSA, 2022). Continuous monitoring of substance concentrations in the breathing zone of workers or throughout the general workplace may be required to comply with exposure controls (Shell, 2014).

High gas concentrations can lead to oxygen displacement, posing an asphyxiation risk to humans. Inhalation is the primary exposure route, although skin or eye contact is also possible. Acute inhalation toxicity is minimal, and skin contact is not expected to be hazardous. However, high concentrations may induce central nervous system depression, causing symptoms like headaches, dizziness, and nausea. Prolonged exposure may lead to unconsciousness and, in extreme cases, death (Shell, 2014).

DME, when released as a liquid, poses a low-temperature exposure hazard. The rapid release of pressurized gases (i.e., liquefied), may cause frost burns due to evaporative cooling. The delivery lines can become cold, presenting a risk of frost burns. During product transfer, it is advised not to use compressed air for filling, discharging, or handling, as pumping may generate electrostatic charges. Such charges, if discharged, may lead to a fire hazard (Shell, 2014).

2.7 HVO

Hydrotreated Vegetable Oil (HVO), also referred to as renewable or paraffinic diesel, is produced from fats, oils and greases (FOGs) though a hydrotreatment process. While the term implies vegetable oils, the feedstock is not limited to such; it can also encompass waste animal fats, algae, cooking oils, and more. HVO consists of paraffinic hydrocarbons and may be blended with other hydrocarbon-only diesels such as MGO. The properties of marine fuels consisting partly or fully of HVO shall align with the specifications outlined in EN 15940, with the requirements and conditions as stated in the most current revision of ISO 8217 (ISO/DIS 8217:2023(E) at the time of this writing). As per ISO 8217, HVO meeting EN 15940 is considered as a petroleum distillate (ISO, 2023).

HVO is recognized as a drop-in fuel. To date, numerous tests have been conducted using HVO or blends thereof in maritime applications, with initial results indicating favourable compatibility with on-board systems. When compared with traditional petroleum diesels, HVO exhibits a comparable flashpoint, good tolerance to cold temperatures, robust stability and oxidation properties, and minimal concerns regarding microbial growth or materials compatibility issues.

Numerous terms are employed to characterize HVO fuels, including Renewable Hydrocarbon Diesel (RHD), Renewable Diesel (RD), Renewable Synthetic Diesel Fuel, Bio-derived Diesel, Renewable Paraffinic Diesel, and more. They are often denoted by an "R" or "RD," followed by a number indicating the percentage of FAME in the fuel (e.g., R99 for 99% HVO). Blends with FAME are designated as well, such as RDB5 (95% HVO and 5% FAME). Occasionally, the term XTL/HVO is used to denote paraffinic fuels. While "renewable paraffinic diesel" theoretically describes HVO, it also refers to Biomass-to-Liquid (BTL) fuels produced by FT synthesis. The designation XTL typically encompasses synthetic Gas-to-Liquid (GTL), Coal-to-Liquid (CTL), and Biomass-to-Liquid (BTL) FT diesel production paths.

2.7.1 Characteristics of HVO and preliminary hazard identification

Table 2-10 presents key properties of HVO, comparing them to those of marine gas oil (MGO). The table exemplifies the typical characteristics by examining a selection of HVO products. For precise specification, refer to the relevant fuel standards, such as ISO 8217 and EN 15940.

Table 2-10: Summary table with key properties and characteristics of HVO compared to marine gas oil. Characteristics not easily quantified is not shown.

Category	Fuel property	Unit	MGO (ref.)[1]	HVO (100%)[4]
Flammability	Flashpoint	°C	≥ 60	61[5]
	Lower & upper flammability limit (LFL and UFL) *	% v/v	0.5 – 7.5	0.8 – 5.4
	Minimum ignition energy *	mJ	-	-
	Auto-ignition temperature *	°C	240 – 350	204
	Laminar burning velocity *	m/s	-	-
Storage, handling release, and dispersion	Normal Boiling point	°C	160 – 400	180 – 390
	Specific gravity (Air = 1)	-	> 1 (V)	> 1 (V)
	Specific gravity (Water = 1)	-	< 1	0.77– 0.79
	Toxicity IDLH	ppm	-	-
	Odour threshold	ppm	0.11[2]	-
	Vapour pressure	mbar	<0.4 (20°C)	0.4[5] (20°C)
	Density (15°C)	kg/m^3	800 – 910	765 – 800
	Kinematic viscosity (40°C)	mm^2/s	≥ 1.4	2.6
	Cloud point **	°C	-	-10 – -34[6]

Category	Fuel property	Unit	MGO (ref.)[1]	HVO (100%)[4]
	CFPP **	°C	-	-
	Oxidation stability	g/m^3	Max 25[3]	Max 25[5]
	Water solubility	g/liter	Negligible	Non-soluble
Remarks:	* Ignition and combustion properties for air mixtures at 25°C and/or 101.3 kPa. ** See ISO 8217 for specification. Cold flow properties of HVO can be similar to MGO.			
IDLH = Immediately Dangerous to Life or Health Concentrations specified by the United States National Institute for Occupational Safety and Health (NIOSH), **L** = liquid, **G** = gas, **V** = vapour				
[1] Unless specified otherwise, source of data is Chevron, BP and Exxon Mobil Safety Data Sheet for distillate marine gas oil (DMA/DMZ) (Chevron, 2023) (ExxonMobil, 2018) (BP, 2021) [2] Applicable for dodecane, a constituent of MGO. Based on Chemical Safety Data Sheet MSDS/SDS (Chemicalbook, 2023) [3] As specified in ISO/DIS 8217:2023 (ISO, 2023) [4] Unless specified otherwise, source of data is BP HVO Safety Data Sheet (BP, 2023) [5] As specified in Technical Data Sheet and Safety Data Sheet Neste MY Renewable diesel (Neste, 2019) (Neste, 2023) [6] As specified in EN 15940 (European Committee for Standardization, 2023)				

In the following sub-chapters, the key implications of HVO's characteristics are described with respect to flammability, storage, handling, release and dispersion, and if relevant compared with MGO. Given its substantial similarity to marine distillate fuels, HVO is expected to pose risks and hazards in line with those fuels.

2.7.1.1 Flammability

The European specification of automotive paraffinic fuel from synthesis or hydrotreatment (EN 15940) define the flashpoint of HVO to be above 55 °C (European Committee for Standardization, 2023). For marine use, ISO 8217 refers to EN15940, but specifies a flash point above 60 °C (ISO, 2023), which is aligned with the flash point requirement for marine distillate fuel grades such as MGO. Consequently, this implies that similar safety measures and hazards related to flammability apply for both HVO and MGO.

According to Safety Data Sheets, HVO as substance or mixture is a flammable liquid. The vapour pressure of HVO and MGO is quite similar, meaning that their tendency to evaporate into the surrounding atmosphere is also the same. Vapours have the potential to create explosive mixtures with air when the temperature exceeds the flash point. Similarly as for MGO; heat, open flame, sparks, oxidizing agents or other sources of ignition should be avoided, and contaminated materials such as clothing or rags are considered a fire hazard and must be dealt with accordingly (BP, 2023) (Neste, 2023). Fires are to be dealt with similarly as for petroleum diesels.

2.7.1.2 Storage, handling, release, and dispersion

Stability
HVO is chemically stable under normal ambient temperatures and when used as recommended, and no potentially hazardous reactions are known (BP, 2023) (Neste, 2023). The oxidation stability of HVO is generally comparable to that of conventional petroleum diesel, indicating similar storage durations, with both fuels sharing the same maximum limit as specified in their respective fuel standards. The overall oxidation stability of fuels hinges on factors such as the initial fuel quality, additives, and exposure to contaminants, heat, air, and light. Storage conditions applicable to conventional diesels are also relevant for HVO. Since neat HVO is a hydrocarbon-only fuel, the stability testing method (ISO 12205) aligns with the method used for fossil diesels, as outlined in both ISO 8217 and EN 15940. However, if blended with FAME above 2% v/v, alternative test methods specified in the fuel standards must be employed.

Cold flow
Numerous fossil diesel grades offer the option to modify CFPP and PP through the use of cold flow additives. However, due to HVO's limited distillation range and carbon chain distribution, incorporating cold flow additives results in only marginal improvements. Alternatively, further processing can be undertaken, allowing for the

adjustment of CP and PP across a broader temperature range while preserving other essential fuel characteristics. If that is the case, HVO exhibits good tolerance to cold temperatures.

In terms of cold flow properties, 100% HVO shall according to ISO 8217 meet EN 15940 apart from the climate dependent requirements and related test methods. For distillate fuels, the purchaser should verify that the cold flow properties, meaning CP, CFPP and PP, are suitable for the vessels fuel storage and management system design and the temperature conditions expected during the voyage (ISO, 2023). It is reasonable to assume that the same must apply during bunkering operations and for bunkering infrastructure.

Materials compatibility
HVO can be regarded as possessing materials compatibility equivalent to that of conventional petroleum diesels with respect to components, tanks, and materials present in storage, transfer, and handling equipment (Neste, 2020).

Miscibility and contamination
Filter clogging is not reported as an issue with pure HVO; however, it may arise when blended with high levels of FAME. Both HVO and fossil diesels share a non-polar nature, contrasting with the polar property of water. Consequently, HVO and fossil diesels exhibit low water solubility, separating from water similarly. This implies that handling water during bunkering operations requires no different measures compared to fossil diesels. Microbial growth poses a comparable risk for both HVO and fossil diesels, necessitating no additional precautions (Neste, 2020). In contrast, FAME is inherently polar and hygroscopic, demonstrating an affinity for water and the ability to dissolve it, activating processes detailed in Chapter 2.8. The nature of HVO allows for its blending with conventional diesel fuels, with blending procedures and considerations similar as when fossil diesels are blended. Additionally, HVO is also considered to have good compatibility with widely used additives.

Safe handling and toxicity
Standard safety practices for fossil diesel fuels apply to HVO, and precautions outlined in the Safety Data Sheet (SDS) must be adhered to for personnel safety. Prolonged exposure may lead to skin dryness or cracking and irritation. Inhalation of vapour, mist, or fumes may cause irritation to the nose, mouth, and respiratory tract. Under normal conditions, vapour inhalation is not a concern due to low vapour pressure. However, entering confined or poorly ventilated spaces contaminated with vapour, mist, or fumes without proper respiratory protective equipment and adherence to a safe work system is extremely hazardous (BP, 2023).

2.8 FAME

Fatty Acid Methyl Ester (FAME), commonly known as biodiesel, is produced through the transesterification process of fats and vegetable oils. These oils can originate from various sources such as plants (e.g., soy, corn, flaxseed, rapeseed, palm), animal fats or waste oils (EMSA, 2022). Due to the wide range of potential feedstocks, the characteristics of the FAME product can exhibit significant variations. The properties of marine fuels containing FAME should however align with the specifications outlined in standards such as EN 14214 or ASTM D6751, with the requirements and conditions as stated in the most current revision of ISO 8217 (ISO/DIS 8217:2023(E) at the time of this writing). This report is based on ISO 8217-compliant FAME products, excluding FAME distillation bottoms, biocrudes, or off-spec FAMEs.

FAME biodiesel is widely used on a global scale, with blends typically containing up to 7% FAME. However, blends containing higher levels of FAME are becoming more widely available. Fuel blends containing FAME have undergone numerous trials within maritime applications, and initial industry feedback shows satisfactory results and does not reveal any major service issues. Biofuels containing FAME do however possess characteristics different from traditional marine distillate fuels such as higher viscosity, lower calorific value, higher acidity and lower oxidation stability.

2.8.1 Characteristics of FAME and preliminary hazard identification

Table 2-11 presents key properties of neat FAME and a common FAME-blend, comparing them to those of marine gas oil (MGO). The table exemplifies the typical characteristics by examining a selection of FAME products. For precise specification, refer to the relevant fuel standards, such as ISO 8217 and EN 14214.

Table 2-11: Summary table with key properties and characteristics of FAME compared to marine gas oil. Characteristics not easily quantified is not included.

Category	Fuel property	Unit	MGO (ref.)[1]	FAME (B100)[4]	FAME (B20)[5]
Flammability	Flashpoint	°C	≥ 60	≥120 - <180	126
	Lower & upper flammability limit (LFL and UFL)*	% v/v	0.5 – 7.5	-	0.6 – 6.5
	Minimum ignition energy*	mJ	-	-	-
	Auto-ignition temperature *	°C	240 – 350	≥256 - ≤266	> 254
	Laminar burning velocity *	m/s	-	-	-
Storage, handling release, and dispersion	Normal Boiling point	°C	160 – 400	≥302.5 - ≤570*	282 – 338
	Specific gravity (Air = 1)	-	> 1 (V)	> 1 (V)	3 (V)
	Specific gravity (Water = 1)	-	< 1	0.87-0.89 (25°C)	0.87
	Toxicity IDLH	ppm	-	-	-
	Odour threshold	ppm	0.11[2]	-	0.5 – 1.0
	Vapour pressure	mbar	<0.4 (20°C)	≥2 - ≤6 (25°C)	~ 2.7 (20°C)
	Density (15°C)	kg/m^3	800 – 910	878-895	820 – 860 [6]
	Kinematic viscosity (40°C)	mm^2/s	≥ 1.4	3.8 – 5.0	2.0 – 4.6 [6]
	Cloud point	°C	**	**	**
	CFPP	°C	**	**	**
	Oxidation stability ***	-	Max 25 [g/m^3] [3]	Min 8 [h] [3]	≥ 20 [h] [6]
	Water solubility	g/liter	Negligible	Negligible	Negligible

Remarks:	* Ignition and combustion properties for air mixtures at 25°C and/or 101.3 kPa. ** See ISO 8217 for specification. Cold flow properties of FAME are generally higher (less tolerant) compared to MGO. *** Test method is different for distillate grades containing FAME (EN 15751) and for petroleum distillate grades (ISO 12205).
IDLH = Immediately Dangerous to Life or Health Concentrations specified by the United States National Institute for Occupational Safety and Health (NIOSH), **L** = liquid, **G** = gas, **V** = vapour	
[1] Unless specified otherwise, source of data is Chevron, BP and Exxon Mobil Safety Data Sheet for distillate marine gas oil (DMA/DMZ) (Chevron, 2023) (ExxonMobil, 2018) (BP, 2021) [2] Applicable for dodecane, a constituent of MGO. Based on Chemical Safety Data Sheet MSDS/SDS (Chemicalbook, 2023) [3] As specified in ISO/DIS 8217:2023 (ISO, 2023) [4] Unless specified otherwise, source of data is REG Safety Data Sheet for REG Eco Premium Biodiesel/Biodiesel B99.9 (REG, 2022) [5] Unless specified otherwise, source of data is Gulf Oil Safety Data Sheet Biodiesel 2%-20% (Gulf Oil, 2023) [6] As specified in Biodiesel sales specification sheet (Greenergy, 2023)	

As stated in ISO 8217, in case of utilizing fuels containing FAME, it is essential to verify that the various on-board systems are compatible both operationally and in terms of materials. FAME offers favorable properties with regards to lubricity and ignition. Nevertheless, potential challenges may arise related to storage and handling of FAME fuels in marine environments, such as oxidation, corrosion, long-term storage issues, risk of microbial growth due to its affinity to water, degradation as a result of low temperatures and formation of solid deposits (ISO, 2023). Such complications may force the use of additives or certain blending strategies to enhance the fuel quality for commercial purposes.

FAME can be blended with petroleum-based diesel fuels and effectively managed by adhering to certain guidelines. The demand for various FAME blends is primarily influenced by national regulations governing blending limitations and the typically elevated cost compared to conventional marine fuels. Based on feedback from maritime industry stakeholders the most common fuel blends containing FAME typically ranges between B20-B30. Normally, the symbol for diesel-type fuels, as per relevant standards or equivalent national legislation, is “BX”, where X denotes the maximum volume percentage of FAME (European Committee for Standardization, 2021). The implementation of this notation is not necessarily consistent, and it should be noted that it is referring to the maximum % v/v, meaning that the FAME content can be significantly lower than the specified number. ISO 8217:2017 introduced distillate fuel grades allowing for a FAME content up to 7 % v/v (DFA, DFZ, DFB). The new revision of ISO 8217 removes the FAME blend ratio limit for DF grades and introduces additional RF grades containing FAME, meaning that the blend component of FAME in both distillate and residual fuels can be up to 100% (ISO, 2023).

The chemical composition of FAME is distinct from fuels containing hydrocarbons only. Therefore, the blending of FAME with conventional petroleum-based fuels may pose challenges requiring consideration during distribution and handling. It should also be noted that the properties of FAME produced from different feedstocks may vary. This comes as a result of variation in carbon number distribution of the fatty acids. Nevertheless, for the FAME product to be ISO8217 compliant, it must adhere to the requirements outlined in EN 14214 (excluding CFPP and sulfur requirements) or ASTM D6751 (excluding sulfur requirements). This goes for both distillate and residual grades up to 100% FAME. Other national FAME standards and alternative bio-based products, such as off-spec FAME or FAME distillation bottoms, are not specifically covered by ISO 8217 (ISO, 2023). Other chemical and physical characteristics of FAME, such as cetane number, cold flow properties and oxidation stability, are also governed by the fatty acid composition (CONCAWE, 2009). Although FAME is chemically different from petroleum-based diesel products, it also has many similarities. To capture potential hazardous characteristics inherent in FAME derived from different feedstocks, the following will address general considerations associated with FAME compared to conventional fossil diesels.

In the following sub-chapters, the key implications of FAME's characteristics are described with respect to flammability, storage, handling, release and dispersion, and if relevant compared with MGO. From a broad perspective, FAME can be considered quite similar to petroleum diesel, and the anticipated risks and hazards primarily pertain to the equipment employed during bunkering and the fuel itself rather than personnel safety.

2.8.1.1 Flammability

The European specification of FAME (EN 14214) define the flashpoint of neat FAME to be above 101 °C (European Committee for Standardization, 2019). In contrast, many distillate marine fuel grades, including MGO, exhibit a minimum flashpoint of 60 °C, implying that neat FAME is less flammable than MGO. This also means that greater attention should be directed towards the biodiesel blends, where the proportion of the petroleum-based component typically exceeds the FAME portion, resulting in increased flammability compared to pure FAME. Similar to any fuel intended for combustion, FAME fuels will also necessitate certain safety measures related to its flammability regardless of the blending ratio.

Similarly, as for MGO, FAME fuels will burn if ignited, and should therefore be kept away from oxidizing agents, elevated temperatures, and potential ignition sources. Care must also be taken in handling items that have been in contact with or have absorbed the fuel. FAME has the potential to undergo rapid oxidation upon exposure to air. The oxidation process can produce a substantial amount of heat, and under favorable conditions the temperature may pass above the auto-ignition temperature. Rags or cloths soaked with neat FAME may therefore be subject to spontaneous ignition (CONCAWE, 2009). Similar as for fire involving petroleum-based diesels, FAME fuels can be extinguished by use of dry chemical foam, Carbon Dioxide (CO_2), water spray/mist or alcohol resistant foam (AGQM Biodiesel e.V., 2020) (McCormick & Moriarty, 2023).

2.8.1.2 Storage, handling, release, and dispersion

Stability
FAME generally exhibits lower oxidation and thermal stability compared to petroleum diesel grades such as MGO. It faces degradation from various chemical and biological processes, such as oxidation, reverse trans-esterification, hydrolysis, thermal polymerization, and microbial growth. The primary threat to stability arises from the reaction of FAME or petroleum diesel with dissolved oxygen, which can lead to formation of gum, sludge and other insoluble compounds. To counteract this, oxidation stability-enhancing additives may be added during production and before storage. Reducing the exposure to air minimizes the fuel oxidation and extends the storage life. While diesel fuels blended with bio-components are stable without oxygen and water, extended storage under elevated temperatures can accelerate degradation. Controlling that the water, glycerol and glyceride levels, as well as other impurities, are within specified limits, and maintaining proper storage and distribution practices help mitigate instability risks (CONCAWE, 2009). ISO 8217 specifies the oxidation stability requirements for marine distillate fuel grades that incorporate FAME (e.g., DFA, DFZ, DFB) and those without (e.g., DMA, DMZ, DMB). Because the test method is different, the specified oxidation stability cannot be directly compared.

Due to its hygroscopic nature, FAME can absorb a significantly higher amount of moisture than pure fossil diesel. The presence of water may result in acid formation and microbial growth, and can lead to diesel bugs, molds, yeasts, and bacteria spreading throughout the fuel. The consequences of the stability characteristics of FAME may potentially affect bunkering equipment, posing a risk for fuel system blockage and clogged filters, formation of sediments or other insoluble compounds in tanks, as well as the risk of degraded fuel quality. It is generally advised to restrict FAME storage to a maximum of six months, with a practical emphasis on using it even faster (CONCAWE, 2009). Some sources suggest using it within a three-month period.

Cold flow
If exposed to excessively low temperatures, biodiesels have the potential to gel or form solid crystals, possibly resulting in filter blockages or becoming too thick for effective pumping. Hence, understanding the cold flow properties of the applicable fuel is crucial before engaging in bunkering operations during such conditions. FAME typically has higher cloud point, pour point and CFPP than MGO. Issues are not anticipated at lower blends, such as for B7 and below, as the characteristics of the conventional diesel fuel should dominate. Necessary precautions should however be implemented for higher blends exposed to cold interfaces when the temperatures are near the specified extremes. For ships bunkering FAME fuels in cold environments, the specific cold flow requirements may be specified contractually (CIMAC, 2013).

Several factors may impact the cold flow characteristics of FAME and blends thereof, the most fundamental being the feedstock. Due to the significant variations, defining low-temperature properties to guarantee optimal performance under all ambient conditions is not practical. Operability properties may be agreed upon based on expected condition and intended use (McCormick & Moriarty, 2023). Cloud point can typically vary between -5 to 20 °C, and CFPP from -18 to 14 °C (CONCAWE, 2009). During bunkering operations where the possibilities to correct cold temperature is limited, it is of essence to understand the impact of the cold flow properties.

Materials compatibility

FAME is a better solvent than hydrocarbon diesel fuels and possess a tendency to redissolve sediment accumulations. The effectiveness of this cleaning action depends on existing sediment levels in the system and the FAME blending ratio, meaning that pure FAME and high-level blends has a much higher solvent effect compared to the lower blends (CONCAWE, 2009). Therefore, it is crucial that bunkering equipment and storage facilities are clean; otherwise, FAME can dissolve accumulated deposits, potentially leading to clogging in the vessel fuel supply system. If clogging occurs onboard, it is essential to identify the root cause. Deposits resulting from the solvent effect of FAME have previously been mistaken for sediments that can occur during unfavorable storage conditions. If the fuel is within specifications, and storage has been appropriate, a potential cleaning effect of bunkering equipment may be the cause, rather than fuel aging or oxidation.

FAME may not be compatible with certain materials and elastomers. Rust and metals like copper, brass, bronze, lead, tin, and zinc can expedite degradation, resulting in the formation of sediments. Ideally, storage of FAME fuels in systems containing these metals should be avoided. Such materials may be replaced by carbon steel, aluminum or stainless steel (McCormick & Moriarty, 2023).

The acid number is a valuable parameter for monitoring signs of oxidation, being the primary threat to the degradation of FAME fuels. Determining the acid number and assessing the corrosive tendencies of fuels can be intricate. While measuring the acid number can provide insights into the existence of acidic compounds, having acid numbers below the limit values outlined in ISO 8217 doesn't ensure the absence of issues linked to acidic compounds. Presently, there's no established correlation between the results of an acid number test result and the corrosive activity of a fossil fuel (ISO, 2023). For biodiesels however, the free fatty acids may lead to corrosion issues, especially in fuel injection equipment and pumps. Acids in FAME commonly originate either from the acids employed in biodiesel production, which are not entirely removed during the production process, or as byproducts from the oxidation of FAME. The presence of water may also lead to corrosion. Consequently, it is recommended to maintain the acid number value for FAME fuels at a minimum (MAN Energy Solutions, 2023). ISO 8217 specifies a maximum of 0.5 mg KOH/g for all distillate marine grades, including those who may contain FAME.

Generally, it is expected that blends containing up to 7 % v/v FAME can utilize the same storage, handling equipment and machinery as ISO 8217 compliant marine diesel fuels (CIMAC, 2013). It should also be noted that blends of B20 or lower, produced according with the current standards (e.g., ASTM D6751 or EN 14214), are reported to have relatively good materials compatibility (McCormick & Moriarty, 2023). For blends containing higher percentages of FAME, an assessment of the affected systems is recommended to ensure compatibility.

Miscibility and contamination

FAME, due to its chemical composition, can be blended with various distillate or diesel fuels but should not be mixed with gasoline. Precautions must be taken during transport and handling to avoid cross-contamination between FAME and other fuels that may have restrictions on FAME content. As specified in ISO 8217, certain fuel grades are constrained or have specified maximum levels of FAME, and they need to be safeguarded against contamination accordingly. The same goes for water as both free and dissolved water can result in corrosion, fuel degradation and microbial growth. Free water may enter tanks through condensation, by contamination from various distribution systems or by leakages in piping, valves or caps. Transportation and distribution, whether via barge, trucks, or pipes, should adhere to the same principles as those applied to petroleum diesel. Transport vessels should be free of potential contaminants from previous loads, and adequate precautions must be taken to prevent the introduction of water, dirt, and rust (CONCAWE, 2009).

Safe handling and toxicity

The safety measures and safety equipment for storage and handling of FAME fuels and petroleum-based diesels are much alike. FAME does not contain hazardous materials and is considered safe to use. It has minimal inhalation effect unless vaporized, which potentially can lead to irritation, dizziness and nausea. Prolonged or repeated skin contact is not likely to cause serious irritation, and accidental ingestion is not expected to be hazardous (CONCAWE, 2009). It is always recommended to familiarize with relevant documentation such as Safety Data Sheets.

3. A Regulatory Review

This chapter is dedicated to examining the current regulatory status for the selected biofuels, with a focus on assessing their applicability to conventional bunkering arrangements and operational procedures.

The objective of this regulatory review is to identify existing industry best practices, rules and regulations, standards, and port and national guidelines related to the safe bunkering of:

- Bio-methanol
- Hydrotreated Vegetable Oil (HVO)
- Fatty Acid Methyl Ester (FAME)
- Bio Dimethyl Ether (bio-DME)
- Bio-Fischer-Tropsch (FT)-diesel

3.1 Approach and limitations

The following steps were taken:

Firstly, the characteristics of each biofuel were mapped, and a reference fuel was chosen for comparison. This facilitates for a regulatory analysis of the bunkering of novel biofuels against conventional fuels, thereby identifying regulatory gaps between the two.

Secondly, a regulatory review of the current state of the maritime sector was conducted, comparing existing regulations, rules, standards, and best practices of the bunkering of the chosen biofuels, to similar conventional fuels.

Thirdly, a similar regulatory review was conducted for the chosen fuels within other industries, to identify regulations, rules, standards, and best practices that could be transferred and applied to the maritime sector.

Lastly, the regulations, rules, standards, and best practices, best suited for each of the chosen biofuels were summarised with the aim of closing the regulatory gap between novel biofuels and conventional fuels.

The scope of this review was limited to:

- The chosen biofuels and the conventional fuels they are compared to.
- Regulations concerning the vessel itself and related operations shoreside.
- Other industries as described in the relevant section.
- Existing industry best practices, rules and regulations, standards, and port/national guidelines.
- The operation of bunkering/transfer of the biofuel, with a focus on safety.
- The loading/offloading of these fuels as cargos could be considered as part of the scope but is not the focus.

3.2 Fuel Comparison

One way to find out which rules or regulations apply to the bunkering of new types of fuels, when there is no specific regulation for them, is to compare them with an existing fuel. If a new fuel is similar to an existing fuel oil, the regulation for the existing fuel oil could be used as a reference for the new fuel. The comparison should also consider the different levels of risk that the new fuel may pose, compared to the existing fuel oil. This could help to determine if the new fuel needs more or less stringent regulation for bunkering. Table 3-1 cover the biofuels and their comparative conventional fuel.

Table 3-1: Overview of selected biofuels and their selected comparatives.

Biofuel	Description	Comparison
Bio-methanol	Bio-methanol is a low carbon emitting liquid fuel produced from renewable biomass. It is corrosive, toxic, and highly flammable.	Methanol
Hydrotreated Vegetable Oil (HVO)	HVO is a hydrocarbon fuel and has similar characteristics to traditional marine distillates and is considered a drop-in fuel.	Diesel
Fatty Acid Methyl Ester (FAME)	FAME is produced from FOGs through a transesterification process. It consists of long-chain mono-alkyl esters, commonly known as fatty acid methyl esters, making it different from hydrocarbon fuels.	Diesel
Bio Dimethyl Ether (bio-DME)	Bio-DME is produced from biomass. It is gaseous at atmospheric pressure and room temperature and is usually liquefied during storage and handling. It has similar characteristics as LPG.	Risk: LPG Use: Diesel
Bio-Fischer-Tropsch (FT)-diesel	Produced from various sources, including biomass, via the Fischer-Tropsch synthesis. Its properties are similar to that of diesel.	Diesel

3.3 Conventional Bunkering Procedure

Bunkering is a safety critical operation, with specific risks towards both humans, marine life, and the environment. There are, therefore, established procedures for bunkering operations within the maritime industry. This section will review conventional bunkering procedures, specifically looking at bunkering procedures for LNG and MGO. Industry best practice, such as *the International Safety Guide for Oil Tankers and Terminals* (ISGOTT 6), and procedures from well-known, well driven ports such as Port of Rotterdam and Port of Gothenburg serve as the foundation for this summary of a conventional bunkering operation (OCIMF, 2020).

For reference, a typical LNG bunkering operation sequence can be the following:

1. Planning phase
   - Risk assessment: Safety and risk assessment phase.
   - LNG bunkering management plan: Safety and risk assessment conclusions undertaken.
   - Compatibility assessment: Safety and risk assessment applied.

2. Operational phase
   - Set-up of safety zone, if required.
   - Pre-bunkering phase: Preparation for safe bunkering.
   - Connection: Inserting, coupling and testing.
   - Bunkering phase: Monitoring and management of the LNG transfer
   - Disconnection: Draining, purging, disconnection and safe storage of the LNG transfer system

3. Post bunkering phase:
   - End of bunkering operation: Documentation

Several checks must be conducted, both by the receiving ship and by the bunker facility. These cover phases such as: pre-arrival, after mooring, pre-transfer conference and pre-bunkering. Repeated checks might be required on a time-fixed interval basis throughout the bunkering operation.

Pre-bunker checks should be carried out prior to bunkering. This includes several action points, such as designated bunker tank to be loaded, establishing maximum loading volume, rates for start of loading, verification of the operation and accuracy of the gauging system, confirming alarm settings on overfill alarm units, confirm spill response and containment arrangements, amongst other aspects (OCIMF, 2020). Several safety precautions must be in place before bunkering operations can start. This includes personal protective equipment (PPE), firefighting equipment and emergency shut down (ESD) systems.

The general bunkering checklists provided in ISGOTT 6 for bunkering conventional fuels cover the most important steps for all parties and should serve as a foundation for safe bunkering. Such checklists should also be the goal for the safe bunkering of biofuels accounting for their different properties.

Emphasis should be placed on the risk assessment stage of the bunkering procedure, since every bunkering procedure is unique, with different vessels, parties, external factors, and fuels, all of which could affect safety during bunkering. These differences are picked up and mitigated during the risk assessment phase and should form an important safety barrier for bunkering with novel fuels.

3.4 Biofuel Quality Measurement

A large portion of current biofuel regulations is related to the quality and testing of the fuel:

- IMO's MEPC.1/Circ.875 – *Guidance on Best Practice for Fuel Oil Purchasers/Users for Assuring the Quality of Fuel Oil Used on Board Ships*, gives guidance and best practices on assuring the quality of bunker fuel with respect to MARPOL.
- IMO's MARPOL Annex 6, regulation 18 – covers fuel oil availability and quality, with a specific paragraph on non-petroleum-based fuel oils. Which should not:
  - *"Jeopardize the safety of ships or adversely affect the performance of the machinery, or*
  - *be harmful to personnel, or*
  - *contribute overall to additional air pollution."*
- ISO 8217 – Covers marine fuel quality standards, biofuels are partly included under this standard, it is currently under revision to include more biofuels. National actors therefore sometimes have their own standards, such as Singapore's WA 2:2022[9].
- ISO 13739 – Specifies procedures and requirements for the transfer of bunkers to vessels.

The Port of Singapore gives additional requirements specifically for the quality of biofuel for bunkering, through Singapore Standards (SS) 524 - *Singapore Specification for quality management for bunker supply chain* and SS 600 – *Singapore Standard Code of Practice for Bunkering*:

- The bunker mass flow meter from the supplier should be designed and approved for biofuel measurement.
- A Certificate of Quality should be issued by the supplier.
- The biofuel product name should be used on the bunker delivery note (BDN).

[9] Specification for marine biofuel

3.5 Maritime - Safe Bunkering of Biofuel

The following sections will assess the current state of the maritime sector by comparing existing regulations, rules, standards, and best practices for bunkering of the selected biofuels with conventional fuels. This chapter presents the regulatory hierarchy, specifying the regulations applicable to vessel during bunkering.

Given that bunkering involves two parties, namely the receiver and supplier, this regulatory review will distinguish between the receiving vessel and shoreside operators (bunkering station, fuel truck, bunkering barge, etc.). A condensed summary of the most pertinent regulations and best practices for biofuel bunkering is presented in Table 3-2 below.

Table 3-2: Maritime regulatory- and best practices overview for biofuel bunkering.

Regulation	Body	Summary
MARPOL	IMO	Covers the prevention of pollution from vessels
MARPOL Annex 1	IMO	Specifically covers the prevention of pollution by oil
MARPOL Annex 2	IMO	Specifically covers the control of pollution by noxious liquid substance, these substances are then listed in the IBC code
MARPOL Annex 6	IMO	Regulation 18, paragraph 3.2 specifically covers fuel oil quality from non-petroleum refining
MEPC.1/Circ.875	IMO	Guidance on Best Practice for Fuel Oil Purchasers/Users for Assuring the Quality of Fuel Oil Used on Board Ships
MEPC.1/Circ.879	IMO	Guidelines for the Carriage of Energy-Rich Fuels and their Blends – “Energy-Rich Fuels” being considered the “an energy-rich fuel is obtained from biological origin or non-petroleum sources”
MSC-MEPC.2/Circ.17	IMO	Guidelines for the Carriage of Blends of Biofuels
MEPC.2/Circ.28	IMO	Provisional Categorization of Liquid Substances In Accordance With MARPOL Annex 2 and The IBC Code
MEPC.2/Circular Annex 11	IMO	Specifies what is considered a “biofuel”
MEPC.2/Circular Annex 12	IMO	Specifies what is considered a “energy-rich fuel subject to Annex 1 of MARPOL”
MSC.1/Circ. 1621	IMO	Interim Guidelines for the safety of ships using Methyl-Ethyl Alcohol (Methanol) as a Fuel
SOLAS	IMO	Specifies minimum standards for the construction, equipment, and operation of ships, compatible with their safety
SOLAS Chapter VII	IMO	Covers the carriage of dangerous goods and incorporates the IBC code
ISM Code	IMO	Covers the safe management and operation of ships and for pollution prevention
IBC Code	IMO	The safe carriage in bulk by sea of dangerous chemicals and noxious liquid substances
IBC Code Chapter 17	IMO	Covers the requirements of safe carriage for specific substances – some of the chosen biofuels are included
IGC Code	IMO	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	IMO	Covers an international standard for ships, other than vessels covered by the IGC Code, operating with gas or low-flashpoint liquids as fuel
ISO		International agreed upon best practices and standards
ISO 8217	ISO	Standard for marine fuels
ISO 13739	ISO	Standard for bunkering procedures
ISO 20519	ISO	Specification for bunkering of liquefied natural gas fuelled vessels

Regulation	Body	Summary
ISO/TS 18683:2021	ISO	Guidelines for safety and risk assessment of LNG fuel bunkering operations
ISO 28460	ISO	Petroleum and natural gas industries, Installation, and equipment for liquefied natural gas – Ship-to-shore interface and port operations
CWA 17540:2020	CEN	Specification for bunkering of methanol fuelled vessels
SS 600	SS	Singapore Standard Code of Practice for Bunkering

3.5.1 Regulation Hierarchy

Regulations related to the bunkering of biofuels can be framed within a hierarchy:

1. International & EU – IMO, ISO, EU Directives, Regulations etc.
2. National & Port – Flag State, Port Administration etc.
3. Other – Standards, Guidelines, Rules, Best Practices etc.

This framework will be used for the regulatory review of the chosen biofuels.

3.6 International & EU

The IMO primarily addresses international regulations. These regulations are subsequently interpreted and enforced by Port Administrations. Specifically for the bunkering of biofuels, the most relevant from IMO is included as part of MARPOL, the IBC Code, and certain circulars.

MARPOL delineates the handling of liquid substances, thereby regulating the bunkering and transfer of such substances. If a bulk liquid falls under MARPOL's Annex 1, it is classified as conventional "oil." If it falls under MARPOL's Annex 2, it is considered a "noxious liquid substance." Further, the IBC Code outlines minimum requirements for these substances, detailed in MEPC 74/18/Add.2.

Gasses and low flashpoint fuels are governed by the IGC & IGF code.

The IMO categorises biofuels under MARPOL Annex 2 instead of Annex 1, which places additional safety considerations on biofuels. The IMO clarifies under which regulation a biofuel falls via MEPC.2/Circular Annex 11 which specifies what is considered a "biofuel" and MEPC.2/Circular Annex 12 which specifies what is considered an "energy-rich fuel subject to Annex 1 of MARPOL".

IBC Code: international requirements for the safe transportation of chemicals in bulk by sea.

IGC Code: international requirements for the safe transport of liquefied gases in bulk by sea.

IGF Code: international safety standards for ships that use gases or other low-flashpoint fuels.

3.6.1 IMO's Biofuel Definition

The IMO defines "*Biofuels*" within MEPC.2/Circ.28 Annex 11, as:

1. tert-Amyl ethyl ether - TAME
2. Ethyl alcohol - Ethanol
3. Fatty acid methyl esters - FAME
4. Vegetable fatty acid distillates - HVO

These therefore fall under MARPOL Annex 2 and the IBC code.

3.6.2 IMO's Energy-Rich Fuel Definition

The IMO defines an "*Energy-Rich Fuel*" within MEPC.1/Circ.879 as:

- Obtained from biological origin or non-petroleum sources (e.g., algae, vegetable oils) or a blend of petroleum-based fuel and a product obtained from biological origin or non-petroleum sources.
- Comprised only of constituents that can be expressed as individual chemicals of the hydrocarbon family.
- A complex mixture that is characterized as "unknown or variable composition, complex reaction products or biological materials" (UVCB), is formed of a relatively large number of constituents, cannot be represented by a simple chemical structure and has a composition that may vary from batch to batch.

An Energy-Rich Fuel falls under MARPOL Annex 1 and the following fuels are recognised as such:

- Alkanes (C4-C12) linear, branched, and cyclic (containing benzene up to 1%)
- Alkanes (C5-C7), linear and branched
- Alkanes (C9-C24) linear, branched, and cyclic with a flashpoint ≤ 60°C
- Alkanes (C9-C24) linear, branched, and cyclic with a flashpoint > 60°C
- Alkanes (C10-C17), linear and branched
- Alkanes (C10-C26), linear and branched with a flashpoint ≤ 60°C
- Alkanes (C10-C26), linear and branched with a flashpoint > 60°C

It can be somewhat unclear under which IMO regulation a fuel falls. Figure 3-1 shows a flowchart from the IMO for determining which regulation a fuel or “liquid substance to be carried in bulk” falls under.

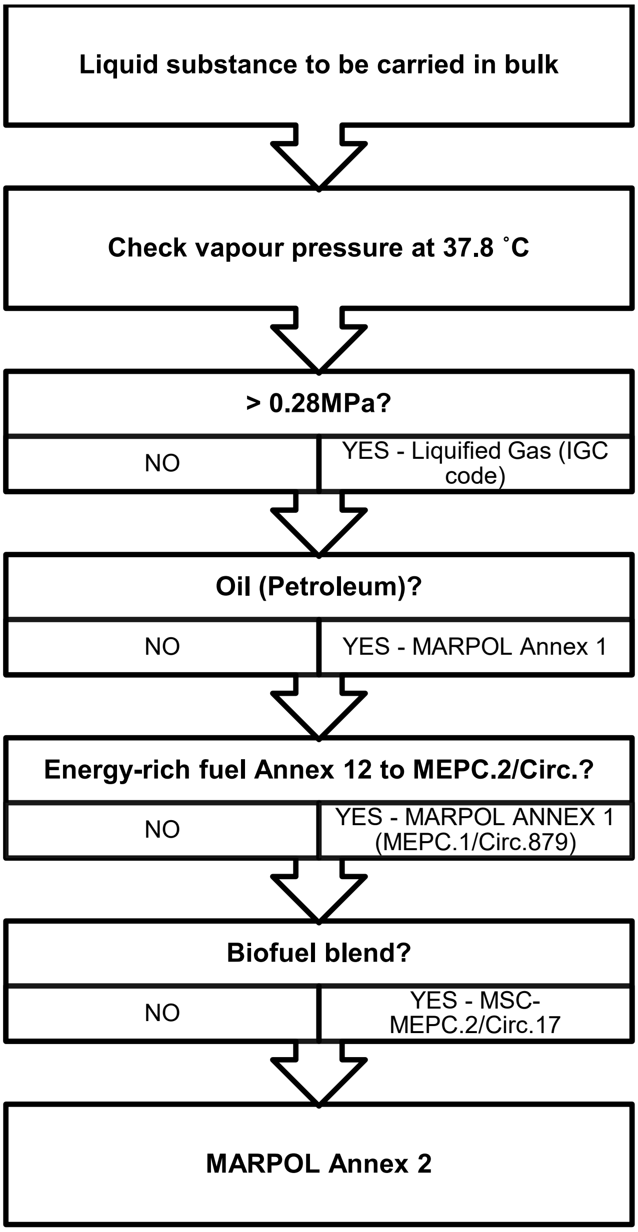

Figure 3-1: Flowchart for determining bulk transported liquid substance regulation, based on IMO’s flowchart (IMO, 2022).

3.6.3 Biofuel Blends

Biofuels can be blended with conventional fuels. The different ratios of these blends of biofuel and conventional fuel define which Annex of MARPOL the biofuel then falls under. These ratios are described in Table 3-3.

Table 3-3: Biofuel Blend Definitions as per MSC-MEPC.2/Circ.17.

Biofuel %	Conventional - Annex 1 %	Blend?	Regulation
Less than 25 %	More than or equal to 75%	Yes	MARPOL Annex 1
Between 25% and 99%	Between 1% and 75%	Yes	MARPOL Annex 2 & IBC Code
More than 99%	Less than or equal to 1%	No	MARPOL Annex 2 & IBC Code

Methanol, HVO, FAME and to some extent bio-DME all fall under the IBC code. While the IBC code determines the requirements for safe carriage of these substances, it does not outline any specific bunkering procedures.

The IMO’s IGC & IGF code covers the use of gas and low-flashpoint fuels. Gas biofuels, such as gaseous or liquified bio-DME, would therefore fall under this code. The IGF code’s “Alternative Design” process is a pathway to adopting novel biofuels that do not clearly fall under any existing regulations.

Generally, conventional liquid fuels fall under MARPOL Annex 1, where liquid biofuels fall under MARPOL Annex 2. Within the scope of this report, IMO’s biofuel definition covers FAME and HVO as fuels. Methanol as a fuel is covered by the IMO’s interim guidelines MSC.1/Circ. 1621, which provides guidelines on the use of Methanol and Ethanol as fuels. Bio-DME is not specifically covered as a fuel, but its carriage falls under the IBC code and due to it likely being a liquified gas under transport falls under the IGC and IGF codes. FT-diesel is not specifically covered in any maritime regulation.

These regulations categorise under which regulatory framework each biofuel falls and by extension the general safety measures to be taken while bunkering and transferring said biofuel. However, specific regulations covering the bunkering of these biofuels as an operation are less available.

3.6.4 Bio-methanol

Accepting the chemical identicalness of bio-methanol and methanol reveals that International/EU regulation covering the bunkering of methanol is relatively developed. This is best described in the IMO’s - *Interim Guidelines for the safety of ships using Methyl-Ethyl Alcohol (Methanol) as a Fuel* and the European Committee for Standardisation’s - *Specification for bunkering of methanol fuelled vessels.*

The IMO’s - *Interim Guidelines for the safety of ships using Methyl-Ethyl Alcohol (Methanol) as a Fuel* are relevant for the safe bunkering of methanol. Although, with respect to bunkering, the guidelines primarily cover the technical requirements for the vessel and not bunkering procedures specific to methanol.

The European Committee for Standardisation’s (CEN) - *Specification for the Bunkering of Methanol* (CEN17540, 2020) gives a comprehensive overview of requirements and provides practical recommendations for a bunkering procedure, including checklists and forms. It covers:

1. Transfer system design requirements
    a. Vessel requirements
    b. Bunkering facility requirements
    c. Transfer equipment requirements
    d. ESD system
    e. Identification of transfer equipment
    f. Transfer system design analysis
    g. Maintenance and maintenance manual
2. Bunkering processes and procedures
    a. Risk assessment
    b. Acceptable bunkering operations parameters
    c. Vessel safety assessment
    d. Mooring
    e. Transfer procedures
    f. Preparations for transfer
    g. Communications during transfer
3. Management system/quality assurance
4. Personnel training
    a. Overall/bunkering training
    b. Port terminal/mobile facility personnel training
5. Documentation
    a. General documentation
    b. Procedures manual
    c. Checklists

It highlights that the vessel should meet all technical requirements pertaining the *IBC Code* and the *Interim Guidelines for the safety of ships using Methyl-Ethyl Alcohol (Methanol) as a Fuel*. It especially regards a proper risk assessment and the evaluation of the bunker operations parameters as acceptable, to be essential.

3.6.5 Hydrotreated Vegetable Oil

- HVO is listed as a biofuel in MEPC.2/Circular Annex 11 and therefore falls under MSC-MEPC.2/Circ.17.
- A fuel blend of more than 25% HVO would fall under MARPOL Annex 2 and the IBC Code.
- MEPC 74/18/Add.2 outlines the IBC classification of HVO and refers to additional requirements it may have. These regulations do not specify bunkering procedures for HVO.
- Chapter 5 of the IBC code covers the transfer of IBC code cargo and gives technical requirements for this.
- Chapter 15 of the IBC code covers some additional technical specifications as referred to from MEPC 74/18/Add.2.

3.6.6 FAME

- FAME is listed as a biofuel in MEPC.2/Circular Annex 11 and therefore falls under MSC-MEPC.2/Circ.17.
- A fuel blend of more than 25% FAME would fall under MARPOL Annex 2 and the IBC Code.
- MEPC 74/18/Add.2 outlines the IBC classification of FAME and refers to additional requirements it may have. These regulations do not specify bunkering procedures for FAME.
- Chapter 5 of the IBC code covers the transfer of IBC code cargo and gives technical requirements for this.
- Chapter 15 of the IBC code covers some additional technical specifications as referred to from MEPC 74/18/Add.2.

3.6.7 Bio-DME

- Bio-DME is not listed as a biofuel in MEPC.2/Circular Annex 11 and therefore does not fall under MSC-MEPC.2/Circ.17.
- Bio-DME is covered by the IBC Code.
- MEPC 74/18/Add.2 outlines the IBC classification of bio-DME and refers to additional requirements it may have. These regulations do not specify bunkering procedures for bio-DME.
- Chapter 5 of the IBC code covers the transfer of IBC code cargo and gives technical requirements for this.
- Chapter 15 covers some additional technical specifications as referred to from MEPC 74/18/Add.2.
- Additional technical requirements for the liquified gaseous transport, storage, and transfer of bio-DME are covered by the IGC & IGF codes.

3.6.8 Bio-FT-diesel

- Bio-FT-diesel is currently not specifically covered by any international regulation for bunkering.

3.7 National & Port Administration

Bunkering regulations vary on a national level, but also from port-to-port within the same state. Port Administrations determine their own rules regarding bunkering, within the wider national framework. Due to the sheer variance of regulations between different port administrations and states, different Port Administrations were chosen as case studies depending on the maturity level of their rules regarding the bunkering of biofuels. Some general safe bunkering considerations are the following, as outlined by the industry stakeholders:

- The vessel must have a certificate of *Minimum Safety Manning* as per SOLAS
- Fuel supply vessels for traditional bunker supply and biofuel bunker supply of a less than 24% blend should have vessel equipment and construction in accordance with the MARPOL Annex 1
- Fuel supply vessels for biofuel bunker supply of a more than 24% blend should have vessel equipment and construction in accordance with the MARPOL Annex 2
- Charging hoses should be approved for their specific fuel type and use, with their corresponding manufacturing certificates and their corresponding annual test certificates
- Fuel Safety Data Sheets should be available
- Bunker checklists, as per ISGOTT format[10]
- Safety Code applicable for IGF vessels, for example bio-methanol and perhaps bio-DME
- Appropriate PPEs depending on fuel classification

Each fuel may have other regulations depending on the Port Administration, these will be considered now.

3.7.1 **Bio-methanol – Port of Gothenburg**

The Port of Gothenburg in Sweden has very clear regulations when it comes to the bunkering of methanol, and by extension bio-methanol. These are outlined in their document - *Methanol Bunkering Operating Regulations*[11]. These regulations cover:

- The set-up of various hazard, safety, and security zones
- Weather condition requirements
- Procedures, simultaneous operations, and bunker operations
- Methanol bunker safety checklist
- Pre-transfer meeting
- Distribution of responsibility for vessels, tanker trucks and shore to ship facilities
- Transfer equipment requirements
- Personal protective equipment, hazards, and fire protection/fighting

The regulation includes several practical checklists and highlights applicable overarching regulation, such as the IBC code, MARPOL, the IMO's interim guidelines for methanol fuelled vessels and CWA 17540:2020[12]. Since bio-methanol is identical to methanol, these regulations apply for both.

3.7.2 **HVO – Port of Singapore**

The Port of Singapore points to SS 600[13] for general bunkering (MPA, 2023). For biofuels specifically, the Port of Singapore considers HVO to fall under MSC-MEPC.2/Circ.17 when blended and refers to MARPOL Annex II and Chapter 17 of the IBC code when not blended. Bunkering with HVO therefore requires the vessel to follow the requirements of the IBC code. However, neither the IBC code nor Singapore Port itself specifies any procedures regarding the specific operation of bunkering of HVO. Additionally, the bunker supplier *"shall ensure that the flag Administration, and Class Society of the bunker craft approve or have no objection to the loading, carriage, and delivery of the biofuel onboard the bunker barge"*.

[10] ISGOTT Checks pre-arrival Ship/Shore Safety Checklist
[11] PoG Methanol bunker operating regulations
[12] Specification for bunkering of methanol fuelled vessels
[13] Code of practice for bunkering by bunker tankers using tank gauging

3.7.3 FAME – Port of Singapore

The Port of Singapore points to SS 600 for general bunkering. For biofuels specifically the Port of Singapore considers FAME to fall under MSC-MEPC.2/Circ.17 when blended and refers to MARPOL Annex II and Chapter 17 of the IBC code when not blended. Bunkering with FAME therefore requires the vessel to follow the requirements of the IBC code. However, neither the IBC code nor Singapore Port itself gives any regulation regarding the specific operation of bunkering of FAME. Additionally, the bunker supplier *"shall ensure that the flag Administration, and Class Society of the bunker craft approve or have no objection to the loading, carriage, and delivery of the biofuel onboard the bunker barge".*

3.7.4 Bio-DME – Port of Singapore

Bio-DME does not fall under MSC-MEPC.2/Circ.17, therefore bio-DME is excluded from the Port of Singapore's biofuel bunkering regulations. Bio-DME does fall under MARPOL Annex II and Chapter 17 of the IBC code when. Bunkering with bio-DME therefore requires the vessel to follow the requirements of the IBC code. However, neither the IBC code nor Singapore Port itself specifies any regulation regarding the specific operation of bunkering of bio-DME.

3.7.5 Bio-FT-diesel

The safe bunkering of Bio-FT- diesel is currently not specifically covered by any national & port administration regulation.

3.8 Standards, Guidelines and Best Practices

There are few standards and guidelines covering the safe bunkering of biofuels outside of the regulatory framework. Again, the most detailed standards and guidelines relate to the bunkering of methanol, which is chemically identical to bio-methanol.

3.8.1 Bio-methanol

Industry best practices regarding the safe bunkering of methanol are summarised generally in a technical reference by Lloyd’s Register. This reference provides a framework for approaching the safe bunkering of methanol by outlining technical requirements and checklists for the bunkering procedure. These checklists are dependent on the flow of the bunkering operation as outlined in Figure 3-2. The checklists themselves cover many of the same topics as outlined in Chapter Bio-methanol 3.6.1. Focusing not only on technical readiness, but also communication and ways of working.

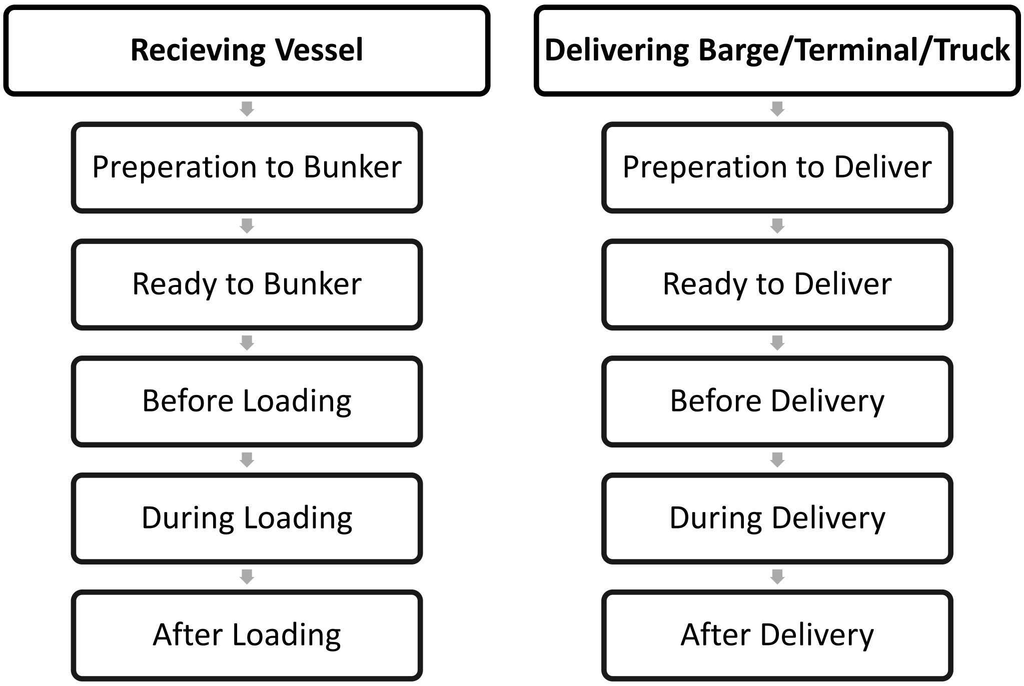

Figure 3-2: Checklist flow for receiving and delivering parties during bunkering, based on LR’s flow (Lloyd's Register, 2020).

This checklist flow aligns with the current industry standard with conventional fuels and highlights the interface between the bunkering supplier and receiver.

The technical reference also stresses the importance of conducting risk assessments on the bunkering process, as required by the IMO’s MSC.1/Circ. 1621.

In terms of technical classification, DNV provides a notation to a methanol fuelled vessel as a low-flashpoint fuelled engine (LFF) in DNV-RU-SHIP Pt. 6 Ch 2. This LFF notation includes the technical requirements for the methanol bunkering system but does not outline bunkering procedures.

3.8.2 Hydrotreated Vegetable Oil

There are no specific standards or guidelines regarding the safe bunkering of HVO. HVO has similar properties to diesel, which is perhaps why the industry has not deemed it necessary to add safety specific guidelines for its bunkering, further than what the IBC code states.

3.8.3 FAME

There are no specific standards or guidelines regarding the safe bunkering of FAME. However, the CONCAWE guidelines state that FAME should, safety wise, be treated similarly to hydrocarbon-only diesel fuels when it comes to storage, transport, and transfer (CONCAWE, 2009). FAME's risk is overall lower due to having a higher ignition temperature, which is perhaps the reason why the industry has not deemed it necessary to add safety specific guidelines for its bunkering, further than what the IBC code states.

3.8.4 Bio-DME

Bio-DME, likely to be used as a liquified gas, has no specific standards or guidelines regarding its safe bunkering.

Although there are no specific guidelines on the safe bunkering of bio-DME, it could be considered that bunkering procedures would be similar to LNG or LPG bunkering. Owing to the similar characteristics and properties of these fuels. Bunkering procedures would, thus, draw on the IGC and IGF codes.

The World LPG Association[14] (WLPGA, 2019) recommends the following for safe LPG bunkering:

- Adequate crew training on the technology, emergency preparedness and fuel characteristics
- Equipment design standards, testing and acceptance
- Risk assessment of the bunkering operation
- Regulated & restricted area surrounding the bunkering operation
- Emergency shutdown and breakaway couplings
- PPEs and spark-proof tools
- Good communication between parties
- Constant supervision of bunkering operation
- Dry chemical and water deluge firefighting equipment
- Local & vessel emergency response plans

Other industry standards for LPG such as the: *National Fire Protection Association's (NFPA's) 58 – Liquefied Petroleum Gas Code* and the US's *Code of Federal Regulations 33 Part 127 – Waterfront Facilities Handling Liquefied Hazardous Gas* could be considered when handling the similar, bio-DME.

3.8.5 Bio-FT-diesel

Bio-FT-Diesel has no specific guidelines or standards when it comes to safe bunkering. It could be considered very similar to conventional fuel in terms of safe bunkering.

[14] Guide for LPG Marine Fuel Supply

3.9 Selected Industries – Safe Fuelling of Biofuel

This section will review the current state of other industries, mapping existing regulations, rules, standards, and best practices of the chosen biofuels. To identify where relevant regulations from other industries could be transferred to the maritime sector.

3.9.1 Aviation

The aviation sector is always worth comparing to the maritime sector, due to their many similarities and aviation's stringent safety requirements. Regarding the implementation of biofuels, or "*sustainable aviation fuels*" (SAF), the aviation sector has taken a different approach than the maritime sector. Aviation requires a SAF to be compatible with existing infrastructure/procedures, while the maritime industry seems to adapt the infrastructure/procedures to the fuel. Table 3-4 shows the SAFs approved for use and their maximum blends (IATA, 2020).

The International Civil Aviation Organization (ICAO) has released guidelines on the use of biofuels in aircraft and follows a strict *"drop-in"* principle. The usage, storage and fuelling of a biofuel must be possible using the same infrastructure as conventional fuels.

What constitutes conventional civil aviation fuel or Jet A-1 is, primarily, determined by specification:

- D1655 – American Society for Testing and Materials (ASTM)
- DEF STAN 91-91 – UK MOD Defence Standard Specification for Jet Fuel

Future "drop-in" SAFs must thereby meet these same specifications to ensure compatibility and an equivalent level of operational safety requirements. This is achieved through the following process:

1. To assess new SAFs the ASTM issued the ASTM D7566 - *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons*. This is considered the main reference for approving aviation fuels for safe use.
2. Approval of a potential new SAF follows ASTM's D4054 - *Standard Practice* which requires stringent testing.
3. Upon passing ASTM D4054 it is certified as meeting ASTM D7566.
4. A SAF meeting ATSM D7566 is then considered a D1655 aviation fuel for normal use and can be blended with Jet A-1 up to a certain percentage.

An approved SAF would thereby meet standard aviation fuel requirements and would not require any alterations in its standard procedures regarding fuelling and operation. A significant limitation for current approved SAFs is that the most promising SAFs can only be blended to a maximum of 50% with Jet A-1. The industry is aiming for the ability to fly commercially with 100% SAF by 2030, which test flights have already been achieved.

Table 3-4: SAFs for use in aviation (IATA, 2020).

Fuel	Max. blend (% v/v)	Feedstocks
Fischer-Tropsch (FT), Fischer-Tropsch containing aromatics (FT-SKA)	50	Wastes (MSW, etc.), coal, gas, sawdust
Hydroprocessed Esters and Fatty Acids (HEFA)	50	Vegetable oils: palm, camelina, jatropha, used cooking oil
HH-SPK or HC-HEFA	10	Oils produced from (botryococcus braunii) algae
Synthesized Iso-Paraffin	10	Sugarcane, sugar beet
ATJ (Isobutanol and Ethanol)	50	Sugarcane, sugar beet, sawdust, lignocellulosic residues (straw)
Catalytic Hydrothermolysis Jet fuel (CHJ)	50	Waste oils or energy oils

3.9.2 Road Transport

Renewable/biofuels are already in widespread use as a blend within road transport, with the commonly available E10 petrol consisting of a maximum of 10% renewable ethanol. Biofuels in road-transport are seeing increased use and are labelled with a “B”. B5 would thereby mean a blend of 5% biodiesel and 95% petroleum-based fuel. Biofuels for road use are colloquially termed “biodiesel” (McCormick & Moriarty, 2023).

Biodiesel for road-transport must follow EN14214 in the EU or ASTM D6751 in the US as a specification. Any road vehicle can utilise a blend of up to 5% (B5) of one of these approved biodiesels. With several manufacturers allowing for the use of 100% (B100) biodiesel for their engines. This indicates that most biodiesels for road use are not simply drop-in, but can be, if blended sufficiently or the engine is designed for its use.

This inability to use B100 with all existing engines does not stem from a safety standpoint, but rather a technological gap between the altered performance properties of biodiesel and petroleum-based diesel regarding, for example, cold weather performance and lubricity. B20 thereby is a popular blend that balances compatibility, performance, and emissions (McCormick & Moriarty, 2023).

There is little difference regarding the safe fuelling of B100 or blends thereof in road-transport compared to conventional petroleum-based fuels. The most important aspect being the handling of cold temperatures when refuelling. Safety wise there are no specific regulations regarding the refuelling of B100 or blends thereof, other than system compatibility.

3.9.3 Maritime

Methanol is presently employed as a marine fuel, with commercial engine technology already in use. DNV's Alternative Fuels Insight platform (AFI) reports that 29 ships, either operational or scheduled for delivery in 2023, are powered by methanol.

Over the past few years, numerous sea trials have been carried out using a diverse range of FAME blends, some reaching up to 100%, all yielding satisfactory outcomes (ISO, 2023). Similar positive results have been observed in trials involving HVO, with both fuels being regarded as drop-in alternatives. Initial and short-term results indicate no major service issues, with only minor modifications required on-board.

At present, no actual sea trials employing DME as marine fuel have been identified; only laboratory testing has been conducted. Bio-FT-diesel is also in the early stages of development, and no specific trials have been identified. In contrast, fossil-based FT-diesel is commercially available. A key barrier to the widespread adoption and commercialization of these novel biofuels is the associated costs.

3.9.4 Other

Sectors other than aviation and road-transport have also seen experimentation with biofuels, with similar results (McCormick & Moriarty, 2023):

- *Rail:* The rail sector is lagging somewhat behind road-transport regarding biodiesel usage due to the long life of locomotives. With older locomotives needing to be phased out before B100 compatible locomotives can be utilised. B20 blend capable locomotives have seen more experimentation. There are no specific regulations or best practices in terms of the safe refuelling of biodiesels in locomotives. This is mainly due to the same reasons as road transport, with biodiesel refuelling varying little from conventional petroleum-based fuels from a safety perspective.
- *Heating:* For biofuel use in the heating of homes, B20 has seen experimentation. Like road transport there are no specific regulations or best practices in terms of the safe refuelling.
- *Power Generation:* Like the above points there are no specific regulations or best practices in terms of the safe refuelling with power generation.

3.10 Overview of Regulations & Best Practices - Safe Bunkering

The chosen biofuels vary when it comes to regulatory coverage and industry best practices in terms of their safe bunkering. Bio-methanol is the most mature, whereas HVO and FAME, exhibiting similarities in regulatory coverage, share commonalities with conventional marine diesels, potentially allowing for the leveraging of existing frameworks. Bio-DME, being gaseous and not commercially available, represents a somewhat unique position in this context and has little coverage. Among the selected biofuels, bio-FT-diesel has the least coverage.

For the safe bunkering of some of the biofuels, especially HVO, FAME, bio-DME and to some extent FT-diesel, an specific design approach as that taken by the Port of Singapore may be a valid method for ensuring safety. While bio-methanol can rely more on earlier industry experience and the specific guidelines that comes with that. A risk-based approach for their safe bunkering therefore seems the most appropriate until their use matures.

Regulations concerning the blending of these fuels have been considered and the safe bunkering of these blends should follow those guidelines.

Other industries do not seem to take the same approach as the maritime sector, preferring a pure “drop-in” approach with a minimal impact to existing infrastructure and procedures for fuelling. Requiring a strict approval process for the fuel to ensure minimal operational impact to existing technologies.

It should be noted that strict rules and guidelines may hinder biofuel adoption, while having a minimal positive impact on safety. Keeping the comparable risk in mind between a biofuel and a conventional fuel through a risk assessment seems an appropriate method for ensuring their safe bunkering, while promoting adoption. The following overview covers each biofuel specifically.

3.10.1 **Bio-methanol**

IMO - MSC.1/Circ.1621, CWA 17540:2020, Port of Gothenburg - Methanol Bunker Operating Regulations, DNV-RU-SHIP Pt. 6 Ch 2 and LR - Introduction to Methanol Bunkering.

Best practices regarding the safe bunkering of bio-methanol are more mature than the other biofuels as it is identical to methanol. The industry has more experience with methanol use as a marine fuel and by extension its bunkering, this has led to more specific procedures, technical requirements, and a regulatory framework. This could be seen as the goal for the other biofuels. The ECS standard for the bunkering of methanol could be considered the current best practice for the bunkering of methanol along with the practical requirements set by Port Administrations such as Gothenburg and IMO’s interim guidelines regarding methanol.

3.10.2 **Hydrotreated Vegetable Oil (HVO)**

IMO - MARPOL Annex 2, IMO - MSC-MEPC.2/Circ.17, IMO – IBC Code, MPA - PORT MARINE CIRCULAR No. 21

HVO has less specific best practices regarding its safe bunkering, although it is clearly defined in MARPOL and the IBC code. Practical procedures for bunkering, such as those of methanol, are lacking. However due to the relative similar characteristics and risk level of HVO, relative to conventional marine diesel, this may not be necessary from a strict safety perspective. An approach, such as the one taken by the Port of Singapore seems the most appropriate.

3.10.3 Fatty Acid Methyl Ester (FAME)

IMO - MARPOL Annex 2, IMO - MSC-MEPC.2/Circ.17, IMO – IBC Code, MPA - PORT MARINE CIRCULAR No. 21

Similar to HVO, FAME is clearly defined under IMO regulation, but there is a lack of practical guidelines for its safe bunkering. It could be considered that FAME has a similar or lower risk level when it comes to bunkering, so it may not be necessary to introduce strict guidelines for the bunkering of FAME from a safety perspective. An approach, such as the one taken by the Port of Singapore seems the most appropriate.

3.10.4 Bio Dimethyl Ether (bio-DME)

IMO – IBC Code, IMO – IGC Code, IMO – IGF Code, WLPG - Guide for LPG Marine Fuel Supply

Bio-DME, is also clearly defined under existing IMO framework. However, specific procedures and technical requirements regarding its bunkering are lacking. Some parallels concerning requirements and procedures could be made with the IGC and IGF code due to the gaseous nature of bio-DME. It is most comparable to LNG/LPG bunkering due to likely being transported as a liquified gas, entailing a similar bunkering procedure. The WLPGA has set some general recommendations for the safe bunkering of LPG which could be drawn on for bio-DME.

3.10.5 Bio-Fischer-Tropsch (FT)-diesel

FT-diesel has the least regulatory coverage of the chosen biofuels. With no specific mention within the IMO regulatory framework. This could hint at its general acceptance as a “drop-in fuel”, but it should be made explicit. Its similarity to conventional marine fuels suggests that a similar risk level would allow for minimal changes to bunkering procedures. FT-diesel should receive more industry and regulatory attention until a similar risk level is proven.

4. Incidents and accidents in land-based industries

This chapter aim to present relevant experience from land-based industries dealing with the selected fuels to serve as input for the guidance for safe bunkering of biofuels, and to highlight hazards with the selected biofuels, compared to hazards that are well known and applicable for conventional fossil fuels.
This has been done through a literature study, review of relevant accidents and collection of input from industry partners. Accidents were considered relevant if the cause of the accident could foreseeably occur either during storage or bunkering operations, or due to the chemical properties of the fuels.

Accidents where the root cause was due to the manufacturing processes or specific equipment uniquely related to production of biofuels or other industrial usages, are not considered relevant. Similarly, transportation accidents (vehicle crash, train derailment, ship collisions, etc.) where the cargo was biofuel and it had no impact on the root cause of the accidents, are also not considered relevant.

4.1 Conclusion

Several accident databases were identified and queried for relevant accidents alongside academic and industry papers. The queries of the database were typically carried out using the keywords in Table 4-1.

Based on the findings presented in Chapter 4.2, no distinctive hazards or causes unique to any of the biofuels included in this study, as opposed to conventional fuels, were identified. All accidents involving biofuels occurred due to processes or equipment which would not be found in bunkering operations, transportation accidents, natural hazards, occupational accidents, equipment failure not unique to biofuels, or due to human error. Example of relevant spill incidents can be read in section 4.2.13 and examples of occupational accidents can be read in section 4.2.15. These incidents include accidents involving hot-work around storage tanks, hose failure and equipment failures. Hazards such as those are considered relevant to bunkering operations but are not unique to the selected biofuels compared to conventional fuels and are well known industry hazards.

Only accidents regarding biodiesel and methanol were identified in any meaningful quantity. Feedback from industry stakeholders involved with any of the five selected biofuels indicated that they had encountered no incidents related to bunkering operations with biofuels.

Nevertheless, there are transferable lessons from accidents in land-based industries. They are however also applicable for conventional fossil fuels, and not unique to biofuels. Lessons such as not to underestimate the danger involved with the storage of hazardous, flammable materials and the importance of adhering to established safe operating practices.

A strong safety culture, sufficient training of operators, clear instructions and a well-planned maintenance system could prevent several relevant accidents scenarios from occurring. Statistically it is shown that most accidents occur within the first few years of operation, and extra preventive measures could be considered during this time. The cause of several fatal accidents involving storage tanks has been attributed to hot work. This activity demands particular attention from organizations to ensure safety. Hot work being defined as activities with the potential to create an ignition source, such as welding, cutting, soldering, and grinding. Specific safeguards against this hazard can be seen in Table 4-4 in section 4.2.3.

Incidentally, the study revealed that several previously used databases are no longer being updated or have become inaccessible.

Table 4-1: List of keywords used for querying databases.

Keywords
Biodiesel, biofuel, bio, FT diesel, Fischer-Tropsch, methanol, methyl alcohol, FAME, Fatty Acid Methyl Ester, Fatty Acid, Methyl Ester, Hydrotreated Vegetable Oil, Vegetable Oil, HVO, DME, Dimethyl Ether.

4.2 Findings from databases and other sources

The following section describes the findings from a variety of databases and sources which was used as the foundation for section 4.1. As such 4.1, summarize the most important findings from the databases and sources which are detailed below.

4.2.1 ARIA

The ARIA (Analysis, Research and information on Accidents) database is managed and administered by the BARPI (Bureau for Analysis of Industrial Risk and Pollution), in collaboration with the French Minister of the Environment and the General Directorate for Risk Prevention.

The database catalogues incidents potentially harmful to human health, public safety, or the environment. It includes accidents from various activities and consist of over 46,000 events globally. Primary sources include emergency services, environmental inspection authorities, the media, and professional bodies. 10 incidents with the fuel types of interest were identified, however the incidents were not considered unique to the selected biofuels compared to conventional fuels.

Table 4-2 Accident Examples from ARIA (translated from French using ChatGPT).

Process failure (10.11.2013)
The failure of a level sensor results in the pumping of glycerine into a waste recovery and biodiesel production facility's distillation column. The accident analysis reveals several failures: 1. Lack of an effluent treatment device contrary to what was stipulated in the operating authorization application file. 2. Failure in the development and implementation of safety rules on-site. 3. Deficient management of requirements for service providers leading to repair delays incompatible with operations. 4. Failure to implement lessons learned from a similar event that occurred three months earlier (ARIA 45348).
Biodiesel spill following cleaning operations (28.11.2021)
Around 6 AM, a spill of biodiesel occurs at sea following the cleaning of a non-compliant tank by a tanker ship. A slick extending 25 km is visible with natural mixing and dilution.
Explosion following welding operation on storage tank (07.07.2006)
An explosion followed by a fire occurs in a biodiesel manufacturing plant. An operator performing welding operations on a storage tank is killed by the explosion. His father, who was attempting to rescue him, and another employee are injured. The fire destroys a building before being brought under control by emergency services. The nearby residents, evacuated during the intervention, have been allowed to return to their homes.
Release of methanol from a waste-to-energy plant (15.02.2013)
At around 10:00 p.m., the fastener of a fan-motor propeller at a waste-to-energy and biodiesel production plant failed, causing the cooling system to fail in turn. The rise in pressure resulting from heating of the distillation column caused the rupture disks to burst, releasing into the atmosphere the 95 tonnes of gaseous methanol that had built up in the top of the column. An analysis by the operator found multiple failures: 1. Innovative system affected by poor design choices. 2. No safety instructions in the event of failure of the cooling system. 3. Lack of supervision in the engineering of new developments.

4.2.2 CAIRS

The Computerized Accident/Incident Reporting System is a database used to collect and analyse injuries, illnesses and other accidents that occur during the operations of the United States Department of Energy. The website was offline at the time of this report (November 2023) and inaccessible.

4.2.3 CSB

The website of the U.S Chemical Safety Board (CSB) contains investigation reports from U.S chemical accidents and follow-up recommendations. One relevant accident involving welding in the vicinity of a methanol tank was identified.

Table 4-3: Bethune Point Wastewater Plant Explosion accident descripting.

Bethune Point Wastewater Plant Explosion (01.11.2006)
Two municipal workers died, and another was seriously injured while attempting to remove a steel canopy above a methanol storage tank at the Bethune Point wastewater plant operated by the City of Daytona Beach. The workers were using a cutting torch that likely ignited methanol vapours from the tank and caused an explosion. The explosion led to the release of the total contents of the tank, approximately 3,000 gallons of methanol.

CSB found that fires and explosions caused by hot work on or around storage tanks is one of the most common causes of worker deaths among the accidents it investigates. In response to this finding a study was conducted, and a safety bulletin released in 2010 containing seven preventive key lessons which can be seen in Table 4-3 (CSB, 2010).

Table 4-4: CSB Lessons learned from Hot-Work accidents.

Lesson	Description
Use Alternatives	Whenever possible, avoid hot work and consider alternative methods.
Analyse the Hazards	Prior to the initiation of hot work, perform a hazard assessment that identifies the scope of the work, potential hazards, and methods of hazard control
Monitor the Atmosphere	Conduct effective gas monitoring in the work area using a properly calibrated combustible gas detector prior to and during hot work activities, even in areas where a flammable atmosphere is not anticipated.
Test the Area	In work areas where flammable liquids and gases are stored or handled, drain and/or purge all equipment and piping before hot work is conducted. When welding on or in the vicinity of storage tanks and other containers, properly test and if necessary, continuously monitor all surrounding tanks or adjacent spaces (not just the tank or container being worked on) for the presence of flammables and eliminate potential sources of flammables
Use Written Permits	Ensure that qualified personnel familiar with the specific site hazards review and authorize all hot work and issue permits specifically identifying the work to be conducted and the required precautions
Train Thoroughly	Train personnel on hot work policies/procedures, proper use and calibration of combustible gas detectors, safety equipment, and job specific hazards and controls in a language understood by the workforce.
Supervise Contractors	Provide safety supervision for outside contractors conducting hot work. Inform contractors about site-specific hazards including the presence of flammable materials.

4.2.4 CTIF World Fire Statistics Center

The International Association of Fire and Rescue Services (CTIF) publish annually the World Fire Statistics which is aggregated statistical data from 66 member countries, however the 2023 report does not contain any information with regards to relevant biofuels (CTIF World Fire Statistics Center, 2023).

4.2.5 eMARS

The eMARS database, initiated in 1982 under the EU's Seveso Directive 82/501/EEC, serves as a publicly accessible repository for accident and near-miss data. Countries affiliated with the EU, EEA, OECD, and UNECE contribute incident reports to the Major Accident Hazards Bureau (MAHB) at the European Commission's Joint Research Center (JRC). These reports, detailing chemical accidents and near misses, are directly integrated into the eMARS database (eMars, 2023).

At the time of writing (November 2023), the database contains 1190 accidents. Most accidents in the database occurred due to processes not seen during bunkering operations and thus not considered relevant. One relevant accident contained within the database occurred on the 26.06.2022 when a storage tank containing methanol exploded due to welding works on its roof.

4.2.6 eNATECH

eNATECH, is an online collaborative system by the European Commission's science and knowledge service, the Joint Research Centre (JRC), and has been operational since 2012 for analysing past accidents and near misses resulting from natural hazards at industrial plants. Accessible to the public at their website [15], the primary goal of eNATECH is the systematic collection of global Natural Hazards Triggering Technological Accidents (Natech) accidents and near misses. The platform facilitates searching and analysis of Natech accident reports, emphasizing support for lessons learned studies. No Natech accident involving the relevant biofuels were found within the 79 recorded accidents in the database as of November 2023.

4.2.7 FACTS

The Failure and Accident Technical Information System (FACTS) database is operated by Unified Industrial & Harbour Fire Department in Rotterdam-Rozenburg. The database contains information on more than 25,700 industrial accidents involving hazardous materials or dangerous goods that have happened around the world during the past 90 years (Environmental Emergencies Center, 2023).

As of November 2023, the website (www.factsonline.nl) is no longer accessible. Using the internet archive services Wayback Machine it can be seen that the site remained online as recent as the spring of 2023, however the database had not received any updates since 2014.

4.2.8 Fireworld Incident log

The Fireworld incident log was a database containing worldwide fire related accidents from 1998 to 2016. According to the internet archive service Wayback Machine, the original domain name (www.fireworld.com) remained online until the end of 2016, after which the site redirects to another domain (https://www.industrialfireworld.com/). This new site did not retain the old incident log, which appears to be no longer available.

4.2.9 IChemE Safety Centre

The Institution of Chemical Engineers (IChemE) is a UK based organization for chemical, biochemical and process engineers. The IChemE's accident database was developed in 1997 and contains over 10 500 entries, with the latest entry made in 2000. The quality of the entries varies, and the cause of accidents and the lessons learned are often omitted. Only one relevant accident involving methanol were found and none for the other biofuels in question. The relevant accident was a Natech accident from 1995 whereas a lightning struck a methanol tank leading to a fire.

[15] https://enatech.jrc.ec.europa.eu

4.2.10 Major accident hazard in biodiesel production processes

In the 2019 paper by Valeria Casson Moreno et all (Moreno, 2019) a database containing 93 accidents in biodiesel production was developed and analysed. Highlights from the report includes that 35% of accidents occur within 1 year from the start of production and 70% occurred withing the first 4 years. Maintenance and operational errors were the more frequent causes of accidents with poor safety cultures being the underlying cause for of several accidents.

The plant unit involved be identified for 80 accidents, with storage tanks being involved in 48% of accidents as seen in Table 4-5. 83% of the accidents occurring in the storage area resulted in either fire, explosion, or multiple scenarios as defined in Table 4-6.

Table 4-5 Plant units involved in reported accidents. The % values are calculated on 80 accidents (85% of the total) where the primary unit involved could be identified (Moreno, 2019).

Plant Unit	% of accidents
Storage Tanks	48%
Process Tanks	18%
Utilities	13%
Pipework	7%
Others	6%
Warehouse	5%
Process Unit	4%

Table 4-6: Definitions of scenarios.

Scenario	Definition
Fire	Ignited release of combustible material
Explosion	Ignited release of combustible material with overpressure effect
Release	Not-ignited release of gas or liquid
Multiple scenario	Combination of above scenarios, happening sequentially or simultaneously
Asphyxia	Access in confined space leading to asphyxiation of the operator

Table 4-7 Correlation between scenarios and causes. Events with “Unknown” causes (29 records) were not considered. The labels refer to the number and % of events having a specific cause within each category of scenario, with [number] denoting the number of accidents. (Moreno, 2019)

Scenario	Component Failure	Equipment Failure	Maintenance Error	Operational Error	Natech[16]	Others
Fire	21% [8]	21% [8]	5% [2]	8% [3]	3% [1]	10% [4]
Explosion	5% [1]	5% [1]	38% [8]	24% [5]	0% [0]	5% [1]
Release	13% [1]	38% [3]	0% [0]	25% [2]	13% [1]	0% [0]
Multiple scenario	8% [2]	8% [2]	29% [7]	8% [2]	0% [0]	0% [0]

A few relevant accidents can be seen in Table 4-5.

[16] Natural Hazards Triggering Technological Accidents

Table 4-8: Sample accidents from *Major accident hazard in biodiesel production processes.*

Date	Accident Description
02.08.2013	**Tank collapse**. The plant was at normal operating conditions when possibly the biodiesel level in a 760 m3 fuel storage dropped below the regulated level and so that the roof of the tank collapsed.
26.08.2009	**Tank explosion during hot work**. Seven workers were working to connect a pipeline to a tank when there was a spark causing the explosion.
22.11.2008	**Lightning strike causing fire**. A lightning stroke on a biodiesel facility, leading to a fire. The building collapsed.
15.04.2008	**Tank explosion during maintenance**. A worker and a subcontractor were creating a new fitting for a malfunctioning sensor on 3 biodiesel settling tanks (9 m). The tanks were drained, only one of them was purged using compressed air. The subcontractor welded the first tank, and then he started welding the second when fumes and methanol inside ignited by heating and caused an explosion, tearing off a chunk of the roof and blowing a hole in the building.

4.2.11 MHIDAS

The Major Hazard Incident Data Service (MHIDAS) was launched in 1986 by the UK Health and Safety Executive (HSE), and the database contained more than 9000 reports from 1950 until the end of the 1990s. The database appears to be unavailable online, and no further efforts was made to include it in this study due to the age of its most recent entry (European Environment Agency, 2016).

4.2.12 Methanol Safe Handing Manual

Appendix D of the Methanol Safe Handling Manual by the Methanol Institute (Methanol Institute, 2013)[17] contains a database of 162 methanol related incidents. 81 of these were used for further analysis within the report. Its findings mirror that from 4.2.3 and 4.2.10 in that the maintenance-related issues account for most incidents with known causes, with equipment and component failure accounting for the rest. Similar to 4.2.3 hot work on or around storage tanks is identified as a major cause of fatal incidents. 5 safeguards are proposed as key elements to effectively handle the safety risks involved with methanol for users and can be seen in Table 4-6.

Table 4-9: Methanol Safe Handling Manual Safeguards.

Safeguard	Description
Process Safety Management	Process Safety Management (PSM) is a safety management system that has been in effect in the chemical industry for more than 20 years. The methanol specific PSM process is described in detail in Chapter 5 of the Methanol Safe Handling Manual.
Corrosion Prevention	Liquid methanol is electrically conductive compared to natural gas and distilled fuels. Because of its high conductivity, containers holding methanol are more susceptible to galvanic corrosion than containers holding hydrocarbons like gasoline. Conductivity increases corrosion of alloys commonly used to handle natural gas and distillate fuel. This is particularly true for aluminium and titanium alloys. Additionally, methanol is a solvent and is compatible with only selected plastics and rubbers. Plastic containers commonly used for gasoline may lose structural integrity when used to hold methanol and must be replaced with more corrosion- and solvent-resistant materials. Storage containers and pipeline conveyance systems should not be used in methanol or methanol vapour service without a rigorous mechanical integrity program.

[17] Methanol Safe Handling Manual

Safeguard	Description
Hot Work Permit Program	The hazards associated with hot work can be reduced by implementing an effective hot work permit program. This should include prior work authorization, safe welding practices, and a fire watch. See Section 4.3, Safety Precautions, in the Methanol Safe Handling Manual for additional information.
Fire Prevention and Response	The three key aspects of fire response are early detection, immediate response, and appropriate action. While the particular application of these principles may vary, a well-planned and developed system depends on training, equipment, and practice. See Chapter 6 in the Methanol Safe Handling Manual for more information.
Employee Training	It is the employer's responsibility to inform all employees of the hazards and risks associated with methanol and to inform them on how to effectively control those risks. Operating personnel need to be trained in interpreting and applying the written operating procedures, as well as those for upset conditions and emergency response. See section 8.4.5 in the Methanol Safe Handling Manual for additional information.

4.2.13 NCR

The United States National Response Centre (NRC) serves as an emergency call centre that is the designated federal point of contact for reporting all oil, chemical, radiological, biological, and etiological discharges into the environment, anywhere in the United States and its territories.

Its database consists of annual reports containing the dataset from a given year. The annual reports from 2018 to 2023 consisted of 142 816 reported calls. All spills involving biofuels (except methanol) spill can be seen in Table 4-7 and a selected number of calls related to methanol can be seen in Table 4-8.

Table 4-10: NCR incidents involving biofuels except methanol.

Call Nr.	Accident Description
1326296	The caller stated while attempting to hook into a vessel, a hose for the port facility was not purged properly. Because of this, bio-diesel released onto the pier and into the Hilo port. The amount of bio-diesel that released is unknown; however, the caller suspects around 10-12 gallons may have released. The cause of the incident was attributed to operator error.
1336217	Caller is reporting the release of 250 gallons of biofuel from a tanker truck during transfer. The released material went onto the pavement, and an unknown amount went into a storm drain that leads to New Haven Marina. The cause of the release is due to equipment failure.
1337490	Caller is reporting the discharge of bio-diesel into the Houston Ship Channel due to a pinhole leak in a loading hose at the transfer facility.
1366451	Caller is reporting a release of approx. 100 gallons of bio-diesel with less than 10 gallons leaving containment and hitting the street and storm drains. This was caused by a failed valve on the filter feed tank. The release has been secured. Containment and clean-up actions are underway.
1297930	Caller is reporting a discharge of approximately 0.25 pints of bio-diesel onto the deck of a barge and into the Kill Van Kull at the incident location. Discharge was a leaking insulating flange on a barge while taking on cargo.
1301037	The caller states approximately 60-70 barrels of bio-diesel fuel released from a tank line from the facility. The cause of the release was a blown gasket on a flange. The material released onto the ground.
1301752	Caller is reporting that on Pier 5 Buoy, the USCG flange on the valve on a line at the pier is discharging bio-diesel into the water. Caller states the amount discharged is less than a gallon.

Call Nr.	Accident Description
1324105	Caller is reporting a discharge of approximately 100 gallons of bio-diesel fuel into containment, through an outfall, and into a pond at the incident location. Discharge was from an unknown source at this time. Caller stated the spill left the containment area because a valve was left open.
1269589	The caller is reporting bio-diesel was discharged onto the roadside and into an unknown creek from a tractor-trailer due to a gasket leaking from lack of maintenance. The caller notes that the company has covered the discharge with sand on the roadside.
1271449	Caller reported a runaway barge struck another barge that was offloading at a petroleum storage facility, which caused a biodiesel release into the Mississippi River.
1287998	Caller reported biodiesel was released from a pipe from three storage tanks on the grounds at a private residence.
1238722	Caller reported 100 pounds of vegetable oil was released onto the ground, and some entered the San Joaquin River from a broken clean-up valve due to equipment failure.
1240223	Caller reported while fuelling a boat, a fuel pump leaked biodiesel at a pier and into the bay due to equipment failure.
1208797	Caller is reporting a 1-gallon discharge of biofuel to the Savannah River due to operator error when the containment bucket was accidentally hit while changing out hoses. The facility owns the hose.

Table 4-11: Selected NCR incidents involving methanol.

Call Nr.	Accident Description
1378769	Methanol released from a storage tank due to a mechanical failure on a man-way bolt.
1358763	Caller states 21,273 gallons of methanol was released onto the dirt within a berm area. The release was from an open bleeder valve on a storage tank at the tank farm.
1383029	Caller is reporting the release of 19,226 gallons of methanol from a storage tank. The released material went into containment. The cause of the release is due to operator error.
1331787	Caller reports a wind blew a box truck off the road during a snowstorm. This truck was carrying 13 300-gallon totes of methanol. 10 of these totes were damaged and discharged 3000 gallons onto a pasture ground. No waterways were impacted. The release is secured.
1337661	Caller reported the release of about 997 gallons of methanol from a leak that developed in an underground flow line. The release impacted the soil ground at the incident location. The cause of the leak in the line is under investigation. No storm drains were impacted by the release.
1322497	Caller is reporting that a tractor-trailer operator opened a valve on the tanker trailer, per protocol, and unknowingly released liquid methanol onto the ground.
1269862	Caller reporting the release of methanol due to a burst hose. Caller reports that employees were instructed by management to wash it all down the drain and that the employees got light-headed from breathing in the fumes.

4.2.14 NTSB CAROL

The United States National Transportation Safety Board (NTSB) maintains a database containing investigations and recommendations related to transportation accidents. This database is accessed through the Case Analysis and Reporting Online (CAROL) portal[18]. A few transportation accidents with methanol as cargo were identified, but not considered relevant to bunkering operations.

4.2.15 OSHA

The U.S. Occupational Safety and Health Administration (OSHA) database is a centralized repository of information related to occupational accidents in the United States. Fatality and Catastrophe Investigation Summaries (OSHA 170 form) are developed after OSHA conducts an inspection in response to a fatality or catastrophe. The summaries provide a complete description of the incident, generally including events leading to the incident and causal factors. These summaries can be searched by keyword, text in the summary description, event date, and industry (OSHA, 2023). At the time of writing (November 2023) the database contained concluded investigations from 1984 until November 2022. Relevant accidents can be seen in Table 4-9.

Table 4-12: Relevant accidents from the OSHA database.

Title and ID	Accident Description
Employee Using Torch On Tank Is Killed In Explosion (200231801)	On July 7, 2006, Employee #1 was working on top of a twenty-two-foot-high steel tank, using an oxyacetylene torch to install a vent. The tank apparently contained some glycerine and methanol from the making of biodiesel fuel, and it exploded. Employee #1 received burns to several parts of his body, and he was killed. It is probable that the flame from the torch ignited the vapours, causing the explosion and subsequent fire.
Employee Is Engulfed In Fuel Fire, Dies (200151645)	On December 30, 2011, Employee #1 was transferring biofuel for a distributer of consumer fuel products. The valve involved in the transfer process for biofuel was blocked. In an effort to break up the blockage, the employee used a propane torch to heat the valve. A hose leading from the truck to the vale suddenly burst, spraying Employee #1 with fuel. The fuel ignited, engulfing the employee in flames. Employee #1 was transported to an area hospital, where he was pronounced dead.
Employee Is Burned In Chemical Fire (27155.015)	At 9:00 p.m. on August 24, 2012, an employee was stirring 180-gallon mixture of Sulfuric Acid (30 gallons) and Methanol (150 gallons) with a piece of PVC pipe while in a cage tote. As the employee stirred the chemicals, a static electricity charge built up in the cage tote and the chemicals exploded causing a fire. The employees' entire body was burned in the fire.
Employee Is Killed By Explosion (200262822)	Employee #1 was working in the hydrogenation area when he removed the lid from Converter Number 1 and placed it on the ground next to the approximately 25-in.-diameter opening to the converter. Employee #1 then removed the gasket from around the lid and used a wire-brush grinder to remove the silicone that had sealed the gasket to the lid. Converter Number 1 contained a mixture of vegetable oil and hydrogen. While Employee #1 was grinding the lid, sparks mixed with the hydrogen and exploded. Employee #1 was thrown approximately 7 ft into the air and onto some overhead pipes. Employee #1's right arm was severed, and he was killed.

[18] data.ntsb.gov/carol-main-public/

4.2.16 JST Failure Knowledge Database

The JST Failure Knowledge Database was launched in 2005 by the Japan Science and Technology Agency (JST) and later transferred to the NPO, Association for the Study of Failure. The database is a repository of accident and failure data, designed to facilitate organizational learning from past incidents. The database categorizes analyses of accidents and failures into 16 categories, offering insights into lessons learned. Its primary objective is to prevent recurring incidents, fostering improvements in technology reliability and safety (Japan for Sustainability, 2005).

The database does not appear to have been updated since its launch, with 2004 being the most recent accident in the database (Failure Knowledge Database, 2023).

4.2.17 Tukes VARO registry

The Safety and Chemicals Agency of Finland, known as "Tukes" in Finnish ("Turvallisuus- ja kemikaalivirasto"). Tukes is a governmental agency responsible for overseeing and regulating various aspects related to safety, chemicals, and consumer protection in Finland. The VARO registry used to contain information regarding chemical accidents in Finland but has recently been closed to public (Tukes - Finnish Safety and Chemicals Agency, 2023)

4.2.18 ZEMA

The German Central Reporting and Evaluation Office for Major Accidents in Process Engineering Facilities (ZEMA) is a database, containing mostly events occurred in the German territory. It is managed by "Umweltbundesamt" (UBA), the main environmental protection agency in Germany. As of November 2023, the database contains 952 recorded accidents ranging from 1980 to 2023 (ZEMA, 2023).

The database contained no relevant accidents except for a Natech accident in 1994 where a methanol storage tank caught fire because of a lightning strike, and a tank explosion accident triggered by welding work.

5. Review and assessment of PPE

This chapter presents the findings of the examination of Personal Protective Equipment (PPE) for the selected biofuels as indicated in their respective Safety Data Sheets. The appropriate level of PPE for different scenarios is contingent upon the specific situation and the preceding risk assessment conducted before fuel handling. Both the exposure risk (e.g., low risk vs. high risk) and the classification of the substance to be transferred (e.g., very toxic cargoes vs. corrosive cargoes) play a role in determining the type of Personal Protective Equipment (PPE) that each crew member must use.

5.1 Bio-Methanol[19]

Exposure to methanol, and thus bio-methanol, may transpire through inhalation, skin absorption, ocular contact, or ingestion during its utilization or handling. The degree of risk associated with methanol exposure determines the appropriate level of personal protective equipment.

As a baseline, it is advisable to use safety glasses with side shields or safety goggles in conjunction with task-specific gloves. Depending on the specific circumstances, additional personal protective equipment may be necessary. Table 5-1 offers guidance on the appropriate personal protective equipment contingent on the presented situation:

Table 5-1: PPE Guidance table (Methanol Institute).

LOW RISK OF VAPOUR/ LOW RISK OF VOLUME SPLASH	HIGH RISK OF VAPOUR/LOW RISK OF VOLUME SPLASH	HIGH RISK OF VAPOUR/ HIGH RISK OF VOLUME SPLASH
Fire Retardant Clothing	Full Chemical Resistant Suit	Full Chemical Resistant, Impermeable Suit
Gloves (Silvershield or Disposable Nitrile)	Chemical-Resistant Rubber Gloves	Chemical-Resistant Rubber Gloves
Safety Glasses with Side Shields	Full Face Supplied Air Respirator	SCBA or Compressed Air Breathing Apparatus (CABA)
Full Boot Cover	Chemical-Resistant Anti-Static Rubber Boots	Chemical-Resistant Anti-Static Rubber Boots

Numerous Material Safety Datasheets, compliant with CLP regulations, are available in the market to provide guidance on the minimum Personal Protective Equipment (PPE) requirements for methanol. For instance, the following outlines the minimum PPE recommendations according to Sigma Aldrich (Sigma-Aldrich, 2023).

- **Eye/face protection**: face shield and safety glasses (eye protection tested and approved under appropriate government standards such as NIOSH (US) or EN 166(EU)).
- **Skin protection**:
    - Full contact
        - Material: butyl-rubber
        - Minimum layer thickness: 0,7 mm
        - Break through time: > 480 min
        - Material tested: KCL 898 Butoject®
    - Splash contact
        - Material: Viton®
        - Minimum layer thickness: 0,7 mm
        - Break through time: > 120 min

[19] Based on Methanol Safety Data Sheet (SDS) from Sigma Aldrich

    - Material tested: KCL 890 Vitoject®

- **Body Protection**: complete suit protecting against chemicals, flame retardant antistatic protective clothing. The type of protective equipment must be selected according to the concentration and amount of the dangerous substance at the specific workplace.
- **Respiratory protection**: where risk assessment shows air-purifying respirators are appropriate use a full-face respirator with multi-purpose combination (US) or type AXBEK (EN 14387) respirator cartridges as a backup to engineering controls. If the respirator is the sole means of protection, use a full-face supplied air respirator. Use respirators and components tested and approved under appropriate government standards such as NIOSH (US) or CEN (EU).

5.2 Bio-FT Diesel[20]

Given the similarities to traditional marine distillates, it is reasonable to presume that comparable PPE can be utilized when handling bio-FT-diesel. The same would be applicable for FT-diesels made from fossil sources. According to the Safety Data Sheet for GtL FT-Diesel (BP, 2023a), the following delineates the minimum required Personal Protective Equipment (PPE):

- **Eye/face protection**: Chemical splash goggles. For eye protection refer to standard EN 166.
- **Hand protection**: safety procedures should be developed for each intended application. Chemical resistant gloves should be used. Glove thickness may vary depending on the activity being conducted, but recommended thickness is typically greater than 0.35mm. For continuous contact, wear gloves with a minimum breakthrough time of 240 minutes, or >480 minutes. Fort short term and splash contact, gloves with shorter breakthrough times may be used, but it is recommended to use the same as for continuous contact. For gloves, refer to standard EN 420 or EN 374.
- **Other skin and body protection**: Wear footwear highly resistant to chemicals. When there is a risk of ignition, wear inherently fire-resistant protective clothes and gloves (ISO 11612). When there is a risk of ignition from static electricity, wear anti-static protective clothing (EN 1149). When the risk of skin exposure is high then a chemical protective suit and boots will be required.
- **Respiratory protection**: Wear suitable respiratory protective devices if there is a risk of exposure limits being exceeded. The choice of suitable respiratory device will depend upon a risk assessment of the workplace environment and the task being carried out. Refer to standard EN 529 for further guidance on the selection, use, care and maintenance of respiratory protective devices.

5.3 Bio-DME[21]

Based on the similarities with LPG fuel, it is reasonable to infer that the PPE employed during fuel handling of DME is likewise comparable. The Safety Data Sheet for DME from Sigma Aldrich suggest protective equipment for use during handling (Sigma-Aldrich, 2023). The following equipment should be worn:

- **Eye/face protection**: Safety glasses. Use equipment for eye protection tested and approved under appropriate government standards such as NIOSH (US) or EN 166(EU).
- **Skin protection**: Recommendation only applies to the product stated in this safety data sheet, supplied by the supplier as stated and for the designated use. For splash contact:
    - Material: Nitrile rubber
    - Minimum layer thickness: 0.4 mm
    - Break through time: 10 min
    - Material tested: Camatril® (KCL 730 / Aldrich Z677442, Size M)
- **Body Protection**: Flame retardant antistatic protective clothing.
- **Respiratory protection**: required when vapours/mists are generated. Recommended Filter type: Filter type ABEK. Recommendations are based on the following standards: DIN EN 143, DIN 14387 and other

[20] From BP Safety Data Sheet, Distillates (Fischer-Tropsch), C8-26, branched and linear
[21] From Sigma Aldrich Safety Data Sheet, Dimethyl ether

accompanying standards relating to the used respiratory protection system. The entrepreneur must ensure that maintenance, cleaning and testing of respiratory protective devices are carried out according to the instructions of the producer. These measures must be properly documented.

5.4 HVO[22]

According to the Safety Data Sheet from Neste (Neste, 2023), the following represents the minimum required Personal Protective Equipment (PPE). Given the similarities to traditional marine distillates, it is reasonable to presume that comparable PPE can be utilized when handling HVO.

- **Eye/face protection**: Spectacles.
- **Hand protection**: Utilize protective gloves made of materials such as Nitrile rubber, Neoprene, or Polyvinyl chloride (PVC). It is important to note that the breakthrough time for any glove material may vary among different manufacturers, necessitating regular glove changes.
- **Other skin and body protection**: Wear protective clothing as needed, and if there is a risk of ignition from static electricity, use anti-static protective clothing.
- **Respiratory protection**: Employ respiratory protection when the airborne contamination surpasses the recommended occupational exposure limit. Wear a respirator equipped with a combination filter, type A2/P2, and ensure the filter is replaced regularly. In instances of high concentrations, a breathing apparatus must be utilized, either in the form of a self-contained breathing apparatus or a fresh air hose breathing apparatus.

5.5 FAME[23]

Because of the chemical composition of FAME, which is not solely a hydrocarbon fuel, there may be distinctions in handling compared to traditional marine diesel. This is particularly evident due to its incompatibility with certain materials and its solvency effects. As per the REG Safety Data Sheet for biodiesel (B99.9), the minimum required Personal Protective Equipment (PPE) are as follows (REG, 2022):

- **Eye/face protection**: Safety glasses. If potential of splash, use splash resistant googles and face shield.
- **Hand protection**: For incidental contact, use disposable nitrile or other similar chemical-resistant gloves. For more substantial contact, wear thicker nitrile or other similar chemical-resistant gloves. Note that the product will cause natural rubbers to degrade at a very rapid rate.
- **Other skin and body protection**: Wear protective garments, such as a chemical apron, chemical resistant coveralls, or chemical resistant coat and pants, along with impervious oil-resistant boots.
- **Respiratory protection**: No exposure limits are available, but appropriate organic vapour or supplied air respiratory protection may be worn if irritation or discomfort is experienced. Respiratory protection must be provided and used in accordance with all local, state, and federal regulations.

[22] From Neste Safety Data Sheet, Neste MY Renewable Diesel
[23] From REG Safety Data Sheet, Biodiesel (B99.9)

6. Preliminary Table of Content, Goals and Functional Requirements

Based on the review of relevant existing rules, regulations, guidelines, standards and best practises, a basis for a preliminary Table of Content of the Guidance document is established and included in Annex 1. The guidance document will include a chapter on Risk assessment frameworks to highlight what type of risk assessment can be applied to identify potential hazards and risks associated with the activities or technologies related to bunkering of biofuels. The structure of the guidance follows the generic guidelines for developing IMO goal-based standards MSC.1/Circ.1394/Rev.2 in the sense that it is structured into (0) Hazards in order to justify functional and technical requirements (1) Goals, (2) Functional Requirements, (3) Technical Requirements and (4) Scope and Criteria for Verification stemming from identified hazards. Furthermore, each technical requirement/recommendation will be accompanied by a brief justification explaining the reasons why such a technical requirement is needed (e.g., based on the actual status of the technology, experience with other similar equipment or systems, best engineering practices, common bunkering arrangements etc). Some examples of possible technical requirements could be:

- Chapter 9 – Hoses should be designed for use with the specific biofuel and be able to handle necessary loads.
- Chapter 11 – The bunkering connection should be able to conduct a dry-disconnect operation.
- Chapter 11 – The transfer system should have a maximum transfer rate and can maintain dry break integrity without leakage during emergency breakaway.
- Chapter 15 – An emergency shutdown system should be in place, minimising loss of fuel during emergencies. Emergency shutdown should be initiated on: fire/leakage detection, power failure, tanks overflowing, abnormal pressure, loss of vessel control, drip-tray overfilling, loading arm overstressed, etc.
- Chapter 18 – A dedicated, manifold and hose watch should monitor the bunkering operation and have direct contact with the person in charge (PIC) of the supplier and receiver.
- Chapter 20 – Depending on the specific biofuel characteristics personnel in close proximity to the bunkering operation should wear a hard hat with face shield, safety boots, gloves with protective sleeves and non-static electricity accumulating, flame retardant clothing.

The Guidance will include operational recommendations in the form of safety checklists, e.g., for documentation review and visual assessment, for the different operational phases (pre-bunkering, simultaneous operations, and post-transfer) based on risk mitigation measures identified for all or in particular for some bunkering configurations. The Guidance will also include recommendations for handling emergencies.

The overall goal of the Guidance document on safe bunkering of biofuels is: *similar, equivalent or better safety and reliability for biofuel bunkering operations in comparison to the bunkering of conventional fuels.*

The preliminary functional requirements needed for the guidance document are listed in Table 6-1 below. The number refers to the chapter in the preliminary structure of the guidance document (as included in Annex 1).

Table 6-1: Preliminary Functional Requirements as per Guidance Table of Contents.

FUNCTIONAL REQUIREMENTS	REFERENCE
8 - Ship Design and Arrangement for Bunkering Operations	**IGF Code**
■ The safety, reliability and dependability of the systems shall be equivalent to that achieved with new and comparable conventional oil-fuelled main and auxiliary machinery. ■ The probability and consequences of fuel-related hazards shall be limited to a minimum through arrangement and system design, such as ventilation, detection, and safety actions. In the event of leakage or failure of the risk reducing measures, necessary safety actions shall be initiated.	

FUNCTIONAL REQUIREMENTS	REFERENCE
■ The fuel tank(s) shall be located in such a way that the probability for the tank(s) to be damaged following a collision or grounding is reduced to a minimum taking into account the safe operation of the ship and other hazards that may be relevant to the ship. ■ Fuel containment systems, fuel piping and other fuel sources of release shall be so located and arranged that released fuel is led to a safe location. ■ The access or other openings to spaces containing fuel sources of release shall be so arranged that flammable, asphyxiating or toxic gas cannot escape to spaces that are not designed for the presence of such gases fuel piping shall be protected against mechanical damage. ■ The propulsion and fuel supply system shall be so designed that safety actions after any fuel leakage do not lead to an unacceptable loss of power. ■ The probability of an explosion in a machinery space with fuelled machinery shall be minimized.	
9 - Fuel Containment System for Bunkering Operations	**IGF Code**
■ Fuel containment system and machinery spaces containing source that might release fuel into the space shall be arranged and located such that a fire or explosion in either will not lead to an unacceptable loss of power or render equipment in other compartments inoperable. ■ The fuel containment system shall be so designed that a leak from the tank or its connections does not endanger the ship, persons on board or the environment. Potential dangers to be avoided include: ■ Exposure of ship materials to temperatures below acceptable limits. ■ Flammable fuels spreading to locations with ignition sources. ■ Toxicity potential and risk of oxygen deficiency due to fuels and inert gases. ■ Restriction of access to muster stations, escape routes and life-saving appliances (LSA). ■ Reduction in availability of LSA. ■ The pressure and temperature in the fuel tank shall be kept within the design limits of the containment system and possible carriage requirements of the fuel. ■ The fuel containment arrangement shall be so designed that safety actions after any fuel leakage do not lead to an unacceptable loss of power. ■ If portable tanks are used for fuel storage, the design of the fuel containment system shall be equivalent to permanent installed tanks.	
10 - Material and General Ship Design for Bunkering Operations	**IGF Code**
■ The design philosophy shall ensure that risk reducing measures and safety actions for the fuel installation do not lead to an unacceptable loss of power. ■ Fuel piping shall be capable of absorbing thermal expansion or contraction caused by extreme temperatures of the fuel without developing substantial stresses. ■ Provision shall be made to protect the piping, piping system and components and fuel tanks from excessive stresses due to thermal movement and from movements of the fuel tank and hull structure. ■ If the fuel gas contains heavier constituents that may condense in the system, means for safely removing the liquid shall be fitted. ■ Low temperature piping shall be thermally isolated from the adjacent hull structure, where necessary, to prevent the temperature of the hull from falling below the design temperature of the hull material.	
11 - Bunkering Infrastructures	**IGF-code & ISO 20519**

FUNCTIONAL REQUIREMENTS	REFERENCE
■ It shall be arranged for safe and suitable fuel supply, storage and bunkering arrangements capable of receiving and containing the fuel in the required state without leakage. Other than when necessary for safety reasons, the system shall be designed to prevent venting under all normal operating conditions including idle periods. ■ The piping system for transfer of fuel to the storage tank shall be designed such that any leakage from the piping system cannot cause danger to personnel, the environment or the ship.	
12 - Fire Safety during Bunkering Operations	**IGF Code**
■ Fire detection, protection and extinction measures appropriate to the hazards concerned shall be provided. ■ Hazardous areas shall be restricted, as far as practicable, to minimize the potential risks that might affect the safety of the ship, persons on board, and equipment.	
13 - Explosion and Toxic Exposure Protection during Bunkering Operations	**IGF Code**
■ Unintended accumulation of explosive, flammable or toxic gas concentrations shall be prevented. ■ Sources of ignition in hazardous areas shall be minimized to reduce the probability of explosions.	
14 - Electric Installations for Bunkering Operations	**IGF Code**
■ System components shall be protected against external damages. ■ Equipment installed in hazardous areas shall be minimized to that required for operational purposes and shall be suitably and appropriately certified. ■ Electrical generation and distribution systems, and associated control systems, shall be designed such that a single fault will not result in the loss of ability to maintain fuel tank pressures and hull structure temperature within normal operating limits.	
15 - Control, Monitoring and Safety Systems for Bunkering Operations	**IGF Code**
■ A single failure in a technical system or component shall not lead to an unsafe or unreliable situation. ■ A fuel safety system shall be arranged to close down the fuel supply system automatically, upon critical failure in systems and upon other fault conditions which may develop too fast for manual intervention. ■ For ESD protected machinery configurations the safety system shall shutdown fuel supply upon fuel leakage and in addition disconnect all non-certified safe type electrical equipment in the machinery space. ■ The safety functions shall be arranged in a dedicated fuel safety system that is independent of the fuel control system in order to avoid possible common cause failures. This includes power supplies and input and output signal. ■ The safety systems including the field instrumentation shall be arranged to avoid spurious shutdown, e.g., as a result of a faulty leak detector or a wire break in a sensor loop. ■ Where two or more fuel supply systems are required to meet the regulations, each system shall be fitted with its own set of independent fuel control and fuel safety systems.	
16 - Manufacture, Workmanship and Testing of Bunkering Equipment	**IGF Code**
■ Commissioning, trials and maintenance of fuel systems and fuel utilization machinery shall satisfy the goal in terms of safety, availability, and reliability. ■ Machinery, systems and components shall be designed, constructed, installed, operated, maintained and protected to ensure safe and reliable operation.	

FUNCTIONAL REQUIREMENTS	REFERENCE
■ The technical documentation shall permit an assessment of the compliance of the system and its components with the applicable rules, guidelines, design standards used, and the principles related to safety, availability, maintainability and reliability.	
17 - Drills and Emergency Exercises for Bunkering Operations	**IGF Code**
■ Drills and emergency exercises on board shall be conducted at regular intervals.	
18 – Bunkering operation	**IGF Code**
■ Maintenance procedures and information for all fuel related installations shall be available on board ■ The ship shall be provided with operational procedures including a suitably detailed fuel handling manual, such that trained personnel can safely operate the fuel bunkering, storage and transfer systems ■ The ship shall be provided with suitable emergency procedures	
19 – Training for Bunkering Operations	**IGF Code & STCW**
■ Companies shall ensure that seafarers on board ships using biofuels shall have completed training to attain the abilities that are appropriate to the capacity to be filled and duties and responsibilities to be taken up, taking into account the provisions given in the STCW Convention.	
20 - Personnel Protection during Bunkering Operations	**IBC Code**
■ For the protection of crew members who are engaged in loading and discharging operations, the ship shall have on board suitable protective equipment consisting of large aprons, special gloves with long sleeves, suitable footwear, coveralls of chemical-resistant material, and tight-fitting goggles or face shields or both. The protective clothing and equipment shall cover all skin so that no part of the body is unprotected. ■ Work clothes and protective equipment shall be kept in easily accessible places and in special lockers. Such equipment shall not be kept within accommodation spaces, with the exception of new, unused equipment and equipment which has not been used since undergoing a thorough cleaning process. The Administration may, however, approve storage rooms for such equipment within accommodation spaces if adequately segregated from living spaces such as cabins, passageways, dining rooms, bathrooms, etc. ■ Protective equipment shall be used in any operation, which may entail danger to personnel.	

7. References

(2023). Retrieved from ZEMA: https://www.infosis.uba.de/index.php/en/zema/index.html

A, N. (2021). Investigating occupational and operational industrial safety data through Business Intelligence and Machine Learning. *Journal of Loss Prevention in the Process Industries, Volume 73*.

AGQM Biodiesel e.V. (2020). *Safedy Data Sheet, REG Eco Premium Biodiesel, version 4.*

AIHA. (2013). *Odor Thresholds for Chemicals with Established Health Standards, 2nd Edition.* American Industrial Hygiene Association (AIHA).

Ajdari, S. (n.d.). *Biomethanol production and use as fuel.* ETIP Bioenergy.

ARIA. (2023). *The ARIA Database*. Retrieved from https://www.aria.developpement-durable.gouv.fr/the-barpi/the-aria-database/?lang=en

ASTM. (2021). D1655-21c - Standard Specification for Aviation Turbine Fuels.

ASTM. (2022). ASTM D7566-21 - Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.

ATSM. (2023). ASTM D4054-22 - Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives.

Bezergianni, S., & Dimitriadis, A. (2013). Comparison between different types of renewable diesel. *Renewable and Sustainable Energy Reviews Volume 21*, 110-116.

BP. (2021, May 14). *BP DMA Marine Distillate Low Sulphur.* Retrieved from Data Sheets: https://www.bp.com/en_au/australia/home/products-services/data-sheets.html

BP. (2023, July 12). Safety Data Sheet BP HVO, Product code SBX2314.

BP. (2023a). *Safet Data Sheet Distillates (Fischer-Tropsch), C8-26, branched and linear.*

CDCP. (2023). *Centers for Disease Control and Prevention*. Retrieved from The National Institute for Occupational Safety and Health (NIOSH): https://www.cdc.gov/niosh/idlh/intridl4.html

CEN17540. (2020). CEN/CWA 17540 - Specification for bunkering of methanol fuelled vessels.

CFR. (2023). CFR 33 part 127 - Waterfront Facilities Handling LHG.

Chemicalbook. (2023, November). *Chemical Safety Data Sheet MSDS / SDS, Dodecane*. Retrieved from https://www.chemicalbook.com/msds/dodecane.htm

Chevron. (2023, November). *Chevron Marine Products - Safety Data Sheets for distillate marine gas oil (DMA-DMZ).* Retrieved from https://www.chevronmarineproducts.com/en_mp/home/fuel-ports/safety-data-sheets.html?src-tab=products

CIMAC. (2013). *Guidline for Ship owners and Operators on Managing Marine Distillate Fuels Containing up to 7.0 % v/v FAME (Biodiesel).* INTERNATIONAL COUNCIL ON COMBUSTION ENGINES (CIMAC).

CONCAWE. (2009). *Report no. 9/09 Guidelines for handling and blending FAME.*

CSB. (2010). *Seven Key Lessons to Prevent Worker Deaths During Hot Work In and Around Tanks.*

CTIF World Fire Statistics Center. (2023). *World Fire Statistics 2023, No. 28.* International Association of Fire and Rescue Services.

DNV. (2022). *Nordic Roadmap Publication No. 1-B/2/2022: Fuel properties and their consequences for safety and operability.* Nordic Roadmap.

DNV. (2023). DNV-RU-SHIP Part 6. *Rules for Classification* .

E4Tech. (2018). *Master plan for CO2 reduction in the Dutch shipping sector.* E4Tech.

ECHA . (2023, December). *European Chemicals Agency*. Retrieved from Substance Infocard, Methanol: https://echa.europa.eu/de/substance-information/-/substanceinfo/100.000.599

ECHA. (2023, December). *European Chemicals Agency*. Retrieved from SCIP database: https://echa.europa.eu/

eMars. (2023). *About eMars*. Retrieved from https://emars.jrc.ec.europa.eu/en/emars/content

Emerging Fuels Technology. (2021). *Fischer Tropsch Diesel - Preliminary Product Specification.* Retrieved from https://emergingfuels.com/wp-content/uploads/2021/10/EFT-FT-Diesel-Spec-Oct-11-2021.pdf

EMSA. (2022). *Update on potential of biofuels in shipping.* Lisbon: European Maritime Safety Agency.

Environmental Emergencies Center. (2023). *FACTS Chemical Accident Database (Failures and Accidents Technical Information System)*. Retrieved from https://eecentre.org/resources/facts-chemical-accident-database/#:~:text=The%20FACTS%20(Failure%20and%20Accidents,during%20the%20past%2090%20years.

EPA. (2023). Retrieved from 40 CFR Part 68: https://www.ecfr.gov/current/title-40/part-68

European Commission, Joint Research Centre, Necci, A. Krausmann, E. (2022). *Introduction to eNATECH - A user guide.* Publications Office of the European Union.

European Committee for Standardization. (2019). *EN 14214:2012+A2:2019, Liquid petroleum products - Fatty acid methyl esters (FAME) for use in diesel engines and heating applications - Requirements and test methods.*

European Committee for Standardization. (2021). *EN 16942:2016+A1:2021 Fuels - Identification of vehicle compatibility - Graphical expression for consumer information.*

European Committee for Standardization. (2023). *EN 15940:2023 Automotive fuels - Paraffinic diesel fuel from synthesis or hydrotreatment - Requirements and test methods.*

European Environment Agency. (2016). *Information sources*. Retrieved from https://www.eea.europa.eu/publications/GH-07-97-595-EN-C2/iss2c2h.html

ExxonMobil. (2018, May 08). Retrieved from SAFETY DATA SHEET: https://www.bunkeroil.no/Userfiles/Upload/files/Marine%20Gas%20Oil_ENG.pdf

f3 Innovation Cluster for Sustainable Biofuels. (2017, April). *Biomass based Dimethyl ether, DME.* Retrieved from Dimethyl ether, DME: https://f3centre.se/en/fact-sheets/dimethyl-ether-dme/

Failure Knowledge Database. (2023). Retrieved from https://www.shippai.org/fkd/en/index.html

FCBI Energy. (2015). *Methanol as a marine fuel.* Methanol Institute.

German Maritime Centre. (2021). Bunker Guidance for Alternative Fuels in German Seaports.

Greenergy. (2023, November). *Technical product information.* Retrieved from https://www.greenergy.com/technical-product-information

Gulf Oil. (2023, November). *Safety Data Sheets.* Retrieved from https://gulfoil.com/safety-data-sheets

IATA. (2020). Sustainable Aviation Fuel: Technical Certification.

IEA AMF. (2023). *Technology Collaboration Programme on Advanced Motor Fuels*. Retrieved from Dimethyl ether (DME): https://www.iea-amf.org/content/fuel_information/dme

IEA Bioenergy. (2023). *Facilities, Global database of biomass conversion facilities, including advanced biofuels, combustion, gasification and pyrolysis plants*. Retrieved from IEA Bioenergy: https://www.ieabioenergy.com/installations/

ILO. (2023). *International Chemical Safety Cards (ICSCs)*. Retrieved from Dimethyl Ether: https://www.ilo.org/dyn/icsc/showcard.listcards3?p_lang=en

IMO. (1973). MARPOL.

IMO. (1983). MARPOL - Annex 1.

IMO. (1983). MARPOL - Annex 2.

IMO. (2010). SOLAS.

IMO. (2013). ISM Code.

IMO. (2017). IGF Code - INTERNATIONAL CODE OF SAFETY FOR SHIPS USING GASES OR OTHER LOW-FLASHPOINT FUELS (IGF CODE).

IMO. (2018). MEPC.1/Circ.875 - Guidance on best practice for fuel oil purchasers/users for assuring the quality of fuel oil used on board ships.

IMO. (2018). MEPC.1/Circ.875 - GUIDANCE ON BEST PRACTICE FOR FUEL OIL PURCHASERS/USERS FOR ASSURING THE QUALITY OF FUEL OIL USED ON BOARD SHIPS.

IMO. (2018). MEPC.1/Circ.879 - GUIDELINES FOR THE CARRIAGE OF ENERGY-RICH FUELS AND THEIR BLENDS.

IMO. (2019). IBC Code - INTERNATIONAL CODE FOR THE CONSTRUCTION AND EQUIPMENT OF SHIPS CARRYING DANGEROUS CHEMICALS IN BULK (IBC Code).

IMO. (2019). MEPC 74/18/Add.1 - REPORT OF THE MARINE ENVIRONMENT PROTECTION COMMITTEE.

IMO. (2019). MSC.1/Circ.1394/Rev.2 - GENERIC GUIDELINES FOR DEVELOPING IMO GOAL-BASED STANDARDS.

IMO. (2019). MSC-MEPC.2/Circ.17 - Guidelines for the Carriage of Blends of Biofuels.

IMO. (2020). IGC Code - INTERNATIONAL CODE FOR THE CONSTRUCTION AND EQUIPMENT OF SHIPS CARRYING LIQUEFIED GASES IN BULK (IGC Code).

IMO. (2020). MSC.1/Circ.1621 - INTERIM GUIDELINES FOR THE SAFETY OF SHIPS USING METHYL/ETHYL ALCOHOL AS FUEL.

IMO. (2022). MARPOL - Annex 6.

IMO. (2022). MEPC.2/Cric.28 - PROVISIONAL CATEGORIZATION OF LIQUID SUBSTANCES IN ACCORDANCE WITH MARPOL ANNEX II AND THE IBC CODE.

IMO. (2022b). *International Maritime Organization*. Retrieved from Sub-Committee on Carriage of Cargoes and Containers (CCC 8), 8th session, 14-23 September, 2022: https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/CCC-8th-session.aspx

ISO. (2004). *Basic considerations for the safety of hydrogen systems.* ISO.

ISO. (2010). 28460 - Petroleum and natural gas industries, Installation, and equipment for liquefied natural gas – Ship-to-shore interface and port operations.

ISO. (2015). *ISO 16861:2015 Specifications of dimethyl ether (DME).* Retrieved from https://www.iso.org/standard/57835.html#:~:text=ISO%2016861%3A2015%20specifies%20the%20characteristics%20of%20DME%20used,and%20to%20replace%20diesel%20fuel%20or%20gas%20oil.

ISO. (2017). 20519 - Specification for bunkering of liquefied natural gas fuelled vessels.

ISO. (2017). 8217 - Specifications of marine fuels.

ISO. (2020). 13739 - Procedures for the transfer of bunkers to vessels.

ISO. (2021). 18683 - Guidelines for safety and risk assessment of LNG fuel bunkering operations.

ISO. (2023). ISO/DIS 8217: Products from petroleum, synthetic and renewable sources - Fuels (class F) - Specifications of marine fuels (Draft International Standard).

J. Patten, & T. McWha. (2015). *Dimethyl ether fuel literature review.* National Research Council of Canada. Automotive and Surface Transportation. doi:https://doi.org/10.4224/23000192

Japan for Sustainability. (2005). *Science and Technology Failure Database Opened on the Web*. Retrieved from https://www.japanfs.org/en/news/archives/news_id026011.html

Lloyd's Register. (2020). Introduction to Methanol Bunkering. *Technical Reference*.

Longanesi, L., Pereira, A., Johnston, N., & Chuck, C. (2022). Oxidative stability of biodiesel: recent insights. *Biofuels, Bioproducts and Biorefining, 16*(1), 265-289. doi:https://doi.org/10.1002/bbb.2306

MAN Energy Solutions. (2023). *Service Letter SL2023-741/JUSV.*

McCormick, R., & Moriarty, K. (2023). *Biodiesel Handling and Use Guide (Sixth Edition).* National Renewable Energy Laboratory (NREL).

Methanol Institute. (2013). *Methanol Safe Handling Manual.*

Methanol Institute. (2016). *Methanol Safe Handling Technical Bulletin. Materials Selection for Neat Methanol Service.* Methanol Institute.

Methanol Institute. (2016). *Physical Properties of Pure Methanol.* Methanol Institute. Retrieved from https://www.methanol.org/wp-content/uploads/2016/06/Physical-Properties-of-Pure-Methanol.pdf#:~:text=Physical%20Properties%20of%20Pure%20Methanol%20Physical%20Properties%20of,Critical%20Pressure%208.084MPa%20Freezing%20Point-97.6%C2%B0C%20%2878.5%20atm%29

Methanol Institute. (n.d.). *Methanol Safe Handling Manual, 5th edition.*

Ministry of Defence. (2022). MOD Defence Standard Specification for Jet Fuel. DefStan 91-091.

Molkov, V. (2012). *Fundamentals of Hydrogen Safety Engineering I.*

Moreno, V. C. (2019). Major Accident Hazard in Biodisel Production. *Safety Science, Volume 113*, 490 - 503.

MPA. (2023). *Supply of Biofuel within the Port of Singapore to Vessels*. Retrieved from MPA - Singapore: https://www.mpa.gov.sg/port-marine-ops/marine-services/bunkering/biofuel-bunkering

MPA Singapore. (2022). PORT MARINE CIRCULAR No. 21 - SUPPLY OF BIOFUEL WITHIN THE PORT OF SINGAPORE TO VESSELS.

Natarajan, R., & Chockalingam Prathap. (2022). Investigation on the laminar burning velocity and flame stability of premixed n-dodecane-air mixtures at elevated pressures and temperatures. *Fuel*, Volume 318, 15 June 2022, 123347.

Neste. (2019, March 16). Technical Data Sheet Neste MY Renewable Diesel.

Neste. (2020). *Neste Renewable Diesel Handbook.*

Neste. (2023, February 02). Safety Data Sheet Neste Renewable Diesel 100%.

NFPA. (2024). *NFPA 58 - LPG Code.*

NTNU. (2023). Retrieved from Accident databases: https://www.ntnu.edu/ross/info/acc-data

OCIMF. (2020). *International Safety Guide for Oil Tankers and Terminals (ISGOTT 6).* OCIMF.

O'Neil, M. (. (2001). The Merck Index - An Encyclopedia of Chemicals, Drugs, and Biologicals. 13th Edition. In M. (. O'Neil, *The Merck Index - An Encyclopedia of Chemicals, Drugs, and Biologicals. 13th Edition* (p. 1084).

OSHA. (2023). *OSHA Database*. Retrieved from https://www.osha.gov/ords/imis/accidentsearch.html

Port of Gothenburg. (2023). Methanol Bunker Operating Regulations.

REG. (2022, April). *Renewable Energy Group Safety Data Sheet Biodiesel.* Retrieved from https://www.regi.com/products/sds-sheets
Shell. (2014, 04 01). *Dimethyl Ether Safety Data Sheet, Version 2.2.* Retrieved from https://www.shell.com/business-customers/shell-liquefied-petroleum-gas-lpg/shell-dimethylether-dme/about-shell-lpg.html
Shell. (2023). *Shell Gas to Liquid (GTL) Fuel - Synthetic Fuel Technology Reducing Local Emissions.* Retrieved from https://www.shell.com/business-customers/commercial-fuels/shell-gtl-fuel/_jcr_content/root/main/section/simple/call_to_action/links/item0.stream/1690476242698/4a61571ebaa80c5096b62de7184e9cf07df10add/shell-gtl-fuel-brochure-2023.pdf
Sigma-Aldrich. (2023). *Safety Data Sheet (Dimethyl Ether).* Retrieved from https://www.sigmaaldrich.com/HK/en/sds/aldrich/295299
Sigma-Aldrich. (2023). *Safety Data Sheet (Methanol).* Sigma-Aldrich. Retrieved from https://www.sigmaaldrich.com/HK/en/sds/sial/322415
Silas et. al, W. e. (2022). Optical investigation and thermodynamic analysis of premixed ammonia dual-fuel combustion initiated by dodecane pilot fuel. *Fuel Communications*, Volume 12, September 2022, 100074.
Singapore Standards. (2021). 524 - Specification for quality management for bunker supply chain.
Singapore Standards. (2022). 600 - Code of Practice for Bunkering.
Singapore Standards. (2022). WA2 - Specification for marine biofuel.
Tukes - Finnish Safety and Chemicals Agency. (2023). *Accidents*. Retrieved from https://tukes.fi/en/do-this/accidents
WLPGA. (2019). *Guide for LPG Fuel Supply.*

Annex 1
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