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TNO report

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Green Maritime Methanol: WP3 factsheet and comparison with diesel and LNG

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Content

Abbreviations

ALARP	As Low As Reasonably Practical
ARA	Amsterdam-Rotterdam-Antwerp
ECA	Emission Control Area
EGR	Exhaust Gas Recirculation
FAME	Fatty Acid Methyl Esters
FSA	Formal Safety Assessment
GA	General Arrangement
GHG	Green House Gas
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HVO	Hydrotreated vegetable oil
IACS	International Association of Classification Societies
ICE	Internal Combustion Engine
IGF	International code of safety for ship using Gases or other low-flashpoint Fuels
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
IWT	Inland Waterway Transport
LNG	Liquified Natural Gas
LSA	Life Saving Appliance
LSMGO	Low sulphur marine gas oil
MDO	Marine Diesel Oil
MEOH	Methanol
MGO	Marine Gas Oil
MDO	Marine Diesel Oil
NO_x	Nitrogen Oxides
P2X	Power to fuel
PM	Particulate Matters
SCR	Selective Catalytic Reduction
SDS	Standard Data Sheet
SO_x	Sulphur Oxides
SOLAS	Safety Of Life At Sea
RoRo	Roll-on-Roll-off
Ropax	Roll-on-Roll-off Passenger
TTP	Tank-to-Propeller
ULSFO	Ultra low sulphur fuel oil
VLSFO	Very low sulphur fuel oil
WTT	Well-to-Tank
WTW	Well-to-Wheels
WHO	World Health Organization

1 Introduction

Introducing alternative fuels on board has many far stretching implications for ship operators, authorities, fuel suppliers, equipment suppliers, engine manufacturers, ship builders and naval architects. In most cases such parties are not familiar with these new fuels. Hence a need exists for them for a means to quickly familiarize oneself with the most important aspects associated with these alternative fuels.
This report is an attempt to provide such a means. It is meant to provide general information for fleet owners, naval architects and public stakeholders like policy advisors and rescue workers, to understand the main benefits and implications of methanol as a maritime fuel. This is done by comparing methanol with diesel (HFO and MGO) fuel and with LNG. For more detailed information, we also refer to other publications of the Green Maritime methanol project.

1.1 Aim of the factsheet report

The aim of the report is to give a high level comparison of methanol, diesel and LNG as a maritime fuels covering the following aspects:
- Market potential
- Engine technology
- Pollutant emissions
- Greenhouse Gas emissions
- Fuel production and infrastructure
- Safety

This report provides facts considered essential for introducing such fuels on board. The report does not claim to be a recipe for success or a good practice guide. It does however claim to provide sufficient information for users to be able to ask the right questions. Moreover the reports provides proper references with a preference to direct access through the internet links provided.

1.2 Structure of the report

Section 1.3 contains an overview of the main fuel properties. The information on the evaluation aspects for diesel fuel, methanol and LNG are reported in a fixed format in the sections 2, 3 and 4. Consecutively section 5 contains a summarizing comparison between the three fuels and section 6 contains high level conclusions.

1.3 Fuel properties

An overview of the main fuel properties for diesel fuel (HFO and MGO), methanol and LNG is given in Table 1. The energy densities are also graphically presented in figure 1. The right figure includes the weight of the bunker tank and a volume factor. The volume factor is 1 for the fuels which are liquid under atmospheric conditions, and two for (liquid) gasses, because of the requirement for cylindrical-cryogenic tanks.

Table 1: Technical characteristics of different fuel types

Properties	**Diesel HFO**	**Diesel MGO**	**Methanol MEOH**	**LNG**
Type of fuel	Liquid fuel	Liquid fuel	Liquid fuel	Liquid gas (cryogenic)
Chemical structure	$C_{20}H_{42}$– $C_{50}H_{102}$	$C_{12}H_{26}$– $C_{14}H_{30}$	CH_3OH	CH_4
Molecular weight (g/mol)	100 - 700	190–220 (170 – 180)	32	16
Density (kg/m3) liquid	900 – 1000	850	790	450
Boiling point (°C)	121 - 600	180-360	65	-161
Min. pump temperature (°C)	40	N/A	N/A	N/A
Lower heating value (MJ/kg)	40 – 42	42.6	19.9	48 - 50
Lower heating value (MJ/dm^3)	38 - 40	36	15.8	22
Flammability limits (vol)		1.85 - 8.2	6.7 - 36	5 - 15
Flash point (°C)	> 60	78	11	-136

Source: TNO, MKC, TU Delft (2018), (European American Petroleum Institute, 2012), Dep of Energy, 2020

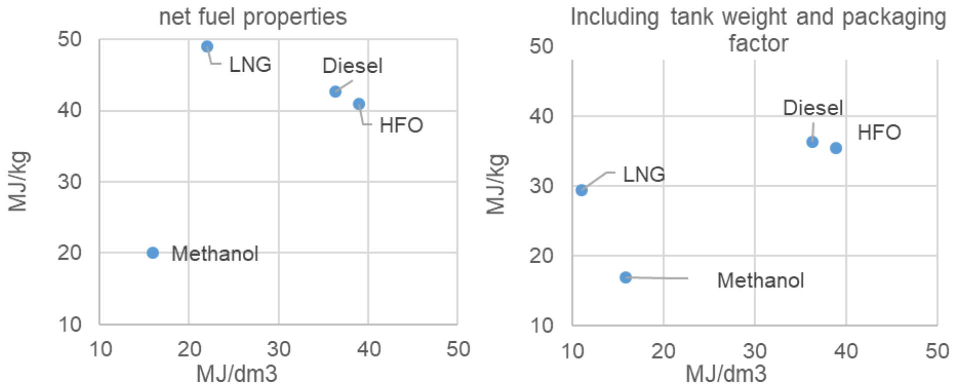

Figure 1. Energy density of fuels. Left: net properties. Right: including (bunker) tank weight and packging factor. Source [van Kranenburg, 2020].

2 Factsheet diesel fuel

2.1 Market potential

Diesel fuels are the standard fuels for ships. They come in several qualities with respect to sulphur content and flow properties (viscosities).
The main options are:

- A fully distilled fuel as MGO, which always has a low sulphur content (S<0.1%) and is only used for Emission Control Areas (ECA).
- A blend of residual oil and distillate fuel, MDO: Marine Diesel Oil.
- A fully residual fuel, Heavy Fuel Oil, which comes either untreated, with high sulphur content, or desulphurised to either the new global requirement (S<0.5%) or even to ECA requirement (S<0.1%).

In Appendix A an overview of the global and regional (ECA) emission legislation with respect to sulphur and NO_x regulations is given.
The standard HFO (S>0.5%) can only be used in combination with a SO_x scrubber to bring back the SO_x emissions below the ECA or global requirements. The choice to use either a low sulphur fuel or a high sulphur fuel in combination with a SO_x scrubber, is often mainly an economic choice. Especially for ships with a high yearly fuel consumption, the lower fuel costs with standard HFO outweighs the investment and operational costs of the SO_x scrubber.
The combination of Tier III NO_x requirement and HFO poses some challenges, due to sulphur and hydrocarbon accumulation with the SCR catalyst. That may lead to a reduction in HFO use and/or a bypass system for the SCR catalyst.

Use of diesel fuels will likely remain an important fuel-type for the coming years for shipping, due to the long life. To improve the sustainability, alternative production routes are available or in development:

- Biodiesel, derived from different biologic feedstocks. Biodiesel includes several types such as FAME and HVO. The impact on the CO_2-performance of these biofuels are largely dependant on the feedstock that is used.
- Synthetic or e-diesel, produced from green hydrogen and a carbon source.

2.2 Engine technology

The energy density of diesel fuel is very high, and also biodiesel comes close to this high energy density. Refer to Table 1 in section 1.3. The diesel engine is known as a very robust energy convertor, also thanks to the long history of continuous technology improvements. Also the specific power output (power density) of diesel engines is high, usually higher when fuelled by diesel than with alternative fuels.
A range of diesel fuel types exist in order to be able to use different residual diesel fuels for shipping and in order to comply with marine pollution legislation. An overview of the IMO MARPOL emission legislation for both fuel sulphur and also NOx is included in Appendix A.

The following diesel fuel types are defined:

- MGO: Marine Gas Oil, a distillate fuel usually with sulphur content lower than 0.1% and suitable for Emission Control Areas and port areas. It can also be referred to as LSMGO,

- MDO: Marine Diesel Oil, a blend of residual oil and distillate fuel,
- HFO: Heavy Fuel Oil, a residual oil, standard with high sulphur content (up to <3.5%). Lower sulphur types include:
    - VLSFO – very low sulphur fuel oil: S < 0.5%
    - ULSFO – ultra low sulphur fuel oil: S < 0.1%

Both MGO and ULSFO are suitable for Emission Control Areas (ECA) without SO_x scrubber. HFO (incl. VLSFO and ULSFO) and MDO usually need to be heated to improve the flow properties such that it can be used in the combustion engines.

2.3 Pollutant emissions

2.3.1 Tank-to-propeller

With respect to diesel fuel, specifically HFO with <0.5% S (VLSFO) and MGO (<0.1%S), pollutant emissions in gram per kilowatt-hour mechanical work at 45% engine efficiency are presented in Table 2. These values are visually presented in a graph in Figure 2. Both fuels show relatively high levels of NO_x and SO_x pollutant emissions, however MGO already proves to be significantly less polluting than its HFO counterpart. It should be noted, that the Tier NOx requirements and also the actual engine NOx output are quite dependent on the maximum engine speed. For example for engines with a maximum speed of respectively 250 rpm and 1200 rpm, the Tier II NOx limit value is respectively 12.4 g/kWh and 9.7 g/kWh. The values in the table below are typical for a medium speed engine with a maximum speed of about 700 rpm. An overview of the NOx and fuel sulphur emission legislation is included in Appendix A.

Table 2: Tank-to-propeller pollutant emissions for HFO 0.5% S and MGO 0.1% S in gram per kWh mechanical work at 45% engine efficiency. Source: (Brynolf, 2014) (ter Brake, Kauffman, & Hulskotte, 2019) (Verbeek & Verbeek, 2015) (IMO, 2016).

g/kWh mechanical work at 45% engine efficiency	HFO 0.5% S (g/kWh)	MGO – Tier II 0.1% S (g/kWh)	MGO – Tier III 0.1% S (g/kWh)
NO_x	12.8	9	2-3
SO_x	2.0	0.36	0.36
PM_{10}	0.74	0.23	0.23

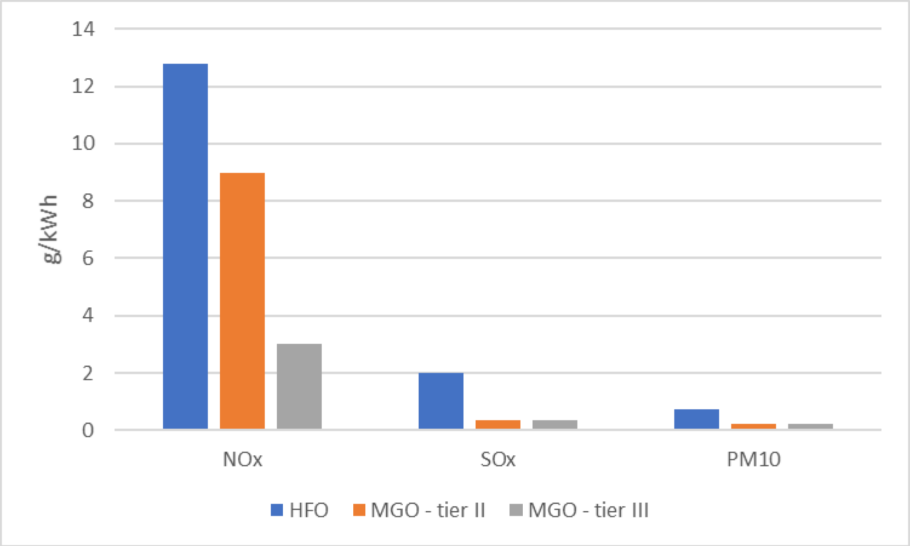

Figure 2: Tank-to-propeller pollutant emissions in g/kWh (engine output) for HFO, MGO-tier II and MG-tier III.

2.4 Greenhouse Gas Emission

2.4.1 Well-to-tank

Figure 3 shows a typical well-to-tank life cycle for diesel fuel, HFO and MGO included. As HFO is a residual product of the oil refining process, assumptions on the distribution of CO_2-equivalent emissions between HFO and MGO are generally based on the relative mass and energy content of both energy carriers.

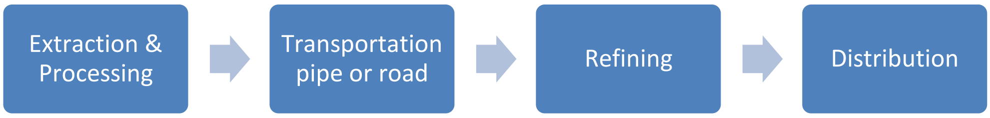

Figure 3: Schematic overview of Well-to-Tank scope definition with respect to greenhouse gas emissions for HFO and MGO fuels.

Life cycle hotspots with respect to emissions can be defined as; fugitive emissions, venting and flaring during crude extraction and refining, efficiency of the refining and transport distance (Gilbert, et al., 2018). Estimates for the greenhouse gas emissions during well-to-tank are presented in Table 3.

This graph includes the 20 and 100 year CO_2-potential. This is calculated using the IPCC[1] global warming potential values for the specific compounds (IPCC, 2013). These GWP values are presented in Table 4.

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[1] IPCC: Intergovernmental Panel on Climate Change: organisation from the united nations to investigate climate chang.

Table 3: Well-to-tank greenhouse gas emissions for MGO fuel in gram per MJ fuel energy. Source: (Brynolf, 2014) With CO_2-equivalents for 20 years and 100 years.

g/MJ	MGO - 0.1% S	CO_2-equivalent 20 year	CO_2-equivalent 100 year
CO_2	12.04	12.04	12.04
CH_4	0.03	2.52	0.84
N_2O	0.00016	0.042	0.043
Total	**-**	**14.57**	**12.89**

Table 4: IPCC[1] Global Warming Potential values (IPCC, 2013).

	GWP 20 year	GWP 100 year
CO_2	1	1
CH_4	84	28
N_2O	264	265

2.4.2 *Tank-to-propeller*

Tank-to-propeller emission factors due to main engine combustion in medium and high speed diesel engines are presented in Table 5 (Brynolg, 2014) (ter Brake, Kauffman, & Hulskotte, 2019). In general there does not seem to be significant difference in greenhouse gas emissions relative to HFO and MGO fuels.

Table 5: Tank to Propeller greenhouse gas emission factors for HFO 0,5% S and MGO 0,1% S in gram per MJ fuel energy. Source: (Brynolf, 2014) (ter Brake, Kauffman, & Hulskotte, 2019).

g/MJ	HFO Diesel 0.5% S	MGO Diesel 0.1% S
CO_2	77	74
CH_4	0.00045	0.00045
N_2O	0.0035	0.0035
$CO_{2equivalent}$ 20 years	78.0	75.0
$CO_{2equivalent}$ 100 years	77.9	74.9

An overview and comparison of the well-to-propeller emissions of diesel, methanol and LNG is presented in section 5.1.2.

2.5 Fuel production and infrastructure

MGO and HFO are the standard fuels applied in maritime shipping today. These fuels are widely available throughout all European ports. The main ports in the ARA-range (Antwerp, Rotterdam -Amsterdam) are bunkering hubs. The three ports as a whole processes around 20 million m^3 per year. Rotterdam transships around 10 million m^3, of which 80% HFO. Amsterdam transships around 1.7 million m^3, of which 1 million for maritime purpose and 0.7 million m^3 for inland shipping purposes. Antwerp transships around 6.5 million m^3 .

Current maritime operations use four types of bunker transfer:

1. Ship-to-ship (common transfer method for maritime vessels);
2. Shore-to-ship (common for barges and local fleet, inland waterway vessels often use a floating pontoon connected to the shore);
3. Truck-to-ship (common for small volumes and in pilot stage); and
4. Bunkering at sea (hardly being applied in merchandised shipping);

Ship-to-Ship indicates the transfer of bunker fuel from one ship to another. A small (typical 110 – 130 m length) ship filled with the fuel or other supplies will go alongside the ship that needs to be bunkered. Then, a hose will be connected between the two vessels. A pump, aboard the bunker barge, will force the liquid to be transferred via the hose. At first, the liquid will be pumped through the hose slowly, so the receiving ship can make sure it gets in the right tanks. When this is going correctly, the liquid will be pumped into the tanks at full speed.

Ship-to-ship bunkering can take place at different locations: along the quayside, at anchor or at sea. It is the most common bunkering method used for bunkering seagoing vessels with HFO and MGO. The capacity of bunkering vessels can range from 1,000 to 10,000 m3. Compared with other bunkering methods, the flexibility of ship-to-ship bunkering is high with respect to capacity and bunkering location. Because the bunker vessels are moored alongside the fueled ships, this bunker method could permit simultaneous cargo handling if approved by the relevant authorities, such as the port authority.

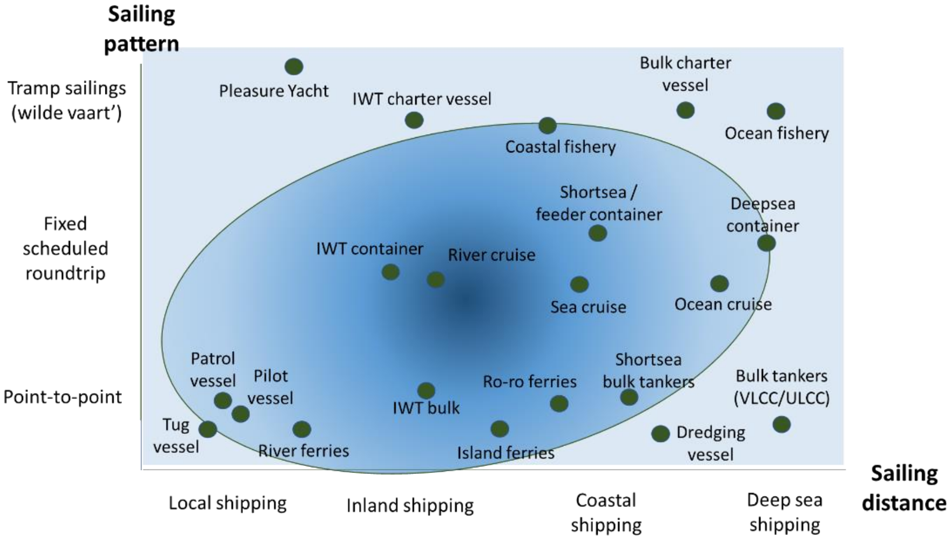
2.6 Safety aspects for HFO, MDO, MGO

Following the reasoning as used in IMO, safety is considered with respect to people, property and the environment.
Regarding *people*, HFO, MDO and MGO are not considered particularly hazardous. There is a small hazard during bunkering because HFO must be heated to a temperature of at least 40 °C for pumping reasons (below this temperature their viscosity is too high). This is typically done through the use of rest-heat from the exhaust fumes. So during bunkering there is the hazard of burning due to heated oil. MGO does not need to be heated. Inside the engine room or fuel treatment room the HFO and MDO are heated to about 60 °C for further purification treatment and supply to the engines. So should leakage occur there is again the hazard of burning. For MGO this hazard is not present because it needs not to be heated. Except for spills on hot surfaces (e.g. engine parts), for none of the fuels, there exists a flammability hazard, because the fuels comply with the requirement in SOLAS regarding minimum allowable flashpoint of fuels on board, which must not be lower than 60 °C (IMO, SOLAS Consolidated Edition, 2018).
Regarding *property* the hazards are considered very low because the fuels are considered not flammable. Here again the exemption must be made for spills/ leakage on hot surfaces (well above 61 °C).
From an environmental point of view HFO, MDO and MGO are hazardous, because they are very toxic to aquatic organisms and they may cause long-term adverse effects in the aquatic environment, albeit for MGO to a lesser extent. The effect of spills/ leakage into the natural environment, especially aquatic, can easily develop from ***localised*** (significant but reversible damage to sensitive areas/species in the immediate vicinity) to ***major*** (extensive or persistent damage to sensitive areas/species (IACS, Rec_No_146, 2016), p. 19).

3 Factsheet Methanol

3.1 Market potential

Based on a data analysis of vessel arrival data in the ports of Rotterdam and Amsterdam, sailing on methanol seems applicable for most midrange shipping markets. The often over-dimensioned tank capacity allows them to bunker methanol without serious adjustments to the bunker frequency, sailing pattern, or tank capacity/ship design. This is particularly the case for shortsea shipping markets and shipping markets with point-to-point sailing patterns. Moreover, inland shipping looks also promising for methanol, whereas ultra large container ship are being built with expanded tank capacity. The methanol applicability heatmap is shown below.



A scenario analysis was made taking into account the bunker volumes for the European market (as discussed in section 2.5) and the bunker volumes of market segments were methanol is applicable. The overall methanol market share was estimated to be 22% in a high scenario and 5% in a low scenario. This results in an estimated methanol bunker volume in the range of 0.6 to 2.6 million m^3 for Rotterdam and 1.1 to 5.0 million m^3 for the whole ARA-region.

3.2 Methanol engine technology

Methanol deviates strongly from diesel fuel, because it has a high auto-ignition temperature. In order to combust it in an Internal Combustion Engine (ICE), several engine technologies are possible:

- Dual fuel or diesel pilot: a certain amount of diesel fuel (e.g. 2% - 20%) is used to initiate the combustion of methanol
- Spark ignition, Otto principle
- Methanol with ignition improver: a chemical liquid (e.g. 5%) is used to lower the auto-ignition temperature such that is can be burned in an (adapted) diesel engine

Within these three main principles, there are also variations possible such as inlet manifold or in-cylinder injection. Dual fuel or diesel pilot is expected to become most popular, because this can be based on current diesel technology and is an easy way to maintain the high diesel cycle efficiency. Dual-fuel methanol engines, with in-cylinder methanol injections from Wartsila and MAN are already installed on ships.

With respect to engine technology and combustion, methanol is partly similar to LNG, although there are also significant differences. Since LNG is a gas, it is more suitable for manifold injection. Lean burn, low NO_x combustion then becomes easier due to the due the homogeneous mixture formation. For methanol in dual-fuel combustion, additional measures are necessary to achieve Tier III NO_x requirements.

Due to the absence of sulphur in the fuel and the pre-mix combustion principle, both SO_x and PM emissions will be a lot lower than with the regular marine diesel fuels.

3.3 Pollutant emissions

3.3.1 Tank-to-propeller

This comparison is based on MGO diesel fuel with 0.1% sulphur content, because the Emission Control Area is most likely the most attractive first market for methanol. Table 6 presents tank-to-propeller emissions for methanol, relative to the MGO diesel 0.1% reference. Significant reductions are achieved with respect to pollutant emissions, the absence of sulphur results in major reductions of SO_x and particulate matter as can be seen in Figure 4. Substantial lower engine NO_x emissions are achieved with methanol. However in order to meet Tier III, additional NO_x mitigation is necessary. This can be SCR aftertreatment (like on the STENA Germanica) or it can be achieved by mixing water into the methanol.

Table 6: Tank-to-propeller pollutant emissions for methanol dual fuel compared to MGO 0.1% S in gram per kWh mechanical work. Source: (Brynolf, Fridell, & Andersson, 2014) (IACS, Rec_No_146, 2016) (Verbeek & Verbeek, 2015) (ter Brake, Kauffman, & Hulskotte, 2019).

g/kWh	MGO – Tier II 0.1% S	Methanol – Tier II	Methanol – Tier III (incl. SCR)
NO_x	9	5	2.2
SO_x	0.36	0.007	0.007
PM_{10}	0.23	0.034	0.034

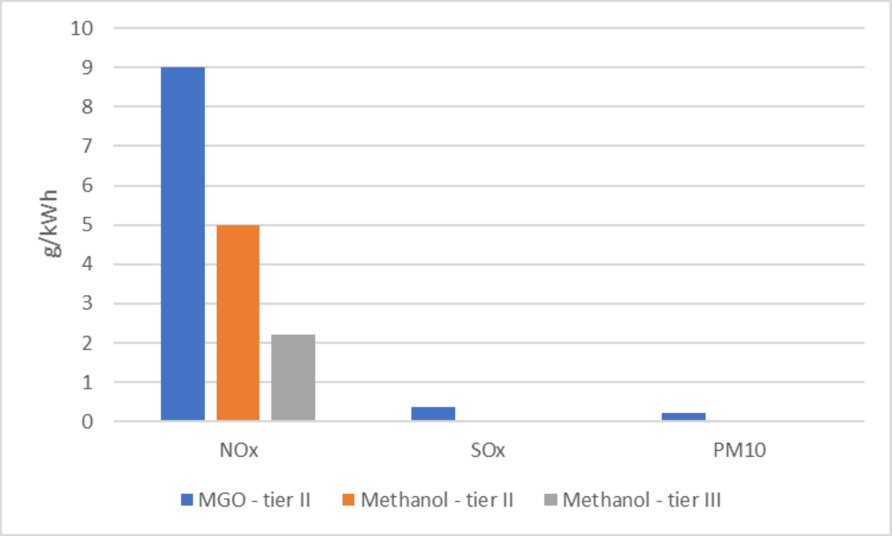


Figure 4: Tank-to-propeller emissions in gram per kWh mechanical work for MGO – tier II, methanol – tier II and methanol – tier III. Source: (Brynolf, 2014) (ter Brake, Kauffman, & Hulskotte, 2019).

3.4 Greenhouse Gas Emission

3.4.1 Well-to-tank

For the well-to-tank greenhouse gas emission analysis, the used feedstocks are to be considered. Figure 5 provides a schematic overview of a typical well-to-tank life cycle, specifying in the first block three feedstocks for methanol production. Production and distribution of methanol can be considered relatively mature, with large scale production for the chemical market already in place and growing use as fuels.

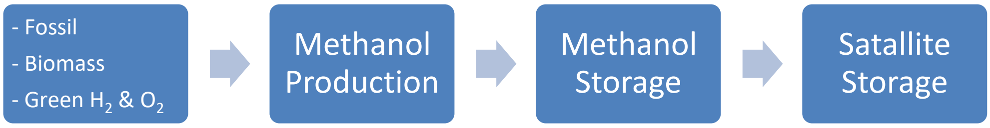


Figure 5: Schematic overview of Well-to-Tank scope definition with respect to greenhouse gas emissions for methanol from natural gas.

With respect to specific compound emissions, Table 7 presents emissions numerically in gram per MJ fuel energy for specific compounds (Brynolf, 2014). Figure 6 gives a graph representation of this data. Both CO_2-equivalents for 20 and 100 years have been accounted for according to IPCC values (Table 4, section 2.4.1).

Table 7: Greenhouse gas emissions for fossil methanol production per specific compound for well-to-tank analysis, in gram per MJ fuel energy. Source: (Brynolf, 2014)

g/MJ	Methanol	CO_2-equivalent 20 year[2]	CO_2-equivalent 100 year
CO_2	20	20	20
CH_4	0.011	0.924	0.308
N_2O	0.00029	0.07656	0.07685
Total CO_2 equivalent	**-**	**21.00**	**20.38**

In Figure 6 greenhouse gas emissions in gram CO_2-equivalent per Mega Joule fuel energy are represented for the previously defined feedstocks. For the two fossil gas feedstocks a distinction is made between natural gas transportation by pipeline and remote natural gas extraction wit onsite methanol synthesis. For the bioderived types of methanol, distinction is made between farmed feedstocks and waste feedstocks used for methanol synthesis. Farmed feedstocks includes farmed wood to methanol and waste feedstock includes waste wood to methanol. With respect to the lifecycle, typical hotspots or determinants of emission are identified as the methane conversion efficiency and the use of specific feedstock (Gilbert, et al., 2018).

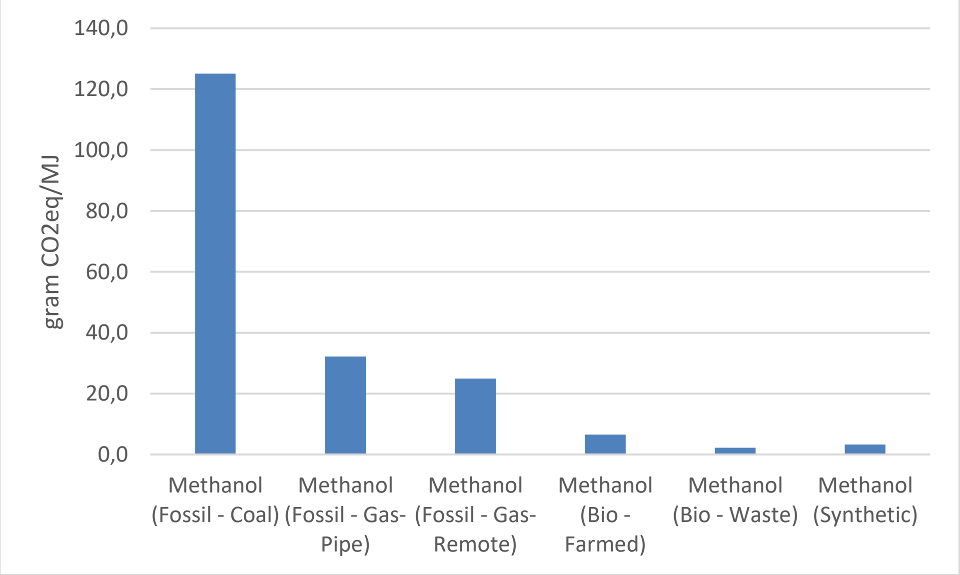


Figure 6: Well-to-tank greenhouse gas emissions for different methanol feedstocks and production/distribution routes in gram CO2-equivalent per MJ fuel energy. Source: (JRC, 2014).

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[2] Source GWP factors: See Table 4; i.e. GWP for CH4 is 84 for 20 years and 28 for 100 years, GWP for N2O is 264 for 20 years and 265 for 100 years (IPCC, 2013).

3.4.2 *Tank-to-propeller*

The tank-to-propeller emissions of methanol are shown in Table 8 relative to MGO diesel 0.1% S. It is presented for fossil as well as for renewable methanol. For renewable methanol this is according to the IPCC definition, which means that the combustion counts as zero- CO_2. The actual CO_2 emission of the combustion is compensated by CO_2 adsorption during the biomass growth.
The table shows, that fossil methanol has a 5 g/MJ lower tank-to-propeller CO_2 emission (~6%) than MGO. The overall GHG emission is uncertain due to the absence of information on CH4 and N2O emissions.
The overall comparison on the full fuel chain, the well-to-propeller, emissions are presented in section 5.

Table 8: Tank-to-propeller greenhouse gas emissions for methanol, compared to MGO diesel, in gram per MJ fuel energy. Source: (Brynolf, Fridell, & Andersson, 2014)

g/MJ	MGO Diesel 0.1% S	Methanol Fossil	Renewable /Green methanol
CO_2	74	69	0
CH_4 ($CO_{2\ \text{equivalent}}$)	0.00045	not available	not available
N_2O ($CO_{2\ \text{equivalent}}$)	0.0035	not available	not available
TTP $CO_{2\text{equivalent}}$ 20 years	75.0	-	-
TTP $CO_{2\text{equivalent}}$ 100 years	74.9	-	-

An overview and comparison of the well-to-propeller emissions of diesel, methanol and LNG is presented in section 5.1.2.

3.5 Fuel production and infrastructure

Methanol has until currently only been applied on a pilot basis in shipping. Currently, there is no dedicated infrastructure available for ship bunkering. However, application of methanol for industrial purposes is a well-established and mature market in Europe. In 2018, around 1.5 Mt is produced in EU27 and around 7.5 Mt is being consumed (TNO based on European Comext and prodcom databases). Significant amounts of methanol get imported from Trinidad, Venezuela, Equatorial Guinea, the United States and Russia. The Netherlands, with an overseas import of 2.5 Mt and a production of 0.5 Mt[3], is an important hub for the current import and European distribution of methanol imported from outside Europe.

As already mentioned in section 3.4, distinction can be made between different production routes (see Figure 7):

- grey methanol, produced from fossil sources like natural gas or coal (called blue methanol when CO_2 from exhaust gases is captured),
- biomethanol, produced from biogas,

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[3] Production values for the Netherlands are confidential for 2018. Estimations were made based on the available production values presented between 2009 and 2017.

- Carbon-recycled methanol, making use of a similar gasification technology as dry biomass, with waste streams that are otherwise non-recyclable used as a feedstock for methanol production, and
- e-methanol, produced from green hydrogen and a carbon source.

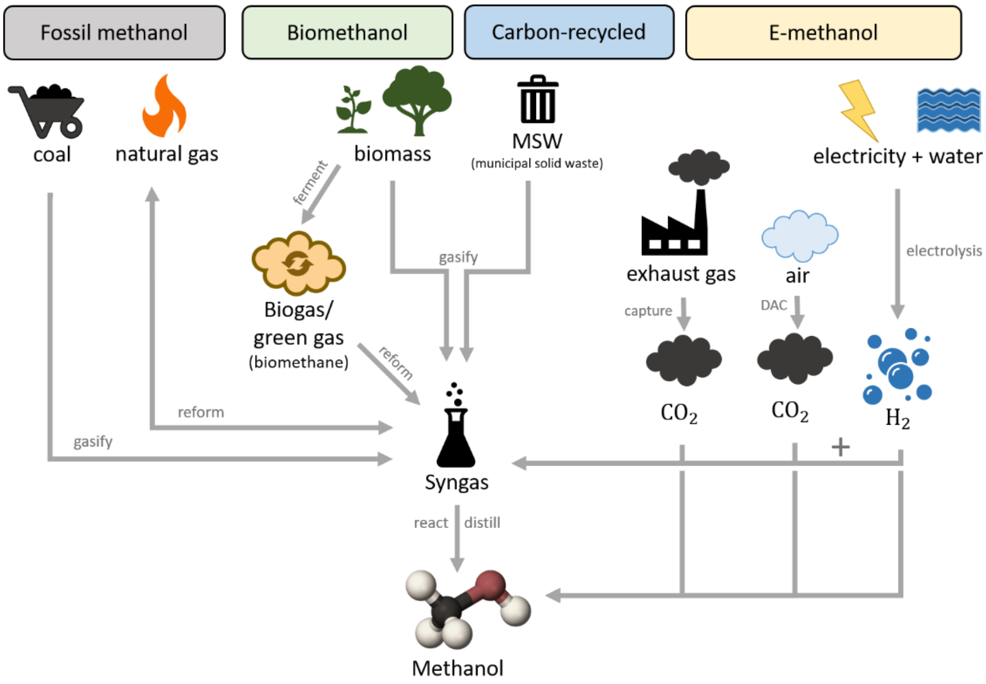

Figure 7: Production Methods of Methanol from different feedstocks

European and global grey methanol production potential are sufficient to produce viable volumes for a transition to methanol as a maritime fuel. European production for biomethanol and carbon-recycled methanol is currently at significantly lower production capacities than their grey counterparts. The attention and demand is however vastly growing, and with that also the supply is expected to increase continuously. E-methanol is currently at a lower technology readiness level as the other feedstocks. Availability and prices depend a lot on the increase in capacity of green electricity (driving the hydrogen price) and the price of of sustainable CO_2-source (DAC).

Methanol as a fuel for ships can be applied via European production facilities in the Netherlands or Germany or via overseas import through the Port of Rotterdam. Distribution from these locations can be performed via trucks or barges (all main production locations have access to IWT). Bunkering can be performed via intermediate storage or directly from a barge/ truck.

Truck-to-ship bunkering is suitable for vessels with low bunker demand and is expected to be used in the first pilot phase. In case of further growth of methanol, ship-to-ship bunkering is expected to become the dominant transfer method. Inland chemical tanker barges currently shipping methanol along the Rhine or between Antwerp and Rotterdam may be used to bunkering in the initial stage. Large multifuel bunker vessels are not foreseen to be a mainstream solution, since most bunker operators prefer to serve one ship instead of applying a ‘milkrun’.

Shore-to-ship facilities may become the standard transfer mode for ship segments with fixed routes such as dedicated cruise or roro terminals.

3.6 Safety aspects

There are no specific regulations yet regarding the use of methanol as bunker fuel on board. However an effort is underway to get such regulations in place. The latest interim results can be found in (IMO, Draft Interim Guidelines for the Safety of Ships using Methyl/Ethyl Alcohol as Fuel CCC6/WP.3, Annex 1, 2019). The final results will become part of the IGF code (IMO, IGF Code (MSC.391(95) Code of safety for ships using gases or other low-flashpoint fuels), 2015). Classification societies keep track of and participate in the development of these regulations. They also include such new regulations in their own rules and regulations and recommended practices.

As mentioned earlier the hazards of interest are those that concern, people, property and the (natural) environment.

Regarding *people* the hazards to be dealt with are (World Health Organization, 2017);

a) flammability,
b) toxicity,
c) corrosiveness (in an indirect fashion)..

ad a)
The flammability is caused by a low flashpoint of methanol, which lies at 11 °C, in conjunction with the vapour density of 1.1 kg/m^2. The latter property means that a flammable vapour can develop in lower parts of the ship should methanol leaks occur. For this reason, conventional regulations (IMO, SOLAS Consolidated Edition, 2018) do not allow methanol as a fuel on board unless special additional safety measures are taken. It is therefore important that leaking of methanol is detected immediately and ample ventilation capacity is available to avoid a build-up of any vapours. Also conventional fire-fighting methods and personal protection equipment on board are not suitable for combatting methanol fires. So fire-fighting systems and training must be dedicated to methanol.

ad b)
Methanol is very toxic to human beings if swallowed (blindness, death). Contact with the skin may cause dermatitis. It is harmful if inhaled, through causing damage to the nervous system (headaches, impaired vision). Harmful contamination of the air can be reached rather quickly on evaporation at 20°C (World Health Organization, 2017). It is therefore important that people handling methanol, e.g. bunkering, wear methanol dedicated protective clothing, masks and sometimes even a breathing apparatus in accordance with Table 9: Selecting personal selective equipment, copied from (The_Methanol_Institute, 2017)..

Table 9: Selecting personal selective equipment, copied from (The_Methanol_Institute, 2017).

LOW RISK OF VAPOR/ LOW RISK OF VOLUME SPLASH	HIGH RISK OF VAPOR/ LOW RISK OF VOLUME SPLASH	HIGH RISK OF VAPOR/ 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	Checmical-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 rubber boots	Chemical-resistant rubber boots

ad c)
Some special care is required regarding materials used for storage tanks, piping and appendages. Methanol contaminated with moist and traces of inorganic salts will cause corrosion in the heat affected zones around welds of mild steels. When such presence is expected one must consider stainless steel 316L (The Methanol Institute, 2017).

Regarding *property,* without additional measures the risk is considered medium because the probability of a fire or an explosion (following a spill) is ***unlikely*** while the consequence category can be ***major damage***. This is illustrated in Figure 8.The IMO regulations currently under development aim at defining additional measures mainly as to reduce the likelihood of spills and consequential fires/ explosion. In the figure this implies that the star indicating the risk location of methanol on board moves to the left.

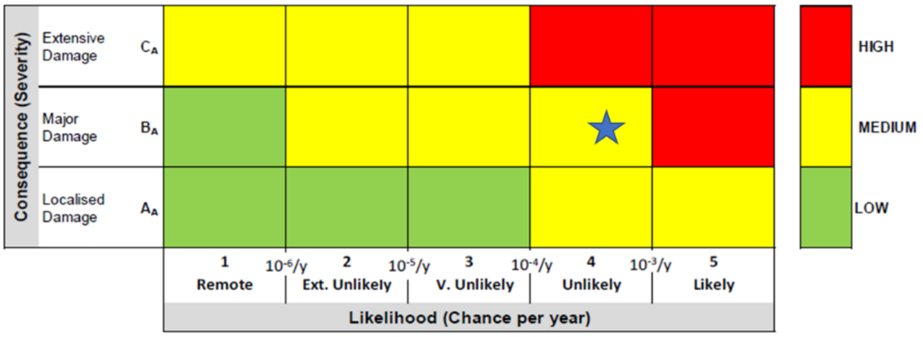

Figure 8: Risk matrix damage to property methanol fuel on board.

From an *environmenta*l point of view methanol is not particularly hazardous. It is not toxic to aquatic organisms and can in fact be digested by some species. Moreover it dissolves rapidly in water.

Bunkering at fixed locations on shore is attractive from a safety point of view because locations can be chosen away from locations where other activities take place. Moreover, the facility can be managed under a strict safety regime which can easily be inspected. A second best option (from a bunkering safety point of view) is the bunker barge which comes alongside to supply the fuel. Also the supplying barge/ ship will be designed and operated entirely dedicated to the fuel, similar to a fixed facility on shore. However the location where the bunkering (hazardous activity) can take place can in principle be anywhere, which may be regarded as a disadvantage.

To mitigate this, harbour or waterway authorities can designate areas where bunkering is allowed. The advantage of bunker barges is that they can come along side when the ship is loading or unloading, which is common practice with conventional fuels. The third option is to supply the methanol fuel by road. This also has the disadvantage of large number of locations where bunkering may take place. Moreover, the trucks will use the quay which is also used for other activities such as cargo (un)loading. So there will be uncorrelated multiple activities involving unrelated individuals in the vicinity of each other which is undesirable from a safety point of view. Finally the quantities which a road tanker can carry are limited, which will be an efficiency disadvantage in case of larger ships.

4 Factsheet LNG

4.1 Market potential

LNG as fuel for ships is already around for a number of years. It started as fuel for LNG carriers (where it could use LNG from the cargo), where it replaces the steam turbines used in older carriers. Over the last five years, the application of LNG engines expanded to tankers, container vessels, cruise vessels, RoRo/Ropax and service vessels. A lot of this was initiated due to the low pollution level of LNG powered engines. It that way they qualify for the Norwegian NO_x fund and also for NO_x emission control areas (NECA, e.g. US east and west coast). In February 2020 there were 175 LNG-fuelled vessels in operation and 203 in order. A further 141 LNG-ready ship were in operation or in order (SEA-LNG, 2020).

The market potential for LNG is good. There is a steady growth of the number of LNG vessels. In the future LNG can be replaced by bio-LNG or possibly e-LNG (synthetic methane) to make it more climate friendly. Forecasts on the market share of LNG show a wide range between different forecast agencies. DNV GL argues that by 2050 the share may be as large as 41% (DNV-GL, 2019).

4.2 Gas engine technology

The main difference with a standard diesel fuel ship are the cryogenic LNG tank on board of the ship and an engine being suitable for LNG. The LNG tank is costly and takes up substantial space. Depending on the ship type, this does often lead to some loss of cargo capacity or otherwise useful space (<5%). For example for container vessels, a part of the container space is sacrified for LNG tanks.

Two types of engine technology have been used up till now:
- Dual-fuel engines
- Spark-ignition single fuel engines (also referred to as pure gas engine)

The dual-fuel engines are primarily delivered by Wärtsilä and MAN. Two types are distinguished, namely with low-pressure (in-manifold) injection and with high-pressure (in-cylinder) injection. Most of the engines however are of the low-pressure type. Main advantages of this type are lower costs and lower NO_x. Because of the latter, compliance with the Tier III NO_x level is possible without aftertreatment. This is a major advantage. A disadvantage is the relative high methane emission of the engine. This eliminates the principle GHG advantage of natural gas with its low carbon content compared to diesel fuel.

The spark-ignition gas engines are popular with the smaller engines up to some 2 MW power output. These are for example used for platform supply vessels. Due to the lean-burn combustion principle, compliance with Tier III NO_x level is also possible for this type without aftertreatment.

4.3 Pollutant emissions

4.3.1 Tank-to-propeller

Tank-to-propeller pollutant emissions for LNG are presented in Table 10 with the MGO diesel (0.1% S) as reference fuel, in combination with a Tier II engine. With respect to LNG usage, significant reductions can be obtained for all specified pollutants. The emission factor values for MGO diesel are specifically for high and medium speed diesel main-engines, LNG values are for LNG dual fuel engines with LNG injection in the inlet-manifold. For those engines no addition NO_x control via exhaust aftertreatment is necessary. Figure 9 gives a graphical representation of the pollutant emission values.

Table 10: Tank-to-propeller pollutant emissions for LNG dual fuel compared to MGO 0.1% S in gram per kWh mechanical work. Source: (Verbeek & Verbeek, 2015) (ter Brake, Kauffman, & Hulskotte, 2019).

g/kWh	MGO – Tier II 0.1% S	LNG – Tier III
NO_x	9	2
SO_x	0.36	0.009
PM_{10}	0.23	0.02

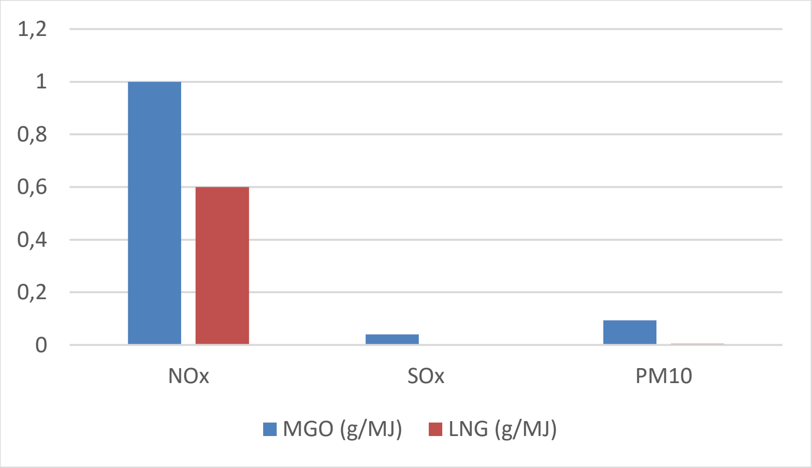

Figure 9: LNG tank-to-propeller pollutant emissions in gram per MJ fuel energy relative to MGO diesel 0.1% S, with HFO pm10 emission values for reference of missing values. Source: (ICCT, 2017).

4.4 Green House Gas Emission

4.4.1 Well-to-tank

A schematic overview of a typical LNG well-to-tank process is presented in Figure 10. Natural Gas extraction and distribution routes and the corresponding infrastructure are widely implemented, with a couple important life cycle hotpots that result in lower well-to-tank efficiency than diesel fuels. Firstly the efficiency of liquefaction and production emission have a negative effect. Secondly, the extent of flaring and venting is significant. Lastly, methane slip contributes to the GHG (Gilbert, et al., 2018); methane has a much higher global warming potential than CO_2, specifically 28 CO_2-equivalents for 100 years and 84 for 20 years. Therefore methane slip represents a real issue regarding LNG emissions.

Figure 10: Schematic overview of Well-to-Tank scope definition with respect to greenhouse gas emissions for LNG.

Table 11 presents compound specific well-to tank greenhouse gas emissions, for LNG in gram per Mega Joule fuel energy.

Table 11: Greenhouse gas emissions per specific compound for well-to-tank analysis for LNG, in gram per MJ fuel energy. Source: (Brynolf, Fridell, & Andersson, 2014).

LNG - g/MJ	Emissions	CO_2-equivalent 20 year	CO_2-equivalent 100 year
CO_2	18.5	18.5	18.5
CH_4	0.033	2.772	0.924
N_2O	0.00017	0.04488	0.04505
Total	**-**	**21.3**	**19.5**

4.4.2 *Tank-to-propeller*

Table 12 presents the tank-to-propeller greenhouse gas emissions for LNG with the MGO diesel 0.1% Diesel fuel as a reference. This shows reductions in tank-to-propeller CO_2 and N_2O emissions of around a third in comparison to MGO diesel fuel emissions. However, methane emissions for LNG are much higher than with regular diesel fuels, due to the composition of LNG and methane slip.

Table 12: Tank-to-propeller greenhouse gas emissions for LNG, relative to MGO diesel 0.1% S, in gram CO2 equivalent per MJ fuel energy. Source: (Brynolf, Fridell, & Andersson, 2014), (ICCT, 2017), (Verbeek & Verbeek, 2015).

g/MJ	MGO Diesel 0.1% S	LNG Fossil	Renewable /Green LNG
CO_2	74	55.1	0
CH_4 ($CO_{2\ \mathrm{equivalent}}$)	0.00045	0.71	0.71
N_2O ($CO_{2\ \mathrm{equivalent}}$)	0.0035	0.0	0.0
Total $CO_{2\mathrm{equivalent}}$ 20 years	75.0	115	60
Total $CO_{2\mathrm{equivalent}}$ 100 years	74.9	75.0	19.9

An overview and comparison of the well-to-propeller emissions of diesel, methanol and LNG is presented in section 5.1.2.

4.5 LNG production and Infrastructure

The market of LNG as a maritime fuel is relatively small compared to the total trading volume. In 2019, a total of 119 billion m^3 LNG was imported in Europe, mainly from Qatar, Russia, US and Algeria (BP, 2020). Imports in the Netherlands are relatively low (10 billion m^3 in 2019) (CBS 2020). The main LNG import terminals in the ARA region are the terminals in Zeebrugge and Rotterdam. LNG is primarily regassified and distributed in the gas network.
Bunker volumes of LNG are limited but are growing rapidly. Bunkering volumes in Port of Rotterdam for example increased from 21,000 m^3 in 2018 to 71,000 m^3 in 2019 to 94,000 in the first two quarters of 2020 (Port of Rotterdam, 2020). Comparatively to the total bunkering market, the volumes however are still a tiny percentage.

Similarly to methanol, liquid gas can also be produced via other feedstock types.

- Liquified biogas, produced via fermentation of biomass. Currently, small-scale (bio-) gas production locations rely on the local biomass and waste supply, and are rather scattered across the Netherlands.
- Synthetic liquified Gas, produced from green hydrogen and a carbon source. Similar to e-methanol, this option still is at a low maturity.

In all main European Maritime ports, bunkering of LNG is feasible. This is partly because ports need to be compliant to the Directive on the deployment of alternative fuels in the EU (2014/94/EU). This directive states that LNG should be available in all major European ports (core ports in the TEN-T network) in 20225. An overview provided by (SEA - LNG, 2020) shows that the maturity of the bunkering infrastructure differs significantly. Some ports only offer truck-to-ship bunkering while others also have ship-to-ship bunkering capacity. In the ARA-regio, several bunkering vessels for ship-to-ship bunkering are available.

4.6 Safety aspects of LNG

Liquefied Natural Gas (LNG) is now well established as a marine fuel. Regulatory authorities and classification societies provide ample guidance on how to arrange LNG fuel systems and how to handle LNG in order to achieve sufficient safety. Sufficient in this context means that risks are tolerable. For example, regarding person related risk, tolerable means that an yearly accident probability between 1 out of 10.000 and 1 out of 100.000 is tolerable, provided that the consequences do not exceed the severity level ‘moderate’, i.e. ‘Major or Multiple Injuries, either reversible or non-disabling permanent injury’ (Safety Integrity Level Platform, 2018).

IMO’s International Code of Safety for Ships using Gases or other low-flashpoint Fuels (IMO, IGF Code (MSC.391(95) Code of safety for ships using gases or other low-flashpoint fuels), 2015) prescribes design and operational measures. This includes conducting a risk analysis on LNG handling/ storage equipment, emergency equipment and supporting structures (IACS, Rec_No_146, 2016). In theory, evidence should be available which shows that, by complying with IGF, using LNG as fuel on board ships, is as safe as using traditional oil fuels. This means that both are ‘located’ in the ‘tolerable’ area of the risk matrix. This needs to be demonstrated regarding risks to *persons*, risks to *property* and risk to the natural *environment*. It seems this evidence is not available explicitly.

The most ‘disruptive’ additional (safety) measures are, compared to traditional oil fuels;

1. more spacious containment systems, either high pressure (350 Barg) tanks or low pressure (10 Barg) cryogenic vacuum tanks,
2. more complicated fuel handling and preparation system,
3. more complicated bunkering system, both hardware and operation (see next paragraphs),
4. in case of cryogenic storage, expensive support structures and 2nd barriers against leaking,
5. more crew training required,
6. substantially higher capital costs.

A guideline is now available from the International Association of Classification Societies (IACS) called LNG BUNKERING GUIDELINES, Rec_No_142. (IACS, Rec_No_142, 2016). The purpose of the guideline is:

Quote
The purpose of these guidelines is mainly to define and cover the additional risks associated with bunkering LNG and to propose a methodology to deal with those additional risks in order to provide a similar level of safety as is achieved for traditional oil fuel bunkering operations.
Unquote

It acknowledges the need for additional measures when using LNG in order to ‘compensate’ for additional risks in comparison with traditional oil fuels. These additional risks are entirely due to the thermodynamic and chemical properties of LNG;

a. LNG needs to be stored at cryogenic temperatures (-162 Celcius),
b. smaller quantities (< 2000 m^3) are generally stored both under pressure (~ @ 10 Barg) and at cryogenic temperatures (-150 Celcius),
c. the flash point of evaporated LNG lies at -187 Celcius.

Another huge hazard regarding the *environment* is the property of NG being a green-house gas. In fact its detrimental effect in this respect is 27 times more severe than CO_2 .Therefore venting, let alone release of NG, is never tolerable.

Because of its gaseous state at ambient temperature and the low flash point temperature, a NG-air mixture may easily ignite. This stand in contrast to traditional oil fuels where flash points are above the SOLAS limit of 60 °C (IMO, SOLAS Consolidated Edition, 2018). Another hazard lies with the low storage temperature. In case of spills contact with the skin will cause burning injuries. Also a large spill on deck will cause brittle fracture of the deck structural material. This may jeopardise the structural integrity of the ship.

The IACS guideline introduces a break-down of the bunkering procedure as shown in Figure 11. It shows that the bunkering operation requires an effort which is substantially more demanding than the effort required in case of bunkering traditional oil fuels.

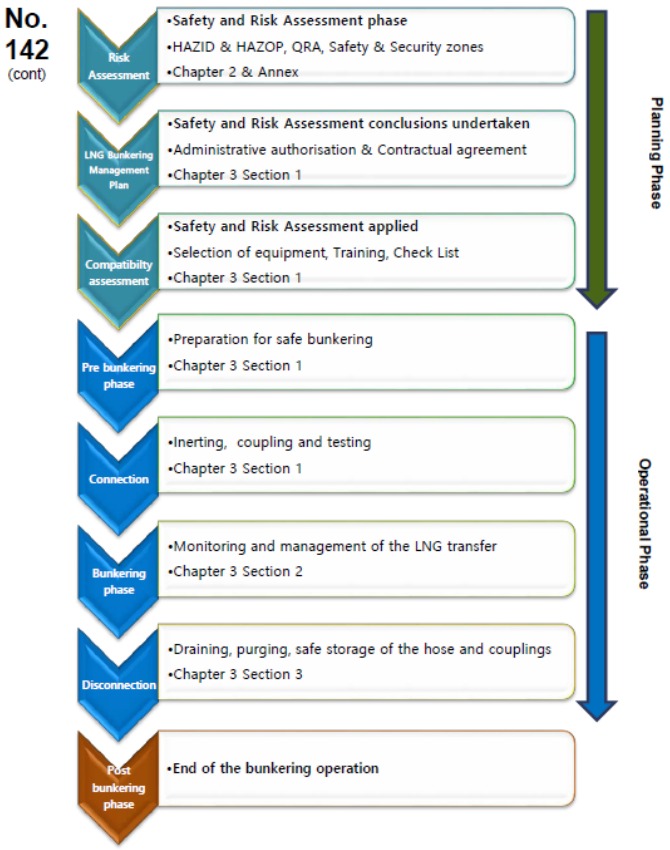

Figure 11: Bunkering process (IACS, Rec_No_142, 2016)

There are four bunkering methods, each with their specific pros and cons.

a) bunker ship/ barge to ship,
b) shore terminal to ship,
c) road tanker to ship,
d) swapping tank containers.

ad a)
This method is very similar to current most common practice of bunkering traditional oil fuels. This practice is now gradually introduced because a few LNG bunker barges have entered the maritime domain (e.g. 2019 Rotterdam (Figure 12), 2019 Brünsbuttel, US 2020). This practice is (safety) attractive because it hardly interferes with (un)loading or any other quay related activities.

Figure 12: Ship to ship bunkering (source: https://titan-lng.com/record-breaking-lng-bunkering-for-sleipnir-in-rotterdam/)

ad b)
The ship to be refuelled needs to come to the dedicated terminal, so bunkering simultaneously with (un)loading is not possible. From a safety point of view this option is attractive, because the ship is engaged in bunkering only, while the LNG bunker terminal will be at a fixed dedicated (safe) location.

ad c)
This practice is currently the most common. The bunkering takes place from the quay side where also other activities are taking place. From a safety point of view this is unattractive because people, not engaged with bunkering, can be in the vicinity so safe distance are harder to observe. Another disadvantage is that bunker locations can be anywhere which in case of emergencies will retard response. The most important drawback is the limited capacity of LNG road tankers which is restricted to about 60 m^3.

ad d)
This option has not been used up to now. It has the same disadvantages as bunkering from road tankers. Moreover it requires crane capacity, which introduces the additional hazard ‘dropped container’. However for some dedicates ships it may be attractive because fuelling can take place very rapidly.

The risk to persons is mostly related to burning in case of contact with cryogenic liquid. The other environmental hazard is methane leakage (GHG effect 27 x CO_2).

5 Comparison methanol, diesel and LNG

5.1 Emissions

5.1.1 Tank to propeller pollutant emissions

Table 13 shows the tank-to propeller pollutant emissions for respectively, NO_x, SO_x and PM in gram per kWh mechanical work (engine output). The SO_x and PM emissions for methanol and LNG are very low. The SO_x emissions are primarily based on the sulphur in the diesel pilot. A diesel pilot of 2% on energy basis is assumed (plus in addition ~5 ppm S within the LNG). MGO and methanol need additional NO_x emission control technologies to meet Tier III NO_x emission level. For MGO this will be SCR aftertreatment or EGR (Exhaust Gas Recirculation). For methanol, the most likely technologies are SCR aftertreatment or application of a methanol-water fuel mixture.

Table 13: Tank-to-propeller pollutant emissions for MGO, methanol and LNG in gram per kWh mechanical work (engine output).

g/kWh	HFO 0.5% S	MGO 0.1% S Tier II	MGO 0.1% S Tier III	Methanol Tier II	Methanol Tier III	LNG Tier III
NO_x	12.8	9	2-3	5	2.2	2
SO_x	2.0	0.36	0.36	0.007	0.007	0.009
PM_{10}	0.74	0.23	0.23	0.034	0.034	0.02

5.1.2 WTP GHG emissions

A comparison of the well-to-propeller CO_2-equivalent emissions in gram per MJ fuel energy is shown in Table 14. This is done for the three fuels; diesel methanol and LNG for both the fossil as well as for the biofuel equivalents. The WTT values are based on JRC, 2014. These values deviate slightly from the values in the more detailed analysis in the previous sections. The GHG emissions are expressed in CO_2-equivalent emissions for 100 year global warming potential. The well-to-propeller GHG emissions are graphically shown in Figure 13.

Table 14: Well-to-tank, tank-to-propeller and well-to-propeller CO2-equivalent emissions for different energy carriers with 100 year GWP (CO2eqg/MJ). Based on: (JRC, 2014) and (brynolf 2014).

	WTT **CO_2 equivalent**	**TTP** **CO_2 only**	**TTP** **CO_2 equivalent CH_4, N_2O**	**WTP** **CO_2 equivalent**
MGO	14.2	74.1	0.9	89.1
HFO	11.1	77.4	0.9	89.4
Bio-diesel	8.1 to 57.1	0	0.9	9 to 58
Fossil MeOH	24.9 to 32.2	69.1	-	94 to 101.3
Bio-MeOH	2.2 to 6.6	0	-	2.2 to 6.6
LNG	19.4	55.1	19.9	94.4
Bio-LNG	2.7	0	19.9	22.6

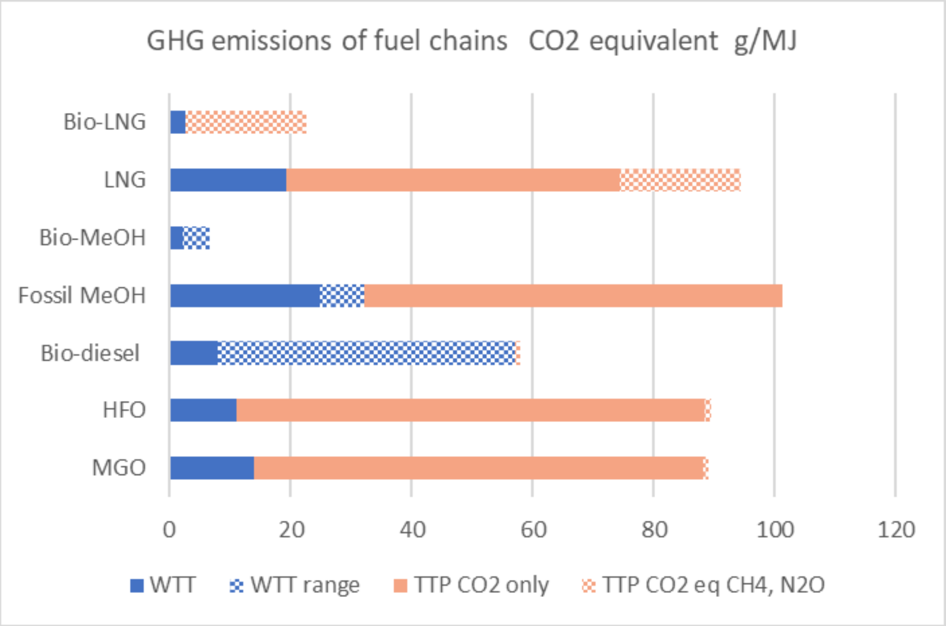

Figure 13: Well-to-propeller CO_2-equivalent emissions for different energy carriers with 100 year Global Warming Potential, GWP (CO_{2eq}g/MJ).

5.2 Safety

As mentioned, risk is assessed with respect to people, property and environment. The final results of the assessment is the location of a particular fuel in the risk matrix. In the examples shown in Figure 14, Figure 15 and Figure 16, related to *persons*, *property* and *environment* respectively, MGO, LNG and methanol have been given a ‘risk location’. LNG and methanol have been given a location in thin print, which would be valid for the case where no additional safety measures are taken. Thick print indicates where the fuel ends up when additional measures are taken. In this example additional measures affect probabilities only. Whether this is the case depends heavily on the definitions used in the risk assessment. In these examples the definition of the hazardous event is *spill/ leakage of containment*. Consequences are injury/ loss of life (people), loss of property (property) and damage to the environment (environment).
The scope of the GMM project does not allow for a full risk analysis. Therefore the locations in the risk matrices and the effect of additional safety measures on such locations are merely an educated guess.

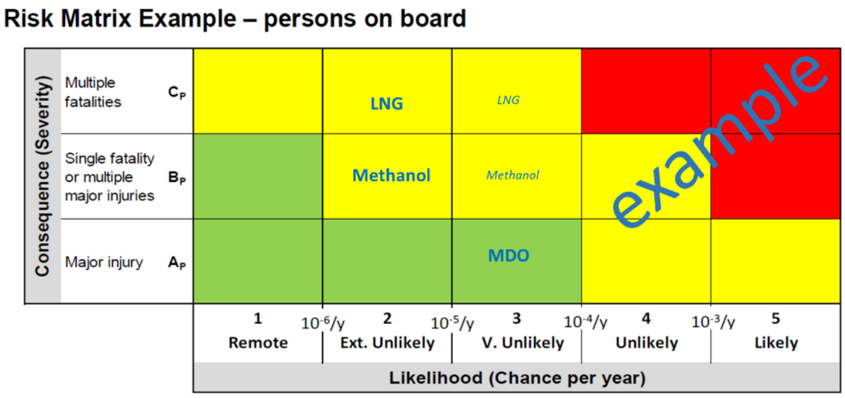

Figure 14: Risk matrix for persons on board (IACS, Rec_No_146, 2016)

IACS gives examples for risk matrices in their publication (IACS, Rec_No_146, 2016). The risk to persons on board and property use the same risk matrix as shown in Figure 14 and Figure 15.

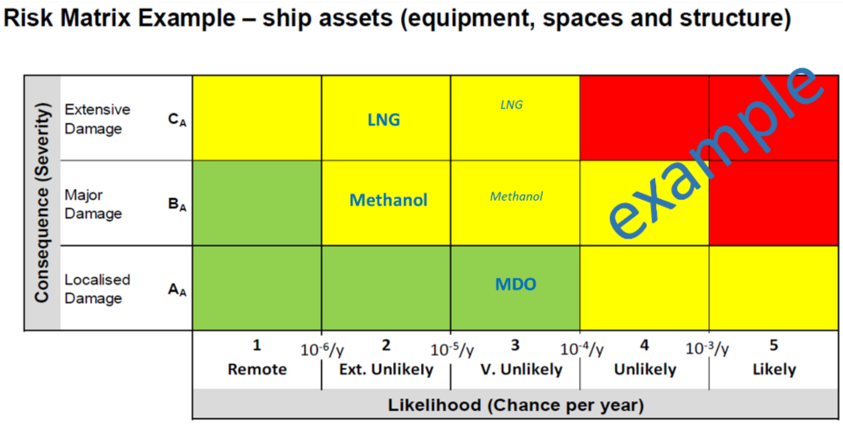

Figure 15: Risk matrix for property (IACS, Rec_No_146, 2016)

Since MDO is acceptable to society and consequences of MDO spills are expected to be low, i.e. level A, the highest possible likelihood is level 3, very unlikely. Assuming loss of containment or spills of LNG or methanol equally likely in conjunction with increase consequences yields the initial location of these fuels in the risk matrix. They are both in the yellow area and must therefore be further considered in order to improve the risk score. Additional measures in this example reduce likelihoods, hence the fuels move horizontally towards a lower likelihood. The presented shift is based on a best guess.

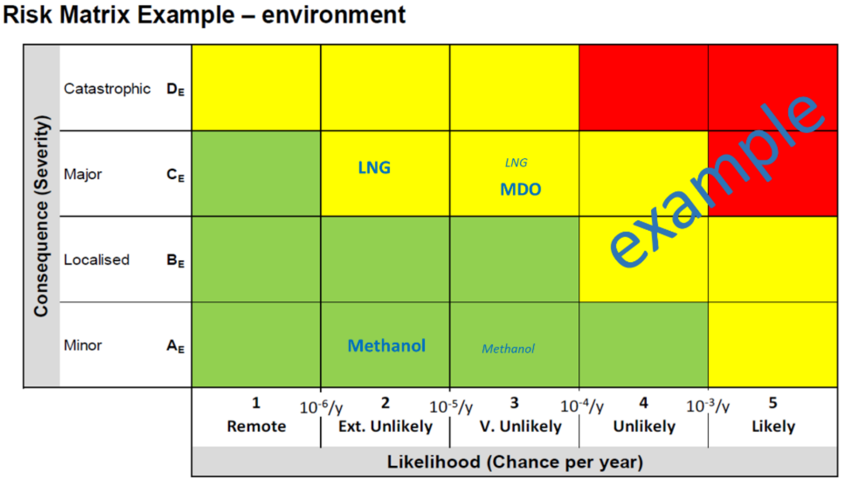

Figure 16: Risk matrix for environment (IACS, Rec_No_146, 2016)

Risk to the environment uses a slightly more sophisticated risk matrix. Again the initial location of LNG and methanol, as well as the likelihood shift due to additional measures have been guestimated. They are mainly intended for illustration purposes.

6 Conclusions

In this factsheet report a comparison is made for diesel fuel, methanol and LNG on market potential, fuel production and infrastructure, safety and environmental aspects. This leads to the conclusions below.

Market potential and practical application
There are several options for ship owners for reducing their emissions. Switching to methanol or LNG depends on the bunker frequency, sailing pattern and technical layout of the vessel. Methanol and LNG offer good options for sustainable fuel production leading to lower GHG emissions than standard, fossil diesel fuels MGO and HFO.

Methanol and LNG may lead to adaptations in the ship specifications, since diesel fuel has by far the highest energy density. If the tank weight and packing factor is included, both weight an volumetric energy density are a factor two to three higher for diesel fuel than for methanol and LNG.
Engine availability is good for both diesel and LNG. Currently, for methanol only a few large engine types from two manufacturers are available.

Pollutant emissions
Compliance with current and future emission legislation can be met with all three fuels. However for LNG and Methanol, NO_x emission control for Tier III will be easier. Also SO_x and PM emissions will be some 75% lower than for diesel fuel (MGO and HFO). Lower SO_x and PM emissions with diesel fuel are also possible, but then almost all sulphur needs to be taken out of the fuel, or a biofuel could be used.

GHG emissions
- Based on fossil fuels, the GHG emissions of methanol and LNG are a bit higher than for diesel fuel. This is respectively 5%-10% (methanol) and 5% (LNG) higher.
- Based on biofuels; methanol probably has the lowest GHG emission. Biodiesel shows a broad range depending on feedstock and production method. LNG is higher than methanol, due to the usual engine methane emission.
- Based on P2X, synthetic production via green electricity and H_2, the GHG emissions will likely be very low for all three fuels.

Fuel production and infrastructure
The uptake for all three fuel types depend a lot on the developments in biofuels and synthetic fuels. As discussed in the WP4 report of Green maritime Methanol, there are large uncertainties in future price developments. In WP6 the impact of this uncertainty will be elaborated in business cases for different vessel types.

Bunkering facilities for LNG are widely available in the main European ports, although the maturity of this infrastructure varies greatly. Ship-to-ship bunkering is possible in the main ARA-ports.
For methanol, there is currently no bunkering infrastructure available. Because methanol is widely available as a feedstock for industry, distribution of the fuel is relative simple. In a first stage truck-to-ship bunkering is feasible.

Safety
Without additional measures, introducing methanol as bunker fuel on board ships increases the associated risks. In fact because of its low flashpoint (< 60 °C) methanol is prohibited by SOLAS. Only by implementing additional safety measures authorities can grant permission for this fuels. The IGF code specifies these additional measures, albeit that currently only LNG is covered, while requirements for methanol are under development and will be included at a later stage. Besides a substantial set of prescriptive guidance the code requires a risk assessment to be carried out where the risks of each specific fuel system are to be determined in term of probabilities and consequences of incidents. In principle these outcomes are to be compared with results for conventional fuels in order to demonstrate equivalent safety. Demonstrating such equivalent safety, can be done in a convenient way by applying the concept of risk.

Entrepreneurs who introduce new technologies are, themselves responsible for generating and interpreting the technical evidence. Statutory authorities should be provided with such evidence including an assessment which must be sufficient to enable them to judge safety implications.

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8 Signature

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Appendix A: Emission legislation

Fuel and pollutant emissions regulations

Under MARPOL, two types of regulations regarding pollutant emissions are introduced:

- Regulations for max sulphur content in the fuel
- Tier legislation to limit NO_x engine emissions

The fuel regulations apply to all ships. The NO_x regulations on the other hand, only apply to new ships, build from a certain date.

Regulations on diesel fuel

IMO Regulation 14 regulations several fuel qualities with respect to the sulphur content, which apply respectively globally (worldwide) and for Emission Control Areas (ECAs). The requirements which become more stringent over time are presented in Table 15. The more detailed fuel composition requirements are specified in ISO 8217.

Table 15: Fuel sulphur requirements in order to limit SOx emissions

Fuel S content	2008	2010	2012	2015	2020
SO_x Emission Control Area (SECA)	1.5%	1.0%		0.1%	
Worldwide	4.5%		3.5%		0.5%

The fuel Sulphur limits limit both the SO_x emissions as well as the particulate emissions of engines.

Regulations on NO_x emissions

NO_x regulation is laid down in IMO Regulation 13, also referred to as MARPOL Annex VI and NO_x Technical code. The NO_x limits are presented in Figure 17. The limits are dependent on the rated (max) engine speed, due to which the limits are more stringent for smaller engines than for larger engines. Tier II entered into force for new ships build from 2011 onwards. The NO_x limits are 15% to 25% lower than Tier I, which entered into force in 2005. The NO_x limits for Tier III are 80% lower than for Tier I. Tier III entered into force for the USA east and west coasts in 2016. It will enter into force in Europe for the North sea and Baltic Sea in 2021.

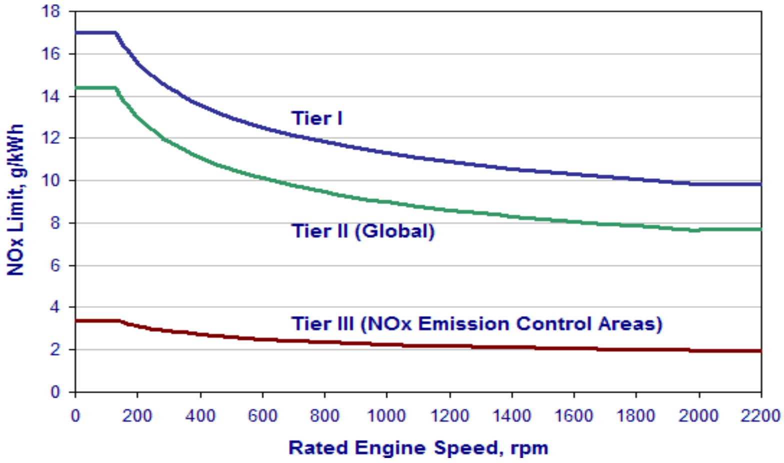

Figure 17: NO_x emission limits for Tier I-III in g/kWh.