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LNG for trucks and ships: fact analysis
Review of pollutant and GHG emissions
Final

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Summary

In recent years, several studies were done in the Netherlands addressing the possibilities of natural gas as fuel for transportation and the options to fulfil future GHG requirements with a range of alternative fuels. These studies covered pollutant as well as GHG emission for road-, inland water - and sea transport. Following these projects, several stakeholders wished to update recent information and to evaluate and compare the possibilities of several alternative fuels in more detail.

The objectives are:

- To compare pollutant and GHG emissions of LNG and several biofuels with diesel fuel, for three transport modalities: heavy-duty vehicles, inland ships and sea ships.
- To review the availability of different biofuels.
- To review the results with experts and stakeholders

In particular the results of the study ‘Natural Gas in Transport’ (2013) [1] and the recent ‘Dutch fuel mix assessment’[2] were used. Both studies were done in close cooperation with CE Delft, ECN, TNO and the Dutch Ministry of Infrastructure and the Environment (I&M) and many outside experts and stakeholders. The reference period of this study is 2015 to 2020. So the technical solutions, performances and emission levels are related to products entering the market in this period.

The focus of this study is on heavy transport, which leads to an evaluation of the following alternative fuels: LNG (Liquefied Natural Gas), biogas (Compressed BioGas, also called bio-CNG or Liquid BioMethane, also called bio-LNG) and liquid biofuels (biodiesel or FAME and Hydrogenated Vegetable Oil or HVO). For a number of reference vehicles/ships charts are produced with pollutant emissions and GHG emissions using a number of fossil - and biofuel options. The GHG emissions are summarized in figure A below.

The main conclusions are as follows[3][4]:

- For trucks the application of LNG will lead to a GHG reduction of 10-15%, provided that the energy consumption increase of gas engines can be limited to some 5-10%.

- The pollutant emissions for all truck engines are expected to be low due to the very stringent Euro VI legislation. Limited available Euro VI data show a range from equal emissions for gas and diesel engine to significantly lower NOx and PM emissions for the gas engine

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[1] Natural gas in transport: An assessment of different routes. R. Verbeek, N. Ligterink, J. Meulenbrugge, G. Koornneef, P. Kroon, H. de Wilde, B. Kampman, H. Croezen, S. Aarnink. Report by CE Delft, ECN and TNO. Publication code: 13.4818.38, May 2013

[2] Duurzame Brandstofvisie met LEF. http://www.energieakkoordser.nl/nieuws/brandstofvisie.aspx. 30 June 2014

[3] Conclusions on pollutant emisions are based on a tank-to-wheel (or propeller) analysis while GHG emissions are based on a well-to-wheel analysis.

[4] The calculations are based on natural gas without significant leakage at gas fields or pipelines

- Trucks with gas engines have lower noise emission than diesel trucks and therefore often qualify for reamer city delivery conditions. Lower noise emission is also expected with Ship gas engines.
- For ships, LNG is especially applied to reduce pollutant emissions. The NOx and particulate mass[5] emissions for both inland and sea ship engines running on LNG are generally more than 75% lower than for conventional diesel engines. Sea ships will also have a 90% lower SO_x emission[6]. The reductions are even higher when diesel engine using MDO/HFO and/or older diesel engines are replaced by gas engines.
- For ships, the GHG emission difference between LNG and diesel powered ships is uncertain due to a lack of data of methane emissions of gas engines[7]. Available data shows similar GHG emissions as for gas and diesel powered ships. Some large engines however show low methane emission. This demonstrates the technical feasibility, for large engines, to reduce up to 15-20% GHG emissions with LNG[8]..
- For substantial GHG emission reduction, biofuels can be used. The largest GHG emissions reduction (~ 80%) are achieved when residual or waste streams of feedstock are used (e.g. manure, municipal waste for biogas, and tallow, used cooking oil for biodiesel). The reduction will be in the range of 30-60% with agricultural crops. Liquid biofuels (biodiesel) from rapeseed or palm oil often have equal or higher GHG emissions than with fossil fuels due to ILUC[9]. This will likely improve over time.
- The availability of biomass for biofuels, chemical products and heat & power production, has been estimated to be between 50 and 150 EJ globally in 2030. For the Netherlands, the availability is expected to be between 5 and 80 PJ in 2030 and maximal 180 PJ in 2050. However if this potential will be realized in practice is highly uncertain and subject to a coherent energy policy. 80 PJ corresponds to about 15% of the current energy use for transportation. The amount of liquid biofuel (biodiesel, bio-ethanol) is in most projections a factor 3-5 larger than the amount of biogas. It is also concluded that even though the European Commission wants a fast transition to second generation biofuels, the volume of second generation may be small compared to the first generation biofuels up to 2030-2035.
- Methane has a higher climate effect than CO2 and according to the latest IPCC report, its Global Warming Potential factor is higher than earlier adapted[10]. Consequently it is very important that methane leakages with production and

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[5] There is no indication that ultrafine or fine particle number emission will increase with lean-burn or dual fuel gas engines compared to diesel engines, but no data was available to support this. Based in experience with truck engines particle number emissions are expected to go down.

[6] Inland ships have already very low SOx emissions due to the use of ultra-low sulphur fuel.

[7] This is based on Global Warming Potential factor for 100 years for methane of 25. For the much shorter 20 years period, the GHG emissions of LNG ships would be up to 50% higher than for diesel when the latest GWP factor of IPCC of 86 is used. In the latest study by IPCC (2013), it is discussed that the impact may also be lower

[8] This is with a methane emission lower than 1 g/kWh. Technology is relatively complex because high engine efficiency and life time needs to be maintained as well. There is also a trade off with pollutant emissions

[9] CO2 emissions due to Indirect Land Use Change (ILUC) occur when due to production of feedstock for biofuel, the original agricultural production is moved to other areas. In this latter area GHG emission can occur due to the change in vegetation.

[10] For international GHG emissions inventories, formally the Global Warming Potential factor for 100 years of 25 is used for methane, which is also used for the projections in this report. According to the latest IPCC report, this factor should actually be 34.

distribution of natural gas and methane emissions of gas engines are minimised.

The following recommendations are done:

- In order to be able to realise a significant GHG advantage with LNG, it is recommended to come to an agreement between authorities and industry about a time path to reduce methane emissions of ship engines to maximal 1 g/kWh and implement this in future legislation as soon as possible. Alternatively legislation can be considered to regulate total GHG emission of gas engines (combined result of engine efficiency and methane emission reduction).
- To obtain more measurement results on methane emissions of dual fuel gas engines for ships and particulates emissions of ship engines with all fuels, such that gaps in information can be filled in.

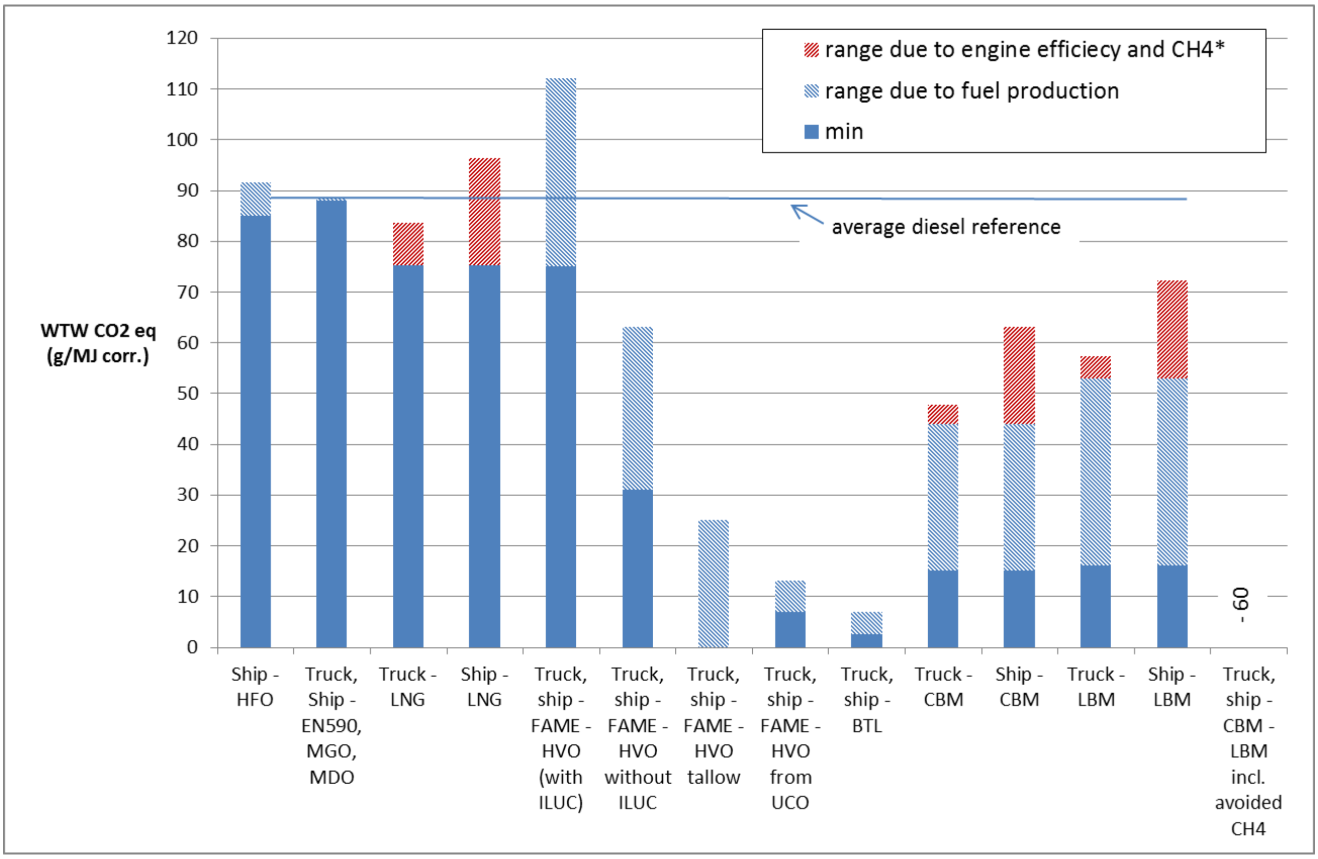

Figure A Well to Wheel GHG emissions for different fuels and transport modalities: truck, inland ship and sea ship. * CH4 emission from engine.

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Appendices

Abbreviations

BTL	Biomass To Liquid
CBG	Compressed Bio Gas (=CBM)
CBM	Compressed Bio Methane
CH_4	Methane
CI	Compression Ignition (diesel)
CO	Carbon monoxide
DF	Dual Fuel (gas and diesel)
ECA	Emission Control Area
EGR	Exhaust Gas Recirculation
EJ	Exa Joule = 10^18 Joule
EN590	Diesel fuel, automotive specification, also used for inland shipping
FAME	Fatty Acid Methyl Esther (biodiesel)
GHG	Green House Gas
GTP	Global Temperature Potential
GWP	Global Warming Potential
HC	Hydro Carbon
HFO	Heavy Fuel Oil (residual diesel fuel)
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ILUC	Indirect Land Use Change
LBM	Liquid Bio Methane
LCA	Life Cycle Analysis
LNG	Liquefied Natural Gas
LSHFO	Low Sulphur Heavy Fuel Oil
LSMDO	Low Sulphur Marine Diesel Oil
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MTOE	Million Ton of Oil Equivalent
N2O	Nitrous oxide
NECA	NOx Emission Control Area
NOx	Nitrogen Oxide
PJ	Peta Joule = 10^15 Joule
PM	Particulates Mass
PN	Particulates Number
SCR	Selective Catalytic Reduction (generally of NOx)
SECA	SOx Emission Control Area
SI	Spark Ignition (Otto)
SOx	Sulphur oxide
TTW	Tank To Wheel
WTT	Well To Tank
WTW	Well To Wheel

1 Introduction

In recent years, several studies were done in the Netherlands addressing the possibilities of natural gas as fuel and the options to fulfil future GHG requirements with a range of alternative fuels.
The options and emissions for CNG and LNG were extensively evaluated in the study Natural Gas in Transport (2013)[11], which was carried out by CE Delft, TNO and ECN. Following that study, in 2014, the implementation of alternative fuels options in order to contribute to future GHG emissions reductions, was investigated with a large number of stakeholders (Dutch fuel mix assessment, 2014). Following these projects, several stakeholders wished to update the first study with recent information and to evaluate and compare the possibilities of several renewable fuels in more detail. This study is focussed on these aspects. This study is set up as a quick scan using existing information, primarily of the studies mentioned above. For more detailed information and scientific references, general reference to those studies is made.

The objectives are:
- To compare pollutant and GHG emissions of LNG with diesel fuel and several biofuels for three transport modalities[12]: heavy-duty vehicles, inland ships and sea ships.
- To review the availability of the different biofuels.
- To review the results with experts and stakeholders and include this in the final report.

1.1 Scope of engines size road & maritime

The scope of typical engine types and power ranges for the three transport modalities, considered in this report, is presented in Table 1. For a full overview of ship engine manufacturers diesel and gas engines, refer to van der Burg (2014)[13]

Table 1. Overview engines for different transport modalities

Modality	**Engine type**	**Power range (per vehicle /ship)**
HD Vehicles	Heavy Duty	100 – 500 kW
Inland ships	High Speed Medium Speed	200 – 2500 kW 1000 – 2500 kW
Short sea ships	Medium Speed Slow speed	2 – 10 MW 4 – 10 MW
Deep sea ships	Medium Speed Slow speed	10 – 30 MW 4 – 50 MW

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[11] Natural gas in transport: An assessment of different routes. R. Verbeek, N. Ligterink, J. Meulenbrugge, G. Koornneef, P. Kroon, H. de Wilde, B. Kampman, H. Croezen, S. Aarnink. Report by CE Delft, ECN and TNO. Publication code: 13.4818.38, May 2013

[12] Not included in this assessment are options such as full electric, hybrid drivelines and fuel cell. These options may be suitable for urban transportation and could lead to pollutant, GHG and noise reduction.

[13] Leo van der Burg: Gasmotoren in der maritimen Anwendung,,Fachsymposium LNG 2014 NHL Hogeschool/MARIKO GmbH. 6 October 2014. http://www.lng-nordwest.de/index.php/technologien-und-innovationen.html

1.2 Assessment of pollutant and GHG emissions

In this study pollutant and GHG emissions are addressed. It is important to clearly define which part of the 'Life Cycle chain' is included in this assessment.

In Figure 1 below an overview of the Life Cycle for transportation and different parts is given:

- LCA is the total life cycle including the production of the vehicle or ship and recycling at the end of its lifetime.
- Well-to-Wheel (WTW), for ships also named Well-to-Propeller or Well-to-Wake: This include the overall fuel chain from production of the feedstock at the source to combustion in the engine.
- Well-to-Tank (WTT): the production and distribution of the fuel up to the fuelling station
- Tank-to-Wheel, Tank-to-Propeller (TTW, TTP): The combustion of the fuel in the engine, or e.g. the energy conversion in electric motor or fuel cell.

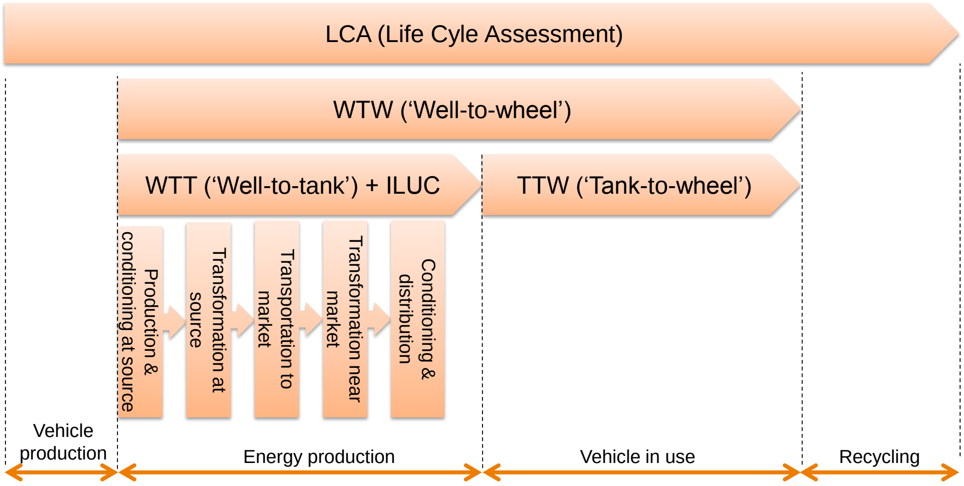

Figure 1 Schematic overview of different ways to define vehicle emissions.

In Table 2 an overview is given about the parts of the life cycle which are addressed for the pollutant and GHG emissions. For a more extensive description on the interpretation of GHG emissions, refer to Appendix A.

Table 2 Assessment of pollutant and GHG emissions

Emission	Components	Part of the Life Cycle
Pollutant emissions	NOx, PM (particulate mass), SOx	Tank-to-Wheel or Tank-to-Propeller
GHG emission	CO2, CH4, N2O	Well-to-Wheel or Well-to-Propeller

2 Engine technologies and emissions legislation

2.1 Gas engine technologies

For gas engines two main technologies can be distinguished:
- Single fuel, spark ignition (also indicated as positive ignition or Otto engine)
- Dual fuel, compression ignition: a small diesel injection is used to ignite the gas. The quantity of diesel can vary from a few percent to some 10% or more.

In figure 2 an overview of different sub-options is given together with typical application areas.

The choice of technologies is generally dependent on the following factors:
- Pollutant emission legislation (NOx, PM, methane)
- GHG emission requirements
- Engine efficiency requirements
- Fuel flexibility and price
- Requirements for robustness and lifetime.

For an overview of the emissions legislation for the different transport modalities, refer to section 2.2 and Appendix B.

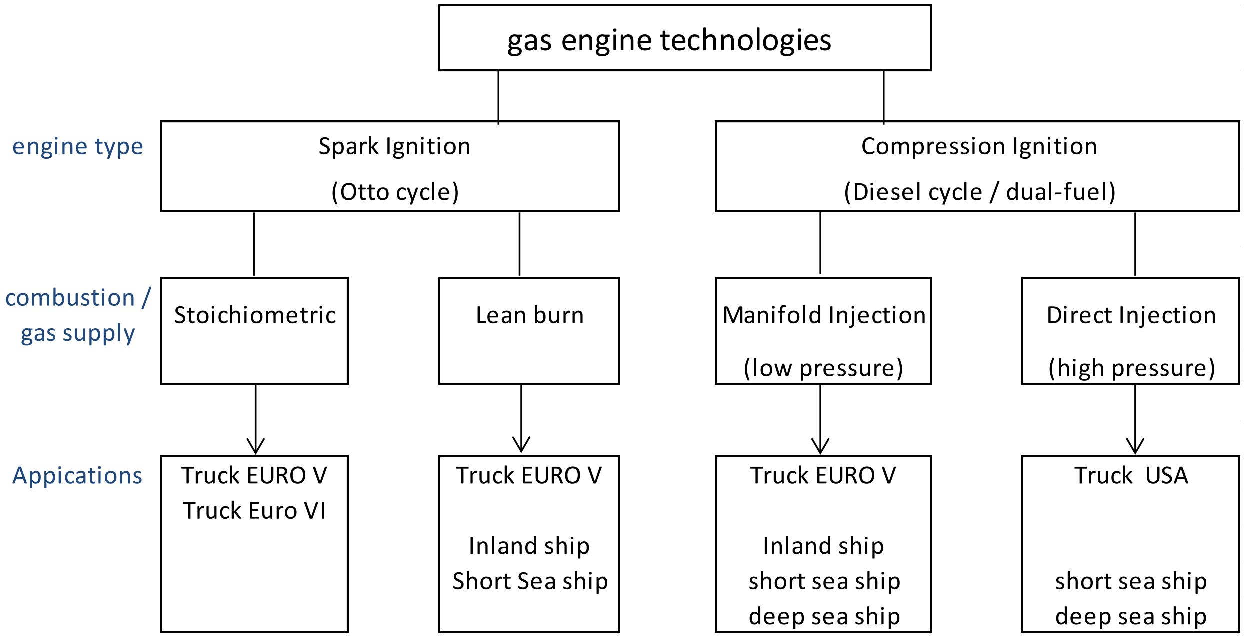

Figure 2 Currently applied gas engine technology options and application areas

2.1.1 Spark Ignition or pure gas engines

Spark Ignition engines are also referred to as ‘positive ignition’ engines and in case of gas as fuel also as pure gas engines. Two main sub-options are possible: with stoichiometric combustion (lambda=1) and lean-burn combustion. For the stoichiometric one generally a 3-way catalyst is installed to control three emission components: NO_x, HC and CO. Engines with a lean-burn combustion principle can achieve down to about 2 gram NOx per kWh without NO_x aftertreatment technology.

In some cases oxidation catalysts are mounted to reduce methane emissions, although insight in effectiveness over engine lifetime is generally not given.

With spark ignition gas engines, the gas is generally injected under low pressure in the inlet manifold. In some cases a venturi is used to dose the gas to the air inlet. Direct injection of gas into the cylinder is still under development, especially for HD vehicles and cars.

2.1.2 *Compression Ignition dual-fuel engines*

These engines use both gas and diesel for combustion. A small amount of diesel is used to ignite the gas. The quantity of diesel can vary considerably from a few percent to some 10% or more.

Dual-fuel engines are especially popular for ships and for trucks. This is due to the fuel flexibility and high efficiency. Often these engines can also run on 100% diesel fuel.

The gas can be dosed to the engine in several ways: in the inlet manifold (low pressure) and directly into the cylinder (high pressure). With admission in the inlet manifold, there can be central admission of gas or admission per cylinder. The latter offers significant benefits compared to central injection. With direct-injection of gas, methane emissions can be lowered more effectively, although it may then be more difficult to obtain the lowest pollutant emissions levels and requires additional attention for safety. Direct injection of gas is currently used by MAN for the large 2-cycle ship engines[14] and also by Cummins[15] USA. Volvo has such as system under development for Euro VI trucks. The quantity of gas varies significantly between manufacturers.

2.1.3 *New or retrofit gas engines*

The precise definition of retrofit can lead to some confusion.

An engine with retrofit LNG system is defined as an engine original produced as diesel engine which is converted to LNG dual fuel. This can be done by an engine importer or another third party (typical gas system supplier). Gas engines which are originally build as single fuel gas engine, dual fuel engine or pilot diesel are called OEM engine.

An existing ship can be retrofitted with OEM gas engines or with retrofit gas engines In this report however the word retrofit always refers to the engine technology and not to a ship.

In practice both new and existing HD vehicles & ships can be equipped with OEM gas engines or with retrofit gas engines. In most cases OEM gas engines are mounted. Some examples of retrofit gas engines are:

- Retrofit dual fuel gas engine in MAN truck(s)
- Retrofit dual fuel gas engine in inland ship (Caterpillar in Argonon[16])

2.1.4 *Methane emissions*

Relatively high methane emissions, also referred to as methane slip, is a well known issue of gas engines. It is basically fuel not taking part in the combustion process.

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[14] Dual Fuel ME-GI engine: Performance and the economy. Rene Sejer Laursen. MAN Diesel & Turbo 2012

[15] Cummins Westport Spark-Ignited (SI) and High Pressure Direct Injection (HPDI) Natural Gas Engines. Natural Gas Vehicle Technology Forum (NGV-TF) 2003

[16] Development of this retrofit solution is currently not pursued

There can be several causes for this methane emission:

- Methane mixed with inlet air flushed from the inlet to the exhaust manifold during the valve overlap (from exhaust to inlet stroke)
- Incomplete combustion due to a too lean mixture, possibly in combination with a too low temperatures near cylinder walls.

Several measures can be taken to reduce methane emissions such as:

- Reduction of valve overlap,
- Precise control of lean air-fuel ratio or switch to stoichiometric combustion,
- In cylinder injection or timed (sequential) injection into the inlet manifold.

As far as know, three engine types are currently showing low methane emissions. These are spark ignition, stoichiometric EURO VI truck engines, a US dual fuel truck engine and some dual fuel ship engines with in-cylinder, high pressure injection. For more detailed information, refer to section 3 and 4.3.1.

2.2 Comparison emissions legislation

A description of the pollutants emission legislations for heavy-duty vehicles, inland ship and sea ship engines is included in Appendix B.
A generic comparison of the three modalities is presented in the tables below. Table 3 shows the pollutant and methane emission limits in g/kWh. In table 4 the fuel sulphur requirements are given. The fuel sulphur in the fuel is responsible for SO2 and also sulphated ash emissions. The first is gaseous, the second is a part of the particulate emissions. Limiting fuel sulphur content reduces also the particulates emission and makes operation of catalysts and particulate filters easier and more effective.

Table 3 Emissions legislation and NO$_x$, PM and methane limit values

Modality	**Current**	**NO$_x$ g/kWh**	**PM g/kWh**	**PN**	**Methane g/kWh**
Trucks	2013 Euro VI	0.4	0.01	$8x10^{11}$	0.5
Inland ships	2007 CCNR II 2018 Stage V	6 – 9.5 (0.4 – 1.2)**	0.2 (0.025 – 0.01)**	-	-
Sea ships	2011 Tier II 2016* Tier III	7.7 - 14.4 2 - 3.4	***	-	**** -

* Only for ECA North America
** Recent proposal from the Commission
*** PM indirectly controlled by fuel sulphur requirements
***** Unofficial target of 6 g/kWh such that GHG emissions of gas engines are not higher than GHG emissions of diesel engines. Refer to section 3.4.1.

Table 4 Fuel sulphur requirements and projected max SO$_2$ emission

Modality	**Year**	**Fuel type**	**Fuel sulphur***	**projected max SO$_2$ g/kWh**
HD Vehicles	2005	EN590	10 ppm	0.004
Inland ships	2011	EN590 / VOS	10 ppm	0.004
Maritime ECA	2010 2015	MDO MGO	1% 0.1% (1000 ppm)	4 0.4
Maritime Global	2012 2020	HFO LSHFO, LSMDO	3.5% 0.5%	14 2

* Fuel S requirements can also be met by applying a SO$_x$ scrubber

In addition to pollutant emissions legislation, for ships there is also legislation for energy efficiency and CO_2:

- EEDI: Energy Efficiency Design Index
- SEEMP: Ship Energy Efficiency Management Plan

For trucks, legislation for energy efficiency and CO2 is under development.

3 Transport modes and pollutant emissions

3.1 Heavy duty vehicles

3.1.1 Engine technology

Diesel engines

The emissions of normal Euro VI diesel engines are very low due to the very stringent emissions legislation. The type approval has thorough procedures for the formal type approval including:

- cold start and particulate number requirements apart from the normal regulated components (NO_x, CO, HC and particulate mass)
- requirements for Real Driving Emissions (RDE)
- on-board diagnostics (with NO_x sensor)
- stringent fuel sulphur requirements (S <10 ppm)

This has led to the application of robust emission control systems such as diesel particulate filters and well calibrated SCR catalysts.

Gas engines (including dual fuel)

For gas engines the same type approval procedure applies. Additionally, for Euro VI, a requirement for methane emissions was introduced ($CH_4 < 0.5$ g/kWh). This limit will probably secure low methane emissions and will consequently limit the technology options. Especially simple dual fuel engines, but also lean-burn gas engines will have a problem fulfilling these kind of requirements.

Before 2014 most HD vehicle manufacturers had Euro V gas engines in their program. The power range was however limited. Most of the OEM engines were spark ignition engines, although Volvo also supplied a dual fuel engine. The spark ignition engines either had stoichiometric combustion (lambda=1) or lean-burn combustion. The latter has a relatively low NO_x emission without the need for NO_x aftertreatment. However this is not sufficiently low for Euro VI requirements.

With the start of Euro VI (2013), the availability of engines shrunk, primarily due to the very stringent NO_x and CH_4 emissions requirements. Most OEMs applied the lean burn combustion, which is not sufficiently clean to meet the stringent NO_x requirements. For the spark ignition engines, in practice it means a switch to the stoichiometric combustion principle and the application of a 3-way catalyst. In this catalyst, commonly applied in passenger car petrol engines since 1990, unburned HC and CO react with NO_x leading to a large reduction in all three components. The currently available Euro VI engines apply the spark ignition and stoichiometric combustion technology (IVECO, Scania, Volvo, Daimler).
Volvo is currently working on a more powerful dual fuel engine. This dual fuel engine will have high pressure –in-cylinder- gas injection. In that way, it is expected that the methane emission requirements can be met and that in practice a high share of gas (target >90%) can be achieved. Target for application are heavy tractor-trailer transport. There are currently no announcements of other HD vehicle OEMs to introduce dual-fuel engines.

An overview of the gas engine technology for the different HD vehicle segments is presented in Table 5.

Table 5 Introduced and expected gas engine technologies for Euro VI HD vehicles

	Bus	**Rigid truck**	**Tractor semi-trailer**
application	public transportation	regional distribution	regional / national distribution
Engine technology	Spark Ignition (SI) Lambda = 1 3-way catalyst	Spark Ignition (SI) Lambda = 1 3-way catalyst	SI, Lambda = 1 3-way catalyst
			Dual fuel (>90% gas), SCR deNO$_x$ catalyst
Fuel(s)	CNG / LNG	CNG / LNG	LNG

3.1.2 Emissions HD vehicles

Up to Euro V, the pollutant emissions of diesel engines were not very low. Consequently NOx and PM emissions of gas engines were in practise a lot lower. With the introduction of Euro VI (2013), robust emission control systems were applied on diesel engines. As a result the difference between diesel and gas engines is reduced even though also gas engines have improved.
An overview of the (expected) emissions in gram per unit of mechanical work (g/kWh) of diesel and different types of gas engines is presented in Figure 3 below. The emissions of diesel and SI gas engines are based on Portable Emissions Measuring System (PEMS) measurement results and type approval data of a limited number of trucks. The emissions of the dual-fuel engine are estimated. PEMS measurements are taken on the road in real traffic situations. The trips chosen include equal time periods of city, rural and motorway driving. The SO$_x$ emissions are only dependent on the fuel sulphur level. Refer to appendix C for more information. The PM emissions are very low for all engine types due to the very stringent requirements for Euro VI. Diesel engines are equipped with wall-flow particulates filters, dual-fuel engines may be as well. Type approval data of two Euro VI gas engines show on average lower NO$_x$ and PM emissions than diesel engines of the same brand. For one of the two gas engines, the NOx emissions are around 50% lower, while PM emissions are about 90% lower than for the comparable Euro VI diesel engine. For the other gas engine, NOx and PM emissions are the same as for the comparable diesel engine. Refer to Table 6.

Table 6 Overview pollutant and methane emissions for Euro VI HD vehicles

g/kWh	**NO$_x$**	**PM**	**SO$_x$**	**Methane**
Diesel	0.2 - 0.4	0.003 – 0.006	0.003	-
Gas SI, Lambda = 1	0.2 – 0.3	0.0004 – 0.003	0.002	0.25
Dual fuel (>90% gas), SCR deNOx catalyst	0.4	0.010	0.002	0.25 – 0.5

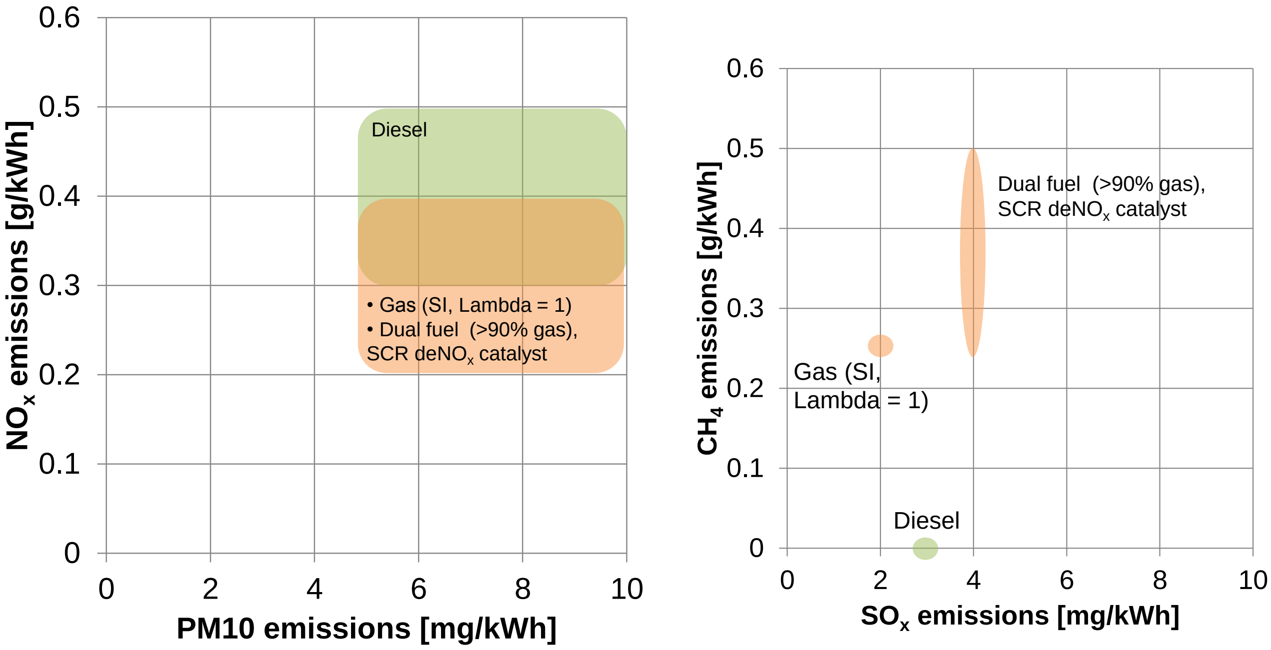

Figure 3 Pollutant and methane emissions for Euro VI HD vehicles

3.2 Inland ships

3.2.1 *Engine technology*

Diesel engines

The diesel engines normally do not have special emission control systems. This is due to not very stringent emission legislation (CCNR II). It is expected that during 2018-2020 much more stringent Stage V emissions legislation will enter into force. This will make special emission control systems such as SCR deNOx, EGR and possibly also diesel particulate filters necessary. SCR deNO$_x$ catalysts and in some cases diesel particulate filters are currently mounted on a small number of ships. This is done for demonstration purposed or stimulated by special incentive programs such as the NO$_x$ fund of the province of Zuid-Holland.

Gas engines

In Table 7 an overview is given of the currently applied engine technologies and the first 5 inland ships in the Netherlands. The lean-burn spark ignition engines are applied in a series-hybrid gas-electric arrangement, where the number of engines running is dependent on the power requirement. The Argonon was the first LNG fuelled inland ship in the Netherlands. Future dual-fuel engine developments are focussed on 90% or more gas. The ships with dual-fuel engine have a conventional arrangement with the main engines mechanically coupled with the propellers. The auxiliary power is arranged via gas-turbines or spark ignited gas engines.

Table 7 Currently used gas engine types for inland ship gas engines

Engine technology	Spark Ignition (SI) lean burn (gas electric)	Dual fuel 80% gas*	Dual fuel >90% gas
Examples	Greenstream, Greenrhine	Argonon	MS Eiger Nordwand Sirocco

The development of large gas fuelled engines has focussed on high efficiency in the power generation and marine markets. For that reason, the efficiency difference with diesel engines is usually very small. An overview of the pollutant and methane emissions is presented in Table 8 and 9. In Figure 4 an emission overview is given for ships which comply with respectively the current CCNR II standards and the recently proposed Stage V standards[17]. The emission levels are based on:

- Natural Gas in Transport (2013)
- Emissions of similar engine types applied for road transport in relations to (stringent) emissions legislation.
- Information obtained from engine producers.

There is hardly any official information on methane emission of inland ship gas engines. No measurement results of the inland ships mentioned in Table 7 were available. The numbers in the table are primarily based on information of stationary engines[1819] earlier investigated in the natural gas in transport study. The values are generally quite high, especially in comparison to trucks engines. This is mainly due to the absence of stringent legislation and the historical development of these engines for stationary power generation. The GHG emission of these gas engines is comparable to those of diesel engines due to this relatively high methane emission.

In the future pollutant emissions of inland vessels will be set by the European Commission and they will be a part of the legislation for road mobile machinery. The limit values are labelled Stage V. It is uncertain whether methane emissions will be included.

Table 8 Overview pollutant and methane emissions of inland vessels complying with the CCNR II standard

g/kWh		**NO_x**	**PM**	**SO_x**	**Methane**
Diesel	CCNR II	6 – 9	0.2-0.3	0.003	-
Gas SI, lean burn	CCNR II	1.2 – 2	0.01-0.02	0.002	4.5 – 6
Dual fuel (>90% gas)	CCNR II	2 – 2.4	0.1 – 0.2	0.002	4.5 – 6

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[17] Proposed: REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL: on requirements relating to emission limits and type-approval for internal combustion engines for non-road mobile machinery, COM(2014) 581 final, 2014/0268 (COD)

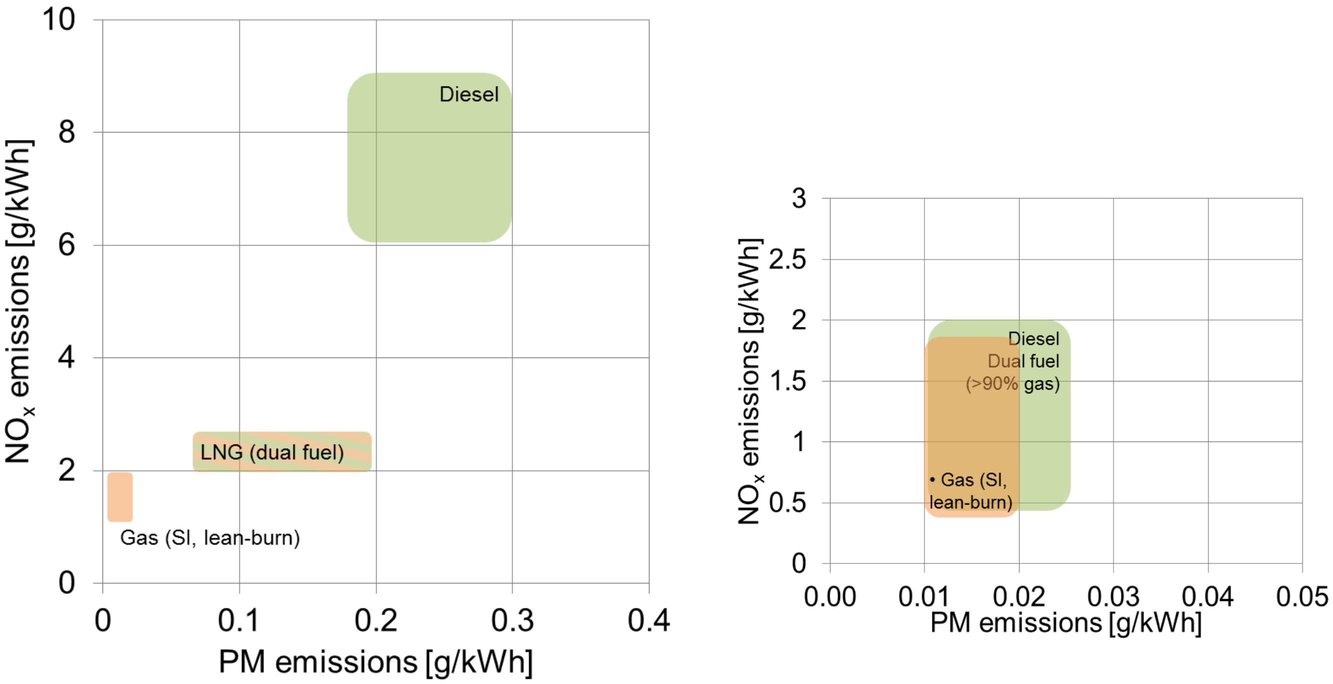
[18] P.A.C. Engelen: Overzichtsrapportage vervolgonderzoek methaanemissies bij gasmotoren op continu vollast, rapport nr 50964183-TOS/TCM 09-6715 Revisie 1, spring 2009

[19] Olthuis, H.J. en P.A.C. Engelen, 2007. Overzichtsrapportage emissieonderzoek methaanemissie bij gasmotoren op continu vollast. KEMA Technical&Operational Services. Report 50762926-TOS/TCM 07-7080, Arnhem, september 2007

Table 9 Overview expected pollutant and methane emissions of inland vessels complying with the proposed Stage V standard which may enter into force during 2018-2020. NOx and PM emissions are dependent on the engine power. No limit values proposed for methane.

g/kWh		**NO_x**	**PM**	**SO_x**	**Methane**
Diesel	Stage V > 2018/2020	0.4 – 2	0.01 – 0.025	0.003	6.2*
Gas SI, lean burn	Stage V > 2018/2020	0.4 – 2	0.01-0.02	0.002	4.5 – 6
Dual fuel (>90% gas)	Stage V > 2018/2020	0.4 – 2	0.01 – 0.025	0.002	4.5 – 6

* This is dependent on the precise engine type and the gas percentage with dual fuel. Limit value can be lower.



A B

Figure 4 Pollutant emissions for inland ships:
A: compliance with CCNR II (currently implemented legislation)
B: compliance with Stage V (proposed legislation for 2018/2020 for new engines)
Note: Enlarged PM and NOx scale in figure B

Table 6 and Figure 4A show lower NO_x and PM emissions for gas engines than for diesel engines, for engines that comply to the CCNR II standard. This difference is expected to disappear to a large extend when Stage V enters into force (Table 7 and Figure 4B). Diesel engines will be equipped with emission control systems such as SCR deNOx and diesel particulate filter such that the emissions requirements are met. For Stage V, an SCR deNOx catalyst or EGR may be necessary for gas engines. Especially for the large engines (>1000 kW) for which the proposed NO_x limit is 0.4 g/kWh. A particulate filter is probably not necessary for the gas engines. The methane emissions of the gas engines is expected to remain relatively high due to the technologies which are used and the large impact of changing engine concept. Efficiency is also a current driving force to reduce methane emission (since methane unburned fuel).

3.3 Sea ships

3.3.1 Engine technology and fuel options

The technology options for maritime engines is enormous, due to a range of fuel qualities and due to the relatively mild legislation. There is also a differentiation between the global requirements and different types of Emission Control Areas (with or without NO_x Tier III). Refer to the overview in Figure 5 below.

Diesel engines

The base fuel options are:

- LSHFO (low sulphur HFO): meant for global applications after 2020 (or 2025). Alternatively, required low SO_x level can also be achieved with HFO and SO_x scrubber.
- MDO (s < 0.5%): higher quality (distilled) fuel for global application after 2020 (or 2025).
- MGO primarily meant for ECAs (2015 and later), but required low SO_x level can also be achieved with HFO and SO_x scrubber.

Different types of emissions control systems can be used:

For SO_x emission reduction:

- SO_x scrubber: in order to meet the required SO_x emissions levels with the use of HFO. The scrubber will also reduce the particulate emission (engine out particulate emission is high due to low quality / high sulphur fuel).

For NO_x emission control:

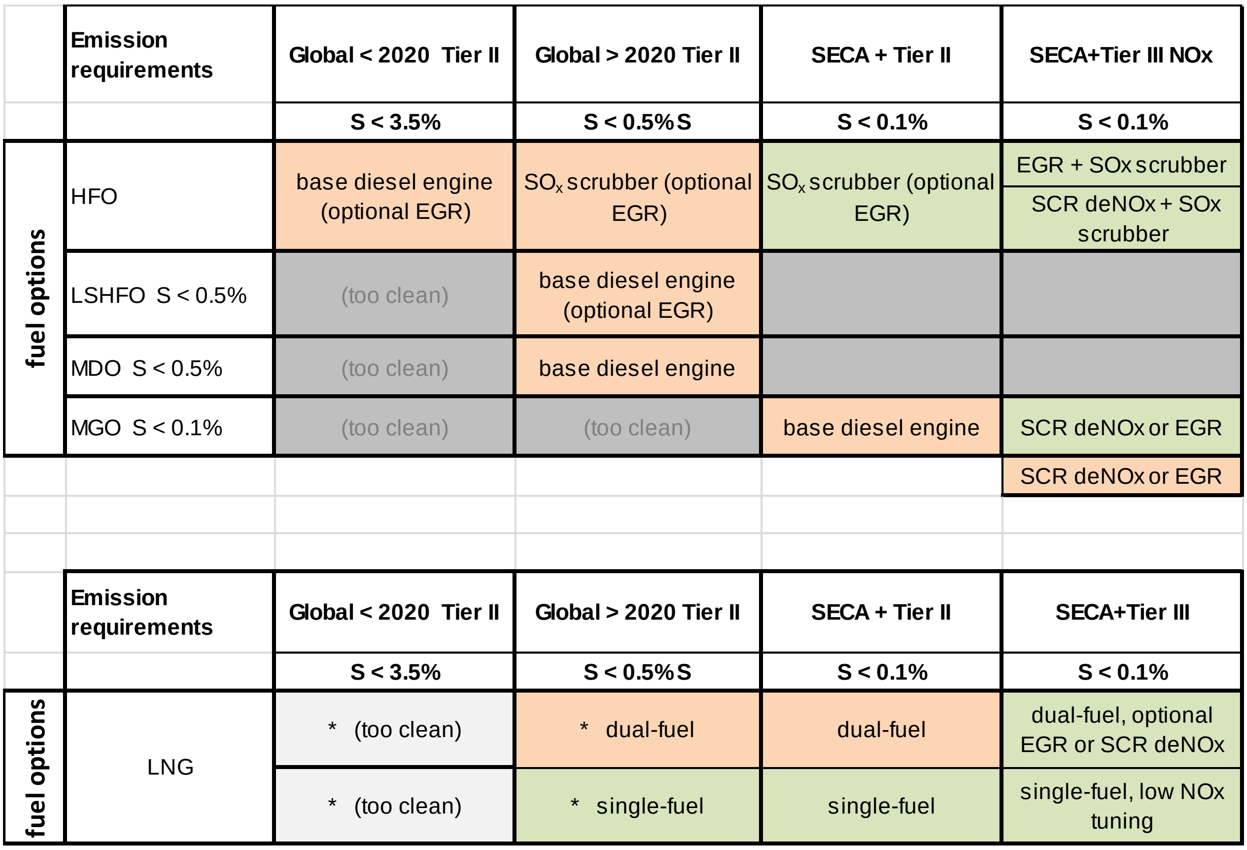
- Exhaust gas recirculation (EGR)
- SCR deNO_x catalytic aftertreatment.

The NO_x control systems will primarily be used to meet the Tier III NO_x level. EGR is also sometimes used to meet the Tier II level.

Gas engines (including dual-fuel)

For gas engines two main technologies can be distinguished:

- Single fuel, spark ignition (also indicated as positive ignition or Otto engine)
- Dual fuel, compression ignition: a small diesel injection is used to ignite the gas. The quantity of diesel can vary depending on the engine concept from a few percent to some 10% or more.



	Emission requirements	Global < 2020 Tier II	Global > 2020 Tier II	SECA + Tier II	SECA+Tier III NOx
		S < 3.5%	S < 0.5%S	S < 0.1%	S < 0.1%
fuel options	HFO	base diesel engine (optional EGR)	SO_x scrubber (optional EGR)	SO_x scrubber (optional EGR)	EGR + SOx scrubber SCR deNOx + SOx scrubber
	LSHFO S < 0.5%	(too clean)	base diesel engine (optional EGR)		
	MDO S < 0.5%	(too clean)	base diesel engine		
	MGO S < 0.1%	(too clean)	(too clean)	base diesel engine	SCR deNOx or EGR
					SCR deNOx or EGR

	Emission requirements	Global < 2020 Tier II	Global > 2020 Tier II	SECA + Tier II	SECA+Tier III
		S < 3.5%	S < 0.5%S	S < 0.1%	S < 0.1%
fuel options	LNG	* (too clean)	* dual-fuel	dual-fuel	dual-fuel, optional EGR or SCR deNOx
		* (too clean)	* single-fuel	single-fuel	single-fuel, low NOx tuning

Figure 5 Overview of fuel and technological options depending on environmental requirements. Orange back ground, more likely options for deep sea, green background, more likely option for short sea.

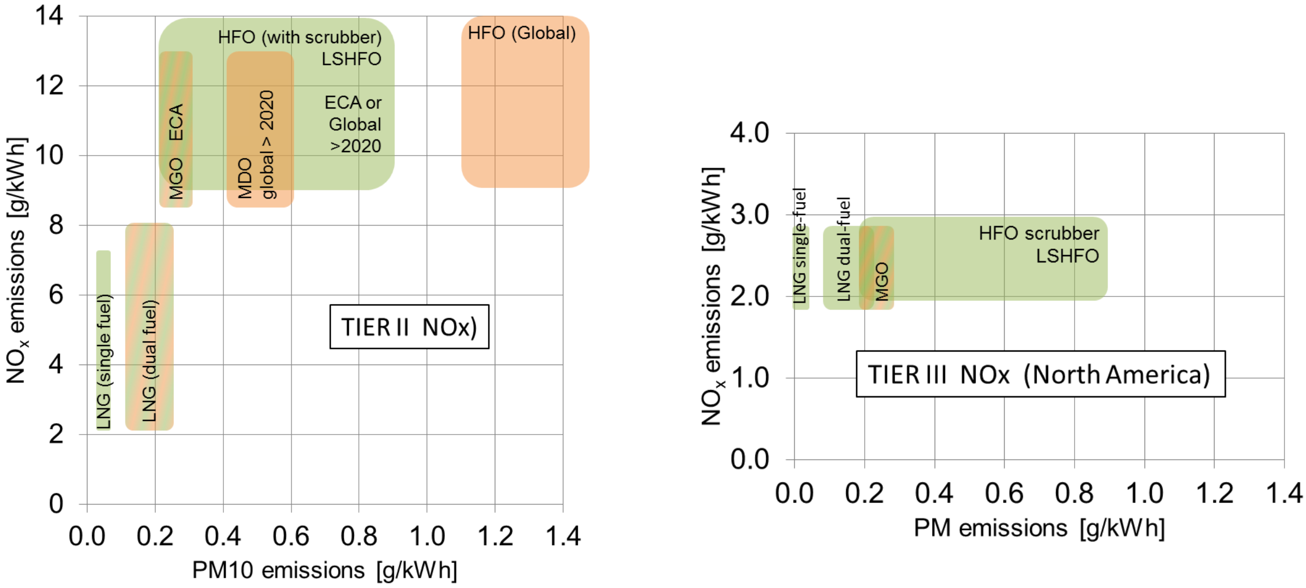
3.3.2 *Emissions of sea ships*

In general, the pollutant emissions of diesel engines will follow the legislation. For sea ships there are requirements for NO_x and for SO_x emissions, and not directly for PM emissions. Indirectly via fuel sulphur requirements PM emissions will be reduced. Tier III limits, require a strong NO_x reduction. Diesel engines can meet this with specific NO_x control technologies such as EGR (Exhaust Gas Recirculation) and SCR deNO_x catalytic aftertreatment. The gas engines can probably meet these requirements just by combustion optimisation.

The projected NO_x and PM emissions based on the different technology and fuel options are presented in Figure 6 below. Figure 6A shows the range for Tier II requirements (global and ECA). Figure 6B shows the emissions for ECA with Tier III NO_x requirements. This is currently only planned for North America ECAs (from 2016).

The PM emissions in Figure 6 below are primarily based on an empirical relations of the PM emissions with the fuel sulphur content. This relation was established in Natural Gas in Transport (2013) based on scarcity available PM emissions data. As mentioned, the SO_x scrubber will also reduce PM emission considerably. Although some sources give a PM reduction rate of up to 85%, in the figure below a conversion rate of 25% to 75% is assumed due to the limited amount of data. The NO_x ranges are dependent on the emissions requirements which is dependent on max engine speed. Also for gas engines, a rather wide range is given. This is due to the fact that limited firm data is available and that also a gas engine publication shows low and higher NO_x values with different calibrations for the same engine. For some engine types, it would be logical that a higher NO_x, lower fuel consumption, calibrations is chosen for Europe due to the absence of Tier III requirements.

In general in the future mode switching between low and high NO_x is expected for diesel engines[20], depending on local NO_x requirements (such as Tier III NO_x requirements in North America ECA). EGR and SCR $deNO_x$ systems can be switched off. In the off position engine maintenance and wear or reagent consumption might be less and engine efficiency might be slightly better. Mode switching may also happen with some gas engine types[21].



A (ECA & global) **B (ECA)**

Figure 6: Projection NO_x and PM emission with different fuel types for diesel and gas. Orange back ground, likely option for global application, green background, likely option for ECA.
A: Compliance with Tier II NOx
B: Compliance with Tier III NOx (only currently applicable to North America ECA)
Note: Enlarged PM and NOx scale in figure B

SO_x and methane emissions are presented in the table below. SO_x emissions are directly based on the fuel sulphur content and whether a SO_x scrubber is mounted. Refer to appendix C. Methane emissions are primarily based on Natural Gas in Transport (2013) and NTNU (2011)[22]. For sea ships, there is variation in gas fuel systems. For high pressure direct-injection a relatively low methane emission is reported. Also refer to section 4.3.1.

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[20] References MTZ 2014

[21] Dual Fuel ME-GI engine: Performance and the economy. Rene Sejer Laursen. MAN Diesel & Turbo 2012

[22] The future potential of LNG as a bunker fuel. Gaute Dag Løset, Rolf Erik Tveten. December 2011. Norwegian University of Science and Technology Trondheim.

Table 10 Overview SO_x and methane emissions of sea ships

g/kWh		**Period**	**SO_x**	**Methane**
HFO		<2020 global	11	-
LSHFO S<0.5% or HFO + scrubber		>2020 global	2.0	-
LSHFO S<0.1% or HFO + scrubber or MGO		>2015 SECA	0.3	-
Gas SI, lean burn or Dual fuel (>95% gas)		all years	0.002	0.2 - 4.5*

Most engines emit around 4.5 g/kWh. Emission can be much lower for engines with direct injection.

3.4 Real-world emissions

The emission for ship engines presented in the previous section are applicable for the legislative emission test cycles. These are the ISO E3 and E2 cycles for the main engines. Emissions in practice may be higher than during these official test cycles. This was especially the case for HD vehicles up to Euro V[23] and also with diesel cars[24]. For Euro VI an improved test cycle and requirements for Real driving Emissions (RDE) were implemented with Euro VI. This lead to an enormous improvement in the real driving emissions[25].

For inland and sea ships, so far nothing has been implemented to limit a possible gap between official test cycle and real world emissions. For that reason, the real world emissions may be substantially higher than those during the official test cycles. This especially applies to NO_x, PM and methane emissions. SO_x will not be sensitive to this (only engine efficiency differences will have some influence).

3.5 Ultrafine and fine particle emissions

The often heard concern that modern engines have lower particle mass but higher particle number emissions is not substantiated by parte size distribution measurements. Usually cleaner engines such as Euro V truck engines have lower particle numbers across the full size range than older diesel engines. In some cases the reduction factor is somewhat larger with larger particles than with smaller particles. Refer to figures in Appendix E. Euro V diesel engines generally have an SCR catalyst but not a diesel particulates filter. The installation of a wall-flow particulates filter, such as is done with Euro VI truck engines is a further large step in particulates mass and number reduction. The mass reduction is generally larger than 90% while the particle number is generally reduced by two orders of magnitude. This reduction is often consistent across the entire size range.

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[23] Real-world NOx emissions of Euro V vehicles, Ruud Verbeek, Robin Vermeulen, Willar Vonk, Henk Dekker. TNO report MON-RPT-2010-02777, November 2010

[24] TNO report MON-RPT-2010-02278 Verkennende metingen van schadelijke uitlaatgasemissies van personenvoertuigen met Euro-6 dieseltechnologie (exploratory measurements on pollutant emissions of Euro 6 diesel cars), W.A. Vonk en R.P. Verbeek, 8 september 2010

[25] Robin Vermeulen, Jordy Spreen, Norbert Ligterink, Willar Vonk: The Netherlands In-Service Emissions Testing Programme for Heavy-Duty 2011-2013, TNO report TNO 2014 R10641-2. May 2014

Spark ignition gas engines and diesel engines with wall flow particulates filter often have quite similar particulates emissions, both in mass and in number. The variations between engines and studies can be quite large though. This is not surprisingly, because test cycles, type of measuring equipment and engines vary and the results are sensitive to this. For example the particulates emission of gas engines is primarily caused by oil consumption and the combustion of oil, which can vary a lot depending on engine type and test cycle. Under specific circumstances (regeneration) diesel particulates filters can release ultrafine particles. Once emitted, ultrafine particles often agglomerate to fine particles (> 0.1µm).

No information has been found on particle size distribution of dual-fuel engines. Also for particle mass emission little information is available. The expectation is that the particulate emission level will be quite depending on type of dual fuel engine and the extend to which particulates emission is optimised. This is supported by emissions measurement with a number of dual-fuel trucks in the Netherlands. These were mostly retrofit dual fuel systems for Euro V trucks which showed in dual fuel operation a particulates mass emission reduction compared to diesel in the range of 0% to 50% depending on engine type and test cycle.
We expect that more advanced dual-fuel engines, such as is often seen with ship engines, will show a much lower particulates emission. This is because the diesel injection is optimised for low quantities and they can actually have Otto engine lean burn combustion characteristics. The particulates emission in that case may be as low as that of a spark ignition, lean burn gas engines, but data to support this is not available.

- From these limited analysis, the following is concluded: For Euro VI truck diesel engines spark ignition gas engines similar very low ultrafine and fine particulates emissions are expected. If Euro VI dual-fuel gas engines become available similar low particulates emissions are expected due to the stringent requirements
- For ship engines, It is expected that most lean-burn and dual-fuel ship engines will have lower ultrafine or fine particle number emissions than the conventional diesel engines although data to support this was not available. There is no indication that ultrafine or fine particle number emissions will increase with lean-burn or dual fuel gas engines compared to diesel engines,

3.6 Noise emission

Gas engines often have a smoother combustion than diesel engines. This is because gas engine (including many dual-fuel engines) do have a typical Otto type combustion with local ignition and a flame front moving through the combustion chamber rather than the typical diffusion type combustion of diesel engines. With the latter the combustion starts parallel at many locations leading to more vibrations and noise.

The lower noise levels are demonstrated with trucks with gas engines and is also observed with one of the first inland ships. Noise measurements are planned for the Ost-Friesland LNG passenger vessel in first quarter 2015[26].

For delivery trucks and fork lifts, a noise certification standard was launched in the Netherlands in 1998. This standard, which is called the ‘Piek’[27], is focused on the

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[26] Refer to MariTim project

loading and unloading of trucks in cities. The PIEK-standard has been adopted in several countries like the UK, France, Germany and Belgium.
In the Netherlands about seven truck types are available with the PIEK-light certificate (< 72 DB(A)). These are five natural gas (CNG or LNG) trucks and two hybrid-electric diesel trucks.

3.7 Conclusions on pollutant emissions

Heavy-duty vehicles
The following is concluded for HD vehicles (based on Euro VI technologies):
- Diesel and gas engines will both have very low pollutant emissions due to the stringent legislation and fuel sulphur requirements.
- First type approval results show up to 50% lower NO_x emission and up to 90% lower PM emissions for spark ignition gas engines (with 3-way catalyst) than for diesel engines. The absolute differences are however very small.
- Methane emissions of gas engines are low due to stringent requirements and chosen technologies.
- Gas engines have lower noise emissions and therefore often qualify for reamer city delivery conditions.

Inland ships
For inland ships the engine technologies up to 2020 are uncertain, due to not yet implemented Stage 5 emission legislation.

Based on CCNR 2 technologies for diesel, the following can be concluded:
- Substantially lower NO_x and PM emissions for gas engines (up to a factor of 2 or possibly more)
- Low SO_x emissions for both gas and diesel engines[28]
- Relatively high methane emissions for both single and dual fuel gas engines (without methane aftertreatment[29]).

If stringent Stage 5 requirements for inland ship engines are implemented, it can be concluded that since engine are developed towards future legislation:
- Diesel and gas engines will both have very low pollutant emissions
- Also gas engines may need special NO_x control technologies if stringent NO_x requirements are implemented (NO_x << 2 g/kWh).

Sea ships
For sea ships, large variations in emissions are expected, especially for diesel engines. This is due to the many fuel and technology options and the not very stringent legislations.
Gas engines are expected to have much lower pollutant emissions:
- Generally 75% lower NO_x emissions
- Up to 10 times lower PM emissions
- Much lower SO_x emissions (factor more than 100 or 1000 lower for respectively ECA and global areas).
- Methane emissions for gas engines will be relatively high, but most major manufacturers achieve GHG levels equal to or better than the equivalent diesel engine[30].

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[27] http://www.piek-international.com/english/
[28] Due to ultra-low sulphur diesel fuel generally used for inland ships since 2011
[29] There are concerns about the durability of methane aftertreatment.

Real-world emissions

For trucks up to Euro V and ships, there is a risk that emissions in practice will be higher than during the official test cycles. This may influence the conclusions above.

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[30] Based on GWP_{100} of 25

4 GHG emissions

4.1 Production of energy carriers

As explained in section 1.2, for pollutant emissions, the focus is on TTW and TTP emissions. For GHG emissions, also emissions in earlier phases of the energy chain are relevant. Therefore, this chapter focuses on WTW or WTP GHG emissions.

4.1.1 Fossil fuels

Liquid fossil fuels

As stated above, the largest share of fuels used in ICE drivetrains are fossil gasoline and diesel obtained by refining crude oil to more useful products. This is achieved by a special form of distillation, i.e. fractionation. The various fractions produced are used for

- fuel (such as gasoline and diesel);
- raw material for numerous other products (petrochemicals);
- lubricant;
- raw material for example, road construction and roofing.

Besides crude oil, also fossil shale oil or tar sands can be refined to obtain petrol and diesel. Currently, these resources are only used limitedly in Europe.

Gaseous fossil fuels

Compressed natural gas (200-250 bar) mainly consists of methane and is not liquid at normal temperatures. Natural gas is produced by extracting fossil gas from the deep underground rock formations, processing to remove impurities, e.g. water, and finally refining. The natural gas used in the Netherlands is mainly produced in the Netherlands, Russia and the Middle East, and transported through pipelines.

This natural gas can also be converted to liquid form for ease of storage or transport. The liquefaction process involves removal of certain components, such as dust, acid gases, helium, water, and heavy hydrocarbons. The natural gas is then condensed into a liquid at close to atmospheric pressure by cooling it to approximately −162 °C. This conversion of natural gas to LNG requires significant amounts of energy, mainly in the form of electricity.

LPG (Liquefied petroleum gas) is a liquefied mixture of propane and butane that is produced during the refining of petroleum (crude oil), or extracted from petroleum or natural gas streams as it is extracted from the earth.

4.1.2 Biofuels

Many different types of biofuels exist, e.g. (liquefied or compressed) biogas and FAME, with even more biofuel feedstock types and production routes. The greenhouse gasses emitted during production vary significantly for the various routes. Moreover, the availability is very different for the various feedstock types.

The chain of biofuels, starts with the production of biomass feedstock and ends at combustion in the vehicle engine, and may consist of the following chain of links:

- Feedstock production - crop growing, collection of waste streams, harvesting of woody biomass from forest or elsewhere;

- Processing of the biomass – drying, separating into individual components such as oils, sugars, protein fractions.
- Conversion processes - for example, fermentation of sugars to ethanol, transesterification of vegetable oil to biodiesel;
- Reprocessing of raw biofuel – for instance, isolating ethanol by distilling;
- Distribution of biofuel production to gas station;

In the biofuel production chain energy is consumed during transportation of the fuels for agricultural machinery and transport and use of fuel and electricity in industrial processes.

Greenhouse gas emissions in the chain are partly related to the energy consumption in the chain. Additional emissions, such as nitrous oxide or methane, may be emitted during agriculture or fermentation of biomass respectively. A third source of greenhouse gas emissions is related to the use of ancillary materials in the production of biofuels. Also in the production processes of these materials, e.g. fertilizers for cultivation, greenhouse gases are emitted.

Finally, emissions can also occur if growing wood or crops reduces the amount of vegetation and/or loss of organic soil matter, e.g. as a result of wood logging for the harvest of timber or to create land for cultivation. These emissions can be directly related to the production of biofuels, or indirectly (ILUC). This is explained in more detail in Appendix A.

4.1.3 Electricity

Similar to biofuels, electricity can be generated from many different raw materials and via even more production routes. Currently electricity in Europe is generated mainly by combusting fossil fuels, such as natural gas and coal, in power plants. Smaller shares of electricity are produced in nuclear power plants and using renewable sources, such as wind and solar. Small amounts of biomass are mixed with coal for electricity production. Biogas, when fed into the grid, can also be combusted in power plants. Environmental fuel characteristics
As explained in Appendix A, different fuels have different environmental impacts. During the last decade, the Joint Research Centre (JRC)[31] has published several studies regarding this subject. Since many stakeholder have been involved in these studies and since they are broadly accepted and used, the data from these JRC studies will also be used in this analysis.

JRC provides the GHG intensities of fuels based on various raw materials and production routes, expressed in WTT CO_2 emissions[32]. The emissions of the most relevant fuel types for this analysis are provided in Table 13.

However, production routes for liquefied biogas are not available from these studies. These are therefore deduced from the available information

<u>Liquefied biogas</u>

Just like its fossil equivalent (i.e. natural gas), biogas can also converted to liquid form. The climate impact of these production routes can be deduced from information available in the JRC studies[32].

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[31] the European Commission's in-house science service

[32] JRC 2013: "Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context" Version 4

Biogas (CBG) is produced gas either by anaerobic digestion or gasification. Hereafter the gas can be compressed to produce compressed biogas, or CBG. Compared to the production process of CBG, liquefied biogas (LBM) does not need to be compressed but does requires a process known as liquefaction. Moreover, the distribution of liquefied biogas is different than that of CBG. This is schematically represented in Figure 7. The CO_2 emissions resulting from liquefaction, compression and distributional differences can be derived from the JRC study and are provided in Table 11.

The energy consumption and GHG emissions during liquefaction are based on relatively large-scale processing. In (Hochshule Emden/Leer 2014)[33] a comparison was presented of the energy efficiency of large and small scale liquefaction. This show that the energy consumption of a small plant (1000 ton/year) is 70-75% higher than medium or large size liquefaction. Electric energy consumption of a medium size plant is about 5% of the LNG fuel energy. This translates to 10-12% primary energy, which is in line with the JRC value. Consequently the CO2 value for liquefaction is increased by 70% in order to get the small scale liquefaction typical suitable for regional biogas liquefaction.
Distribution of the final product is for LNG higher than for CNG. For LBM however the same value is used, since it is assumed that production and fuelling locations will be relatively close[34].

The JRC study does not provide information on biogas production routes from wood as feedstock, probably because this technology is not yet available on a commercial basis. The route is important though due to the higher yield of second generation feedstock (e.g. wood). Since the principle of this production route is rather close to that of the production of methanol from wood, WTT CO_2 emission of this route are used instead.

Table 11 WTT CO_2 emissions resulting from liquefaction, compression and distributional differences

Conversion factors CBG-->LBM	**CO_2/MJ**	
Liquefaction	+6.20 + 70% →	+10.5
Compression		-1.20
Distribution final product		+ 0
Conversion factor CBG --> LNG		**+9.3**

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[33] Prof. Dr. Sven Steinigeweg, Prof. Freerk Meyer, Wilfried Paul, EUTEC-Institut, Hochschule Emden/Leer: „Perspektiven und Potentiale von Low-Emission-LNG im Nordwesten“. Client: LNG Initiative Nordwest (Germany). Presentation 2014.

[34] Refuelling trucks with LBM close to the production location has been put forward as an important safety advantage (no long transport with tanker trucks)

Table 12 WTT CO_2 emissions resulting from various production routes of CBG and the deduced emissions of LBM

Final product	**Raw material**	**CO_2/MJ**
CBG	Municipal waste	14.8
CBG	Liquid manure (closed storage)	-69.8
CBG	Maize (whole plant)	40.8
CBG	Wood	6.6
LBM	Municipal waste	24.1
LBM	Liquid manure (closed storage)	-60.5
LBM	Maize (whole plant)	50.1
LBM	Wood	15.9

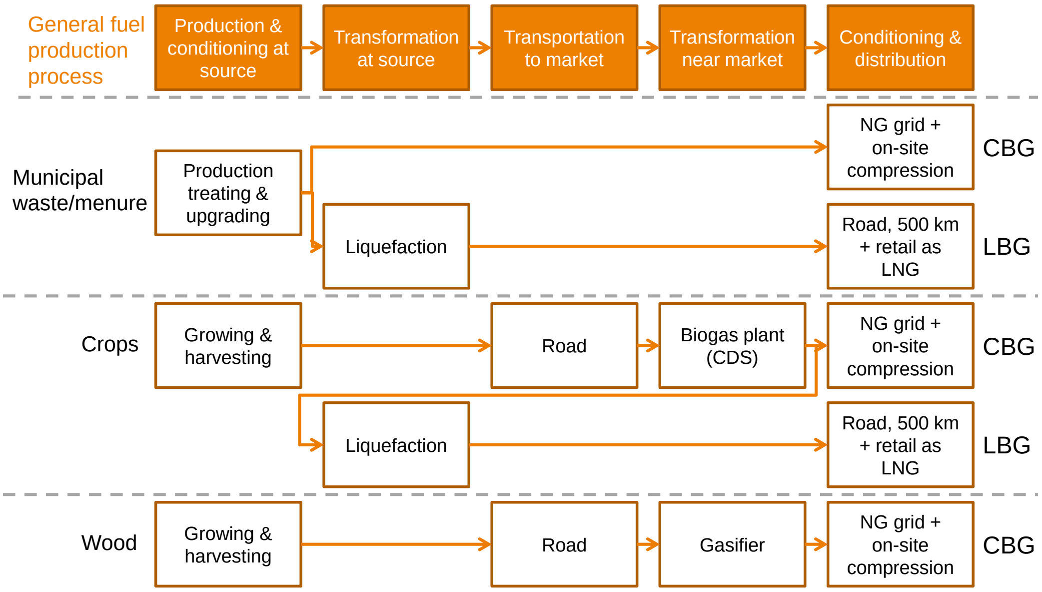

Figure 7 Schematic representation of differences in the production routes of CBG and liquefied biogas.

Table 13: Environmental impact various fuels based on the raw materials and production routes (excluding GHG from engine methane emission)[35]

				WTT Energy use	**WTT GHG (excl ILUC)**	**WTT ILUC**	**WTT GHG (incl ILUC)**	**TTW GHG**
				MJ/MJ	*g/MJ*	*g/MJ*	*g/MJ*	*g/MJ*
Fossil diesel	Crude oil	Refining	Diesel	0.19	16.7	0	16.7	73.2
FAME (biodiesel)	Rape seed	meal export to animal feed, glycerine export as chemical or animal feed	Bio-diesel	1.15	57	54.1	111	0
FAME (biodiesel)	Rape seed	meal export to animal feed, glycerine to internal biogas production	Bio-diesel	0.68	37	54.1	91.1	0
FAME (biodiesel)	Palm oil	kernel meal to animal feed, no CH4 recovery from waste storage, heat credit from residue se as fuel, oil to EU, glycerine to biogas	Bio-diesel	1.33	63	43.5	107	0
FAME (biodiesel)	Palm oil	kernel meal export to animal feed, no CH4 recovery from waste storage,no heat credit from residue use as fuel, oil transport to EU, glycerine to biogas	Bio-diesel	1.18	51	43.5	94.5	0
FAME (biodiesel)	Palm oil	kernel meal to animal feed, CH4 recovery from waste storage, heat credit from residue use as fuel, oil to EU, glycerine to biogas	Bio-diesel	1.17	31	43.5	74.5	0
FAME (biodiesel)	Waste cooking oil	Purification and transesterification	Bio-diesel	0.28	13.8	0	13.8	0
FAME (biodiesel)	Tallow	Purification and transesterification	Bio-diesel	0.48	26.3	0	26.3	0
HVO	Rape seed	meal export to animal feed, hydrotreate oil	Bio-diesel	1.06	57	55	112	0
HVO	Rape seed	meal export to internal biogas production, hydrotreate oil	Bio-diesel	0.66	37	55	92.0	0
HVO	Palm oil	kernel meal export to animal feed,no CH4 recovery from waste storage, heat credit from residue use as fuel, oil transport to EU	Bio-diesel	1.13	48.6	55	104	0
HVO	Waste cooking oil	Purification and transesterification	Bio-diesel	0.16	8.1	0	8.10	0
HVO	Tallow	Purification and transesterification	Bio-diesel	0.44	24.5	0	24.5	0
BTL	Wood	Fischer-Tropsch Syndiesel: Farmed wood, diesel pool	BTL	1.2	7	?	7.00	0
BTL	Wood	Fischer-Tropsch Syndiesel: Waste Wood via black liquor, diesel pool	BTL	0.91	2.5	0	2.50	0
CBG	Municipal waste	Municipal waste (closed digestate storage)	CBG	0.99	15	0	15.0	0
CBG	Manure	Manure (closed digestate storage)	CBG	2.01	-70	0	-70.0	0
CBG	Maize	Maize (whole plant) (closed digestate storage)	CBG	1.28	41	3	44.0	0
LNG	Natural gas	Liquifying natural gas, no CCS, shipping, road transport to retail	LNG	0.24	19.05	0	19.1	56.1
LBM	Municipal waste	Closed digestate storage	LBM	1.03	24.1	0	24.1	0
LBM	Manure	Liquid manure (closed digestate storage)	LBM	2.05	-60.5	0	-60.5	0
LBM	Manure*	Liquid manure (closed digestate storage)	LBM	2.05	24.5	3	27.5	0
LBM	Maize	Whole plant (closed digestate storage)	LBM	1.32	50.1	3	53.1	0
LBM	Wood	Gasification	LBM	1.11	15.9	0	15.9	0
MGO	Crude oil	Refining	MGO	0.16	14.2	0	14.2	74.1
HFO	Crude oil	Refining	HFO	0.16	14.2	0	14.2	77.4
	* Positive effect of preventing methane emissions by stroring and use in biogas instead of letting go into the atmosphere not attibuted the use of biogas							

A summarised overview of the Well to Wheel GHG emissions (CO2 equivalent) for the different fuel options is presented in Figure 8 below. This is on a per MJ fuel energy basis and does not include possible differences in engine efficiency and engine methane emissions. These parameters vary substantially depending on the transportation mode. These parameters are included in the detailed figures 10 to 16.

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[35] G. Koornneef e.a. (TNO), H. van Essen e.a. (CE Delft), M. Londo e.a. (ECN): Verzamelde kennisnotities t.b.v. de visie duurzame brandstoffenmix (collected knowledge notes for Dutch fuel mix assessment). 27 June 2014

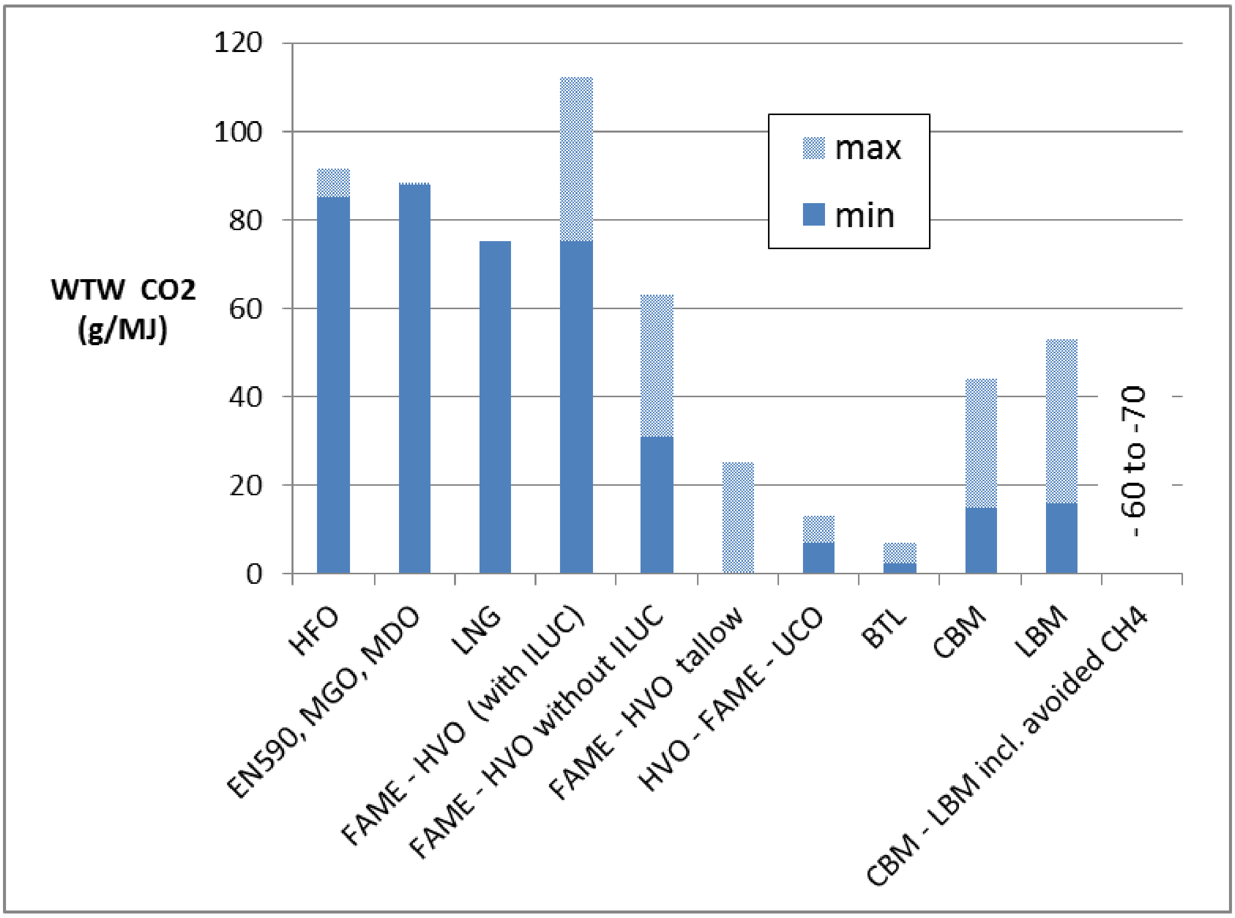

Figure 8 Well to Wheel CO2 emissions of fuels per MJ fuel energy (does not include engine efficiency differences and possible engine methane emissions.

4.2 Use in vehicles and ships

Road vehicles and vessels use energy when in use. Depending on the vehicle's or vessel's drivetrain type and energy carrier, this energy use results in GHG emissions. For instance, in case of a combustion engine burning fossil fuels, greenhouse gasses are emitted. As explained in Appendix A, it depends on the definition, whether the use of biofuels also results in TTW GHG emissions.

4.2.1 Methane emissions of combustion engines

The direct CO_2 emission with combustion of natural gas is about 25% lower than for diesel fuel, for the same amount of fuel energy. There are however two effects that reduce this advantage: 1) the efficiency is often slightly lower, 2) natural gas engines often emit some methane (fuel which is not taking part in the combustion). These characteristics are primarily dependent on the basic choice of engine/combustion concept and on the stage of development of the engine.

In Figure 8 below a comparison of GHG (CO_2 equivalent) emissions between a diesel and natural gas engines is presented, as a function of methane emissions of the gas engine. It shows, that with a methane emission of approximately 6 g/kWh, the GHG emission of a diesel and gas engines is equal.

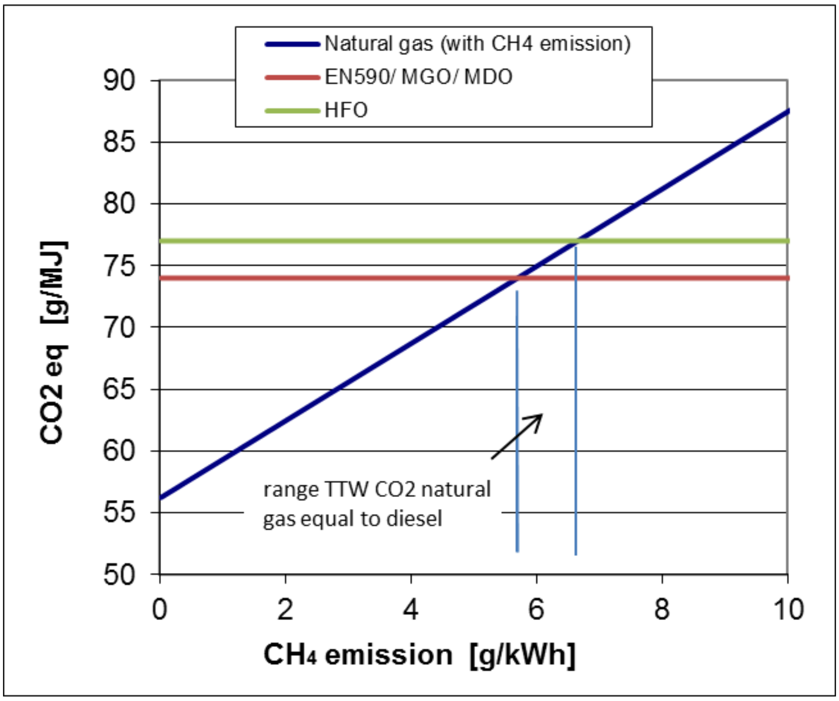

Figure 9 Comparison of GHG (CO_2 equivalent) emissions between diesel (EN590/MGO) and natural gas engine as a function of methane emissions of the gas engine. Source Natural Gas in Transport (2013).

In Table 14 below, an overview of the emissions per modality and engine technology is given. Methane emissions are not regularly made available by the engine OEMs.

The methane emission is multiplied by 25 in order to obtain the CO_2 equivalent for the contribution to the GHG emissions. This is based on a GWP factor for methane for 100 years. For a shorter period, this factor is higher. Refer to section 6.5. The values in the table below are based on direct feedback from engine manufacturers and from some publications. The publications include (Engelen, 2009 and Olthuis and Engelen, 2007), which shows average methane emission of a large number of stationary SI gas engines. Marintek (2014)[36] reports on emission factors for dual-fuel LNG engines. For low-pressure dual fuel; 4 and 8 g/kWh are given for respectively high and low power output. For high-pressure dual fuel; 0.2 and 2 g/kWh are given for respectively high and low power output. Low power is defined as 50-90% of MCR and low power as 25-30% of MCR. Kryger et al. (2011)[37], also reports a methane emission of 0.2 g/kWh for a large 2-stroke dual fuel engine (HP injection).. One of the dual fuel engines for sea shipping is based on this value. For shipping also an energy consumption penalty of 2% is added due to a loss of cargo space due to the LNG tanks. This is an average. For some ship types such as oil and chemical tankers, the loss in cargo space is often zero, but for bulk and container ships, there is a loss in cargo space which can be up to some 5%[38].

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[36] Dr. Haakon Lindstad 1 (M), Inge Sandaas 2 (V): Emission and Fuel Reduction for Offshore Support Vessels through Hybrid Technology. Manuscript ID SNAME-008-2014 Emission reductions for the offshore supply fleet through hybrid technologies. Conference Proceedings SNAME 2014 October 2014 Houston

[37] Kryger, M ., Juliussen, L., Andreasen, A.: MAN B&W ME-GI Engines; Recent research and results. Marine Low Speed Research and Development. Copenhagen, Denmark : Marine Low Speed Research and Development, 2011

[38] Natural gas in transport: An assessment of different routes. Ruud Verbeek, Norbert Ligterink, Jan Meulenbrugge, Gertjan Koornneef, Pieter Kroon, Hein de Wilde, Bettina Kampman, Harry

Table 14. Assumptions for energy consumption (compared to standard diesel) and methane emissions. Primary source: Natural Gas in Transport (2014).

Modality	**Technology**	**Energy consumption**[39][40]	**CH4 g/kWh**
Trucks	SI stoichiometric	+ 10%	0.35
	Dual-fuel > 90% gas	+ 3%	0.35
Inland ships	SI lean burn	+ 3%	4.5
	Dual fuel manifold injection	+ 3%	4.5
Short sea and Deep sea	SI lean burn	+ 3%	4.5
	Dual fuel manifold inject	+ 3%	4.5
	Dual fuel, direct injection (HP injection)	+ 3%	0.2?

4.2.2 *GHG emissions of reference vehicles and ships*

In Natural Gas in Transport (2013), reference vehicles and ships were defined. The size and the usage pattern of the vehicles and ships determine the energy consumption per km, which on its turn determines the GHG emission. The same reference vehicles are used for this study. An overview of the specifications is presented in the 3 tables below.

Table 15 Reference trucks and buses

Type	**Application**	**Reference weight**	**Reference Power**	**Reference usage**
Rigid truck, box type, 18 ton, 2 axles	Regional distribution 60,000 km/y	15 ton	220 kW	Motorway + 15% urban
Tractor – trailer, box type, 5 axles, 50 ton	Long haul 120,000 km/y	30.5 ton	330 kW	Motorway + 5% urban
City bus, 18 ton, 12 m	Urban line, 60,000 km/y	15 ton	200 kW	Urban bus cycle

Table 16 Reference inland ship

Type	**Application**	**Water displacement**	**Reference max. power**	**Reference fuel**
110 m x 11.45 m CCR4	Rotterdam–Ludwigshafen (bunkering in R'dam)	2,865 ton	1,125 kW 1,300 rpm	Diesel EN 590 S < 10 ppm

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Croezen, Sanne Aarnink. Report by CE Delft, ECN and TNO. Publication code: 13.4818.38, May 2013

[39] Ruud Verbeek, Gerrit Kadijk, Pim van Mensch, Chris Wulffers, Bas van den Beemt, Filipe Fraga: Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands. TNO-RPT-2011-00166, March 2011.

[40] Natural gas in transport: An assessment of different routes. Ruud Verbeek, Norbert Ligterink, Jan Meulenbrugge, Gertjan Koornneef, Pieter Kroon, Hein de Wilde, Bettina Kampman, Harry Croezen, Sanne Aarnink. Report by CE Delft, ECN and TNO. Publication code: 13.4818.38, May 2013

Table 17 Power and operational characteristics of reference sea ships

	Max speed (at 80% MCR)	**Cruise speed**	**Max. power**	**(Average) propulsion power**
	Knots	**Knots**	**MW**	**MW**
Inland ship	7 (upstream)	7	1.1	0.9
Short sea ship	20	17	8.4	4
Deep sea 5,500 TEU	20	20	30	24

Table 18 Energy consumption and Methane slip emissions per modality and per drivetrain configuration

	TTW energy use [MJ/km]						Emissions [g/MJ$_{fuel}$]	
	Share of LNG	Diesel	LNG	MGO	HFO	Totaal	Methane slip	CO2, eq of methane slip
Rigid truck								
Diesel, hybrid	0%	8.46				8.46	0	0
LNG SI, hybrid	100%		9.3			9.31	0.031	0.8
City bus								
Diesel, hybrid	0%	9.12				9.12	0	0
LNG, SI hybrid	100%		10			10.0	0.031	0.8
Tractor trailer								
Diesel	0%	12.4				12.4	0	0
LNG, SI	100%		13.64			13.6	0.035	0.9
LNG 90%, dual fuel	90%	1.24	11			12.4	0.039	1.0
Inland ship								
Diesel	0%	581				581	0	0
LNG, lean burn SI	100%		610			610	0.53	13.1
LNG, dual fuel, 3%D	97%	18.3	592			610	0.70	17.5
Short sea ship								
MGO	0%			1026		1026	0	0
HFO -scrubber	0%				1026	1026	0	0
LNG lean-burn	100%		1078			1078	0.56	14.1
LNG dual fuel, 3% MGO	97%		1046	32		1078	0.56	14.1
Deep sea ship 5500TEU								
MGO	0%			4963		4963	0	0
HFO	0%				4963	4963	0	0
LNG dual-fuel, 10% MGO	90%		4693	521		5214	0.03	0.6

4.3 Results: WTW, WTP emissions

Combining the energy consumption of different drivetrain configurations (Table 18), TTW and WTT emissions for various (production routes) of energy carriers (Table 13) and possibly methane slip (Table 18) results in WTW or WTP emissions per drivetrain configuration per production route.

In this section, the WTW and WTP GHG emissions of different energy carriers and production routes are compared per modality. Moreover the WTW and WTP energy consumptions are compared as a proxy for the costs of the different energy carriers and their production routes.

4.3.1 *Emissions of a standard rigid truck*

In Figure 10 the WTW GHG emissions and WTW energy consumption of two different drivetrain configurations of a rigid truck are compared, i.e. hybrid diesel and hybrid LNG. For the bio-equivalents of LNG and diesel, i.e. LBM and biodiesel, various production routes are taken into account.

From Figure 10 can be concluded that the GHG emissions of fossil diesel are slightly higher (approximately 7%) than those of fossil LNG. On the other hand, the WTW energy use of LNG are slightly higher, which is mainly the result of the relatively energy intensive liquefaction process. Moreover methane slip results in respectively approximately 1.4% and 1.0% of TTW and WTW GHG emissions.

For the bio-equivalents of these two fuels, the WTW GHG emissions vary significantly for the analysed production routes and raw materials. Biodiesel from waste streams, such as municipal waste or manure result in the lowest GHG emissions, partly because no ILUC emissions are involved. LBM from waste streams also result in low GHG emissions for the same reasons. In case the prevention of manure methane emissions from manure storage into the atmosphere is accounted for in the WTT production of the biogas, GHG emissions can even be negative[41]. The WTW energy use for LNG is higher, mainly because of the relatively energy intensive liquefaction process.

As can be seen in Figure 11, ILUC has a significant contribution to the overall WTW GHG emissions. In case ILUC would not be taken into account, the WTW GHG emissions of all biofuel production routes from rapeseed and palm oil would be lower than the WTW GHG emissions of fossil diesel.

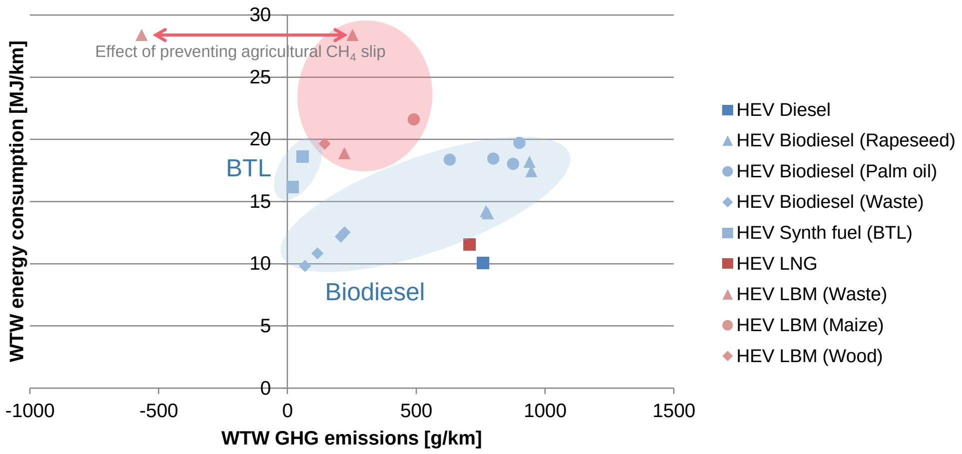

Figure 10 WTW CO_2 emissions and WTW energy use of a standard rigid truck with various drivetrain types using energy sources from various raw materials, including ILUC emissions and methane slip.

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[41] It can be argued whether the manure storagestorage is a good reference. If manure is left on the land, there is no significant methane emission.

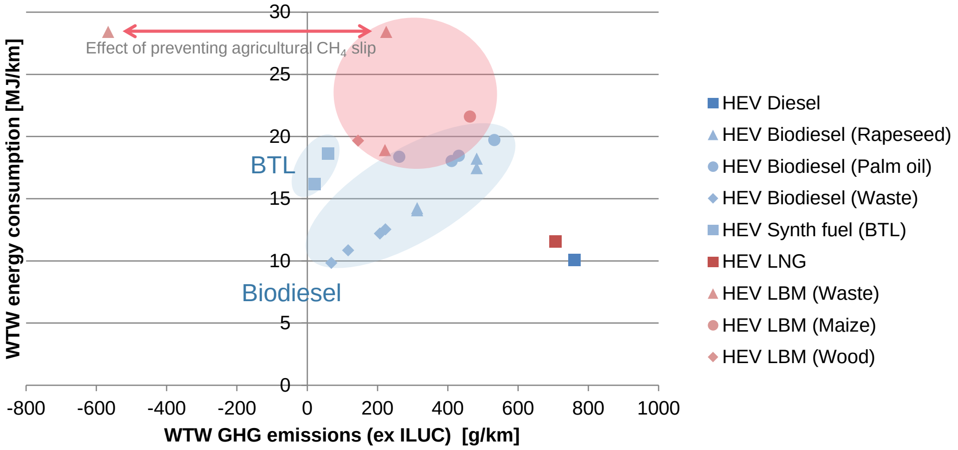

Figure 11 WTW GHG emissions and WTW energy use of a standard rigid truck with various drivetrain types using energy sources from various raw materials, excluding ILUC emissions and methane slip.

4.3.2 *Emissions of a standard city bus*

In Figure 12 the WTW GHG emissions and energy use are depicted for a defined standard city bus. The selected drivetrain configurations for the city bus are the same as for the rigid truck (section 4.3.1). Conclusions for this modality are therefore very similar to the conclusions drawn for the rigid truck discussed in section Figure 10.

Again ILUC has a significant contribution to the overall WTW GHG emissions. In case ILUC would not be taken into account, the WTW GHG emissions of all biofuel production routes from rapeseed and palm oil would be lower than the WTW GHG emissions of fossil diesel. This is shown in Appendix D.

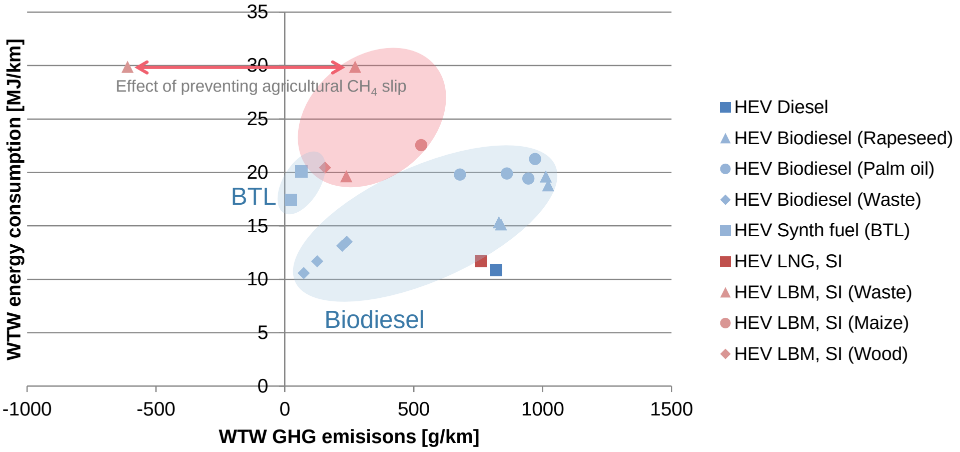

Figure 12 WTW CO_2 emissions and WTW energy use of a standard city bus with various drivetrain types using energy sources from various raw materials, including ILUC emissions and methane slip.

4.3.3 *Emissions of a standard tractor trailer*

For the tractor trailer combination, three different drivetrain configurations are analysed,

- ICEV using (bio)diesel
- ICEV using LNG or LBM
- ICEV using 90% LNG and 10% diesel.

As shown in Figure 13, the WTW GHG emissions of the third configuration are lowest, mainly resulting from the lower energy consumptions compared to the LNG configuration. Since the production of biodiesel, apart from waste as raw material, results in higher WTT GHG emissions and lower WTT energy use than the production of biogas, the use of biofuels in the third configuration results in higher WTT GHG emissions and lower WTT energy use than the use of biofuels in the second configuration.

Similar as in previous modalities, methane slip accounts for respectively approximately 1.7% and 1.3% of TTW and WTW GHG emissions.

Again ILUC has a significant contribution to the overall WTW GHG emissions. In case ILUC would not be taken into account, the WTW GHG emissions of all biofuel production routes from rapeseed and palm oil would be lower than the WTW GHG emissions of fossil diesel. This is shown in Appendix D

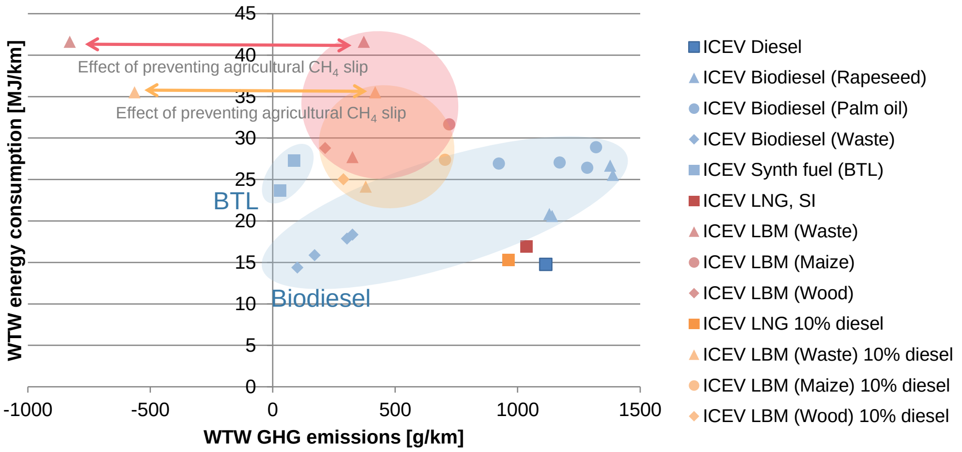

Figure 13 WTW CO_2 emissions and WTW energy use of a standard tractor trailer with various drivetrain types using energy sources from various raw materials, including ILUC emissions and methane slip.

4.3.4 *Emissions of a standard inland ship*

For the defined inland ship, three different drivetrain configurations are analysed,

- ICEV using (bio)diesel
- ICEV using LNG or LBM
- Dual fuel ICEV using 97% LNG and 3% diesel.

In contrary to the three road vehicles analysed in sections 4.3.1 to 4.3.3, the WTP CO_2 emissions of the LNG vessel are slightly higher than those of the diesel vessel (Figure 14). This is mainly caused by the high share that the methane slip has in the total GHG emissions. This methane slip account for respectively approximately 24% and 19% of the TTP and WTP GHG emissions. For the HD road vehicles assessed above, this was approximately only 1% to 2%.

As methane slip occurs to the same extent for LBM, the use of LBM results in WTP GHG emissions of LBM are not as much lower as those of biodiesel as they are for the above HD road vehicles.

Again ILUC has a significant contribution to the overall WTW GHG emissions. In case ILUC would not be taken into account, the WTW GHG emissions of all biofuel production routes from rapeseed and palm oil would be lower than the WTW GHG emissions of fossil diesel. Refer to Appendix D

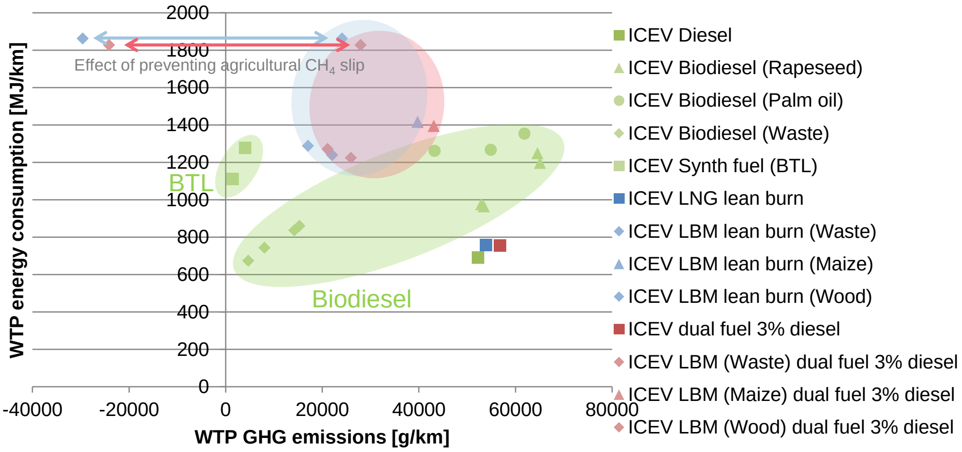

Figure 14 WTW CO_2 emissions and WTW energy use of a standard inland ship with various drivetrain types using energy sources from various raw materials, including ILUC emissions and methane slip.

4.3.5 *Emissions of a standard short sea ship*

Similar to the analysed inland ship above, the methane slip has a relatively large impact on the GHG emissions for the defined short sea ship, i.e. respectively 16% and 20% of the total TTP and WTP GHG emissions. As a result of the large contribution of the methane slip to the CO_2 equivalent emissions, the WTP GHG emissions of the configuration consuming LNG (i.e. lean burn and dual fuel) are not lower than those of engine burning MGO or HFO (with scrubber). This is shown in Figure 15.

Moreover, as methane slip occurs to the same extent for LBM, the use of LBM results in WTP GHG emissions of LBM are not as much lower as those of biodiesel as they are for the above HD road vehicles.

Since the energy consumption of the MGO and HFO (with scrubber) vessels are equal, the use of biodiesel in either configuration results in equal WTP GHG emissions. However since the carbon content of MGO is slightly lower than that of HFO, a slight difference in WTP GHG emissions exists when comparing these fossil fuels.

The duel fuel and lean burn drivetrains perform similar, both in WTP emissions as well as WTP energy use.

Again ILUC has a significant contribution to the overall WTW GHG emissions. In case ILUC would not be taken into account, the WTW GHG emissions of all biofuel production routes from rapeseed and palm oil would be lower than the WTW GHG emissions of fossil diesel. Refer to Appendix D

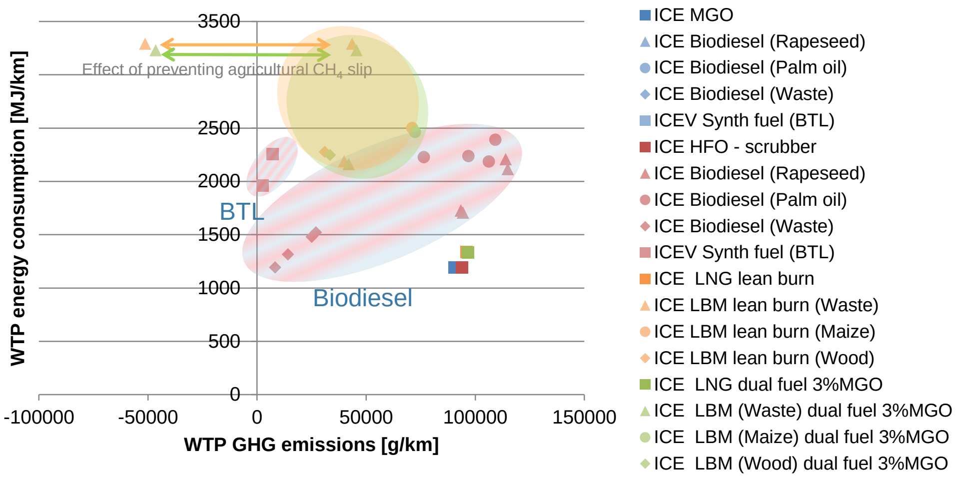

Figure 15 WTW CO_2 emissions and WTW energy use of a standard short sea ship with various drivetrain types using energy sources from various raw materials, including ILUC emissions and methane slip.

4.3.6 *Emissions of a standard deep sea ship 5500TEU*

In contrary to the two vessel types analysed above, the contribution to methane slip to the total GHG emissions is relatively limited, i.e. approximately 1%. As a result, the WTP GHG emissions of the LNG dual fuel configuration are approximately 12% lower than those of the configurations using MGO or HFO (see Figure 16). Because of the required liquefaction, the WTP energy use of the LNG dual fuel configuration is slightly higher than that of the MGO and HFO configurations.

Because of this liquefaction process, the WTP energy use of biogas is also higher than that of biodiesel. The WTP GHG emissions of the biofuels is very different for the various raw materials and production routes.

Again ILUC has a significant contribution to the overall WTW GHG emissions. In case ILUC would not be taken into account, the WTW GHG emissions of all biofuel production routes from rapeseed and palm oil would be lower than the WTW GHG emissions of fossil diesel. Refer to Appendix D

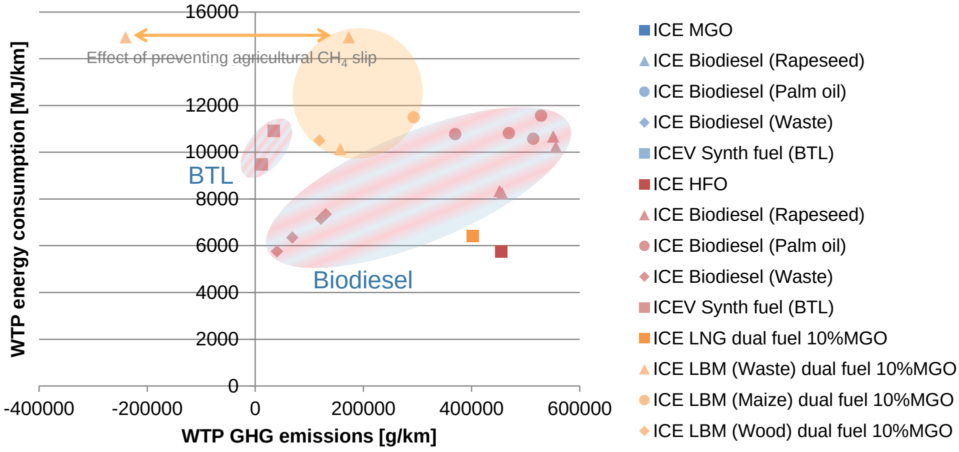

Figure 16 WTW CO_2 emissions and WTW energy use of a standard deep sea ship (5500TEU) with various drivetrain types using energy sources from various raw materials, including ILUC emissions and methane slip.

4.4 Conclusions on the GHG WTW and WTP emissions

The (WTW or WTP) CO_2 emissions of all analysed modalities are lower for the LNG based configurations. However, the benefits are often mostly undone by the methane emissions which many inland vessels and short sea ship engines produces.

In all cases, the total energy consumption over the complete energy carrier chain, from production to use in the vehicle or vessel, are higher for LNG than for the non-LNG based configurations. This is partly because of the energy consuming liquefaction process of the methane gas.

The GHG emissions resulting from bio based fuels vary significantly depending on the raw material and production route. In general, producing biodiesel from waste (e.g. tallow or waste cooking oil as shown in Table 13) results in the lowest possible GHG emissions energy consumption. For most other raw materials, the use of LBM leads to lower GHG emissions but higher energy consumption than production and the use of biodiesel.

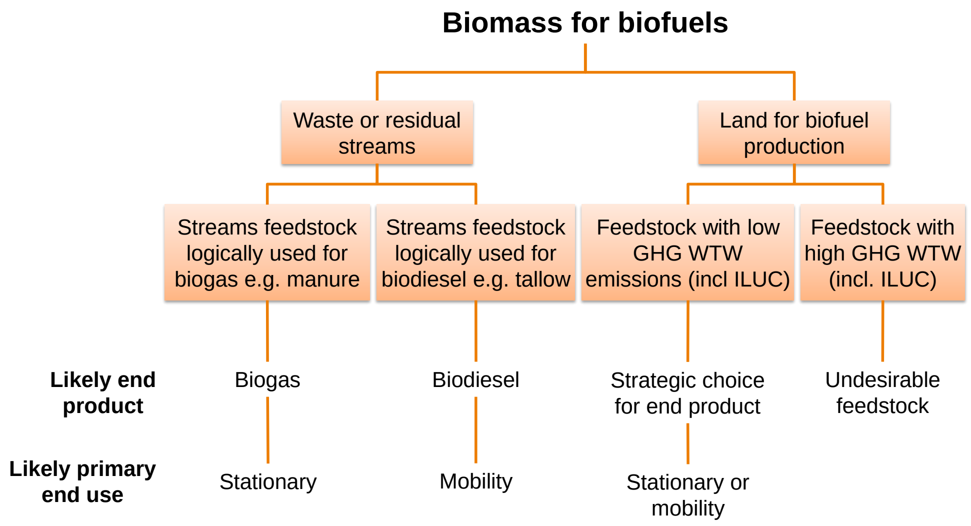

Figure 17 Production path ways and use of biofuels

An overview of the Well to Wheel GHG emissions (CO_2 equivalent) for the different fuel options is presented in Figure 18. This is based in figure 8 in section 4.1, but now it includes correction for engine efficiency and engine methane emissions for different modalities; trucks and ships. Inland ships and sea ships do not deviate much and are combined in one set of columns. Some main assumptions for this study and for figure 18 are summarised in table 19. CNG trucks are not separately included in figure 18, but the results are very comparable or slightly better than for LNG trucks.

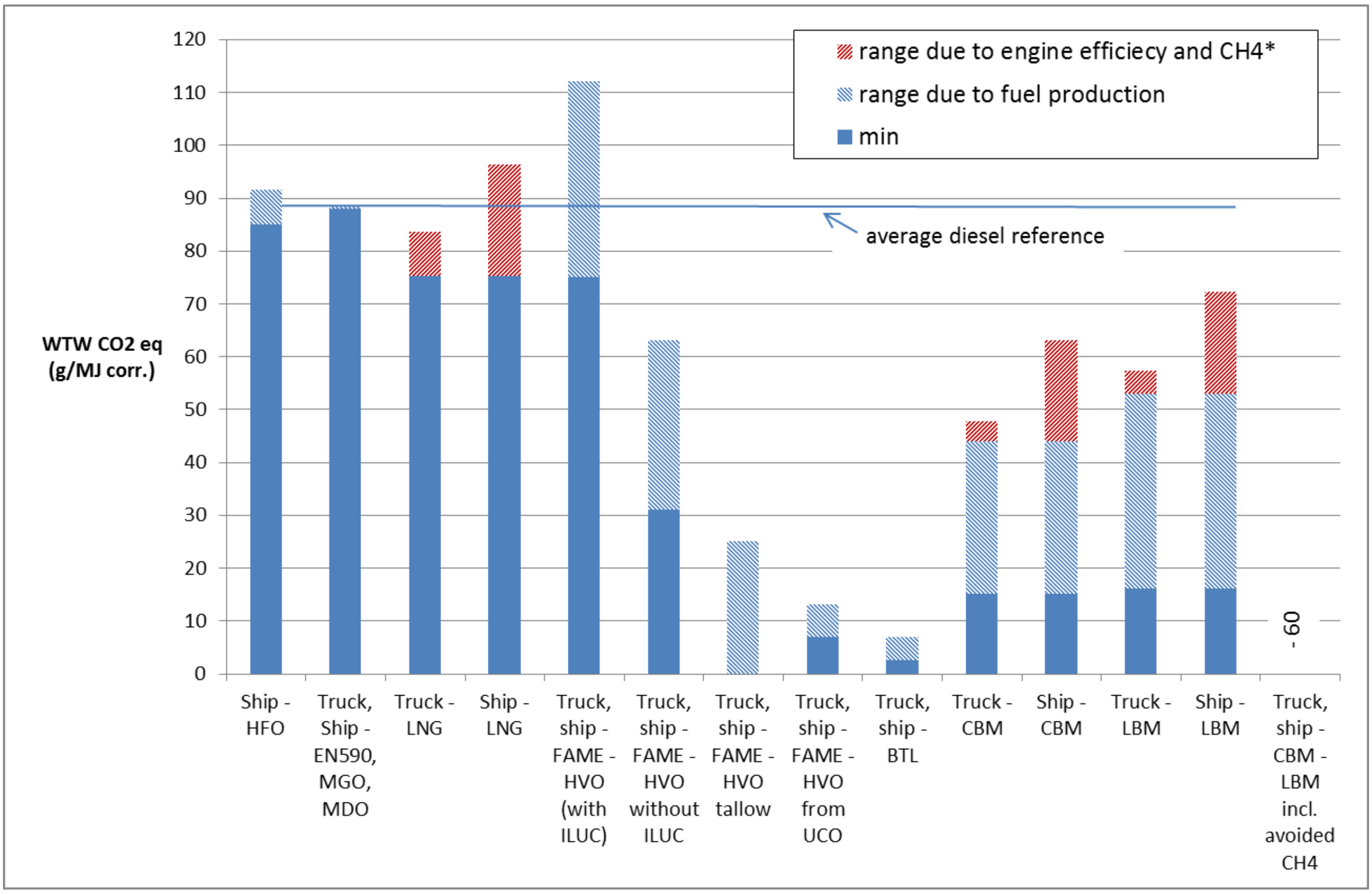

Figure 18 Well to Wheel and Well to Propeller GHG emissions for different fuels, including correction for engine efficiency, cargo loss and engine methane emissions.
* CH4 emission from engine, includes 2% average cargo loss for ships due to LNG tanks

Table 19 Assumptions used for this study

Parameter	Assumption
Truck engine efficiency	Gas spark ignition engine: 10% higher fuel consumption
Ship engine efficiency	Gas engines: 3% higher energy consumption on average[42]
Ship cargo loss	2% average cargo loss due to LNG tanks

From figure 18, it can be concluded that there is a very large variation in GHG emission depending on the feedstock and other parameters:

- For biodiesel this is the fact whether ILUC is included or not. The GHG emission can be higher than with fossil diesel fuel if ILUC is included. GHG emissions are very low for biodiesel from tallow or Used Cooking Oil (UCO); in the range of 5-15% of fossil diesel.
- For biogas, CBG or LBM, GHG varies strongly depending on the production method; from waste, crops or manure. For waste and crops, the GHG emission ranges from 25% to about 70% of those of diesel fuel. If produced from manure, there could even be a GHG reduction, but this is due to a very poor reference situation: the manure collected and emitting large amounts of methane.

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[42] In some cases energy efficiency can improve substantially if LNG engine is put in a hybrid or series electric configuration. For example refer to Ost-Friesland passenger ferry in MariTim project.

- Trucks running on LNG can have lower GHG emission than diesel trucks, but this is based on the assumption that the energy consumption is about 10% higher than that of the diesel engine. In practice this can be higher.

5 Availability of biomass for fuels

As shown in section 4.3, the use of certain biofuels results in lower WTW or WTP GHG emissions than the use of fossil equivalents even after accounting for ILUC. Therefore, biofuels are an important part of European government's strategies to reduce GHG emissions from transport. Biomass is currently the main source of renewable energy in The Netherlands. Between 2010 and 2020 the Dutch government aims to double the amount of energy from biofuels.

On the other hand, not all biofuels produced actually result in net CO_2 reduction. Moreover, biomass is only limitedly available and the production costs of biofuels are generally higher than the costs of producing fossil equivalents. Therefore, most of these biofuels are currently not used on large-scale.

5.1 Potential effects of the growing demand for biomass

In recent years concerns have been raised regarding potential negative effects of the growing demand for biomass for the production of biofuels in the EU, which may lead to 'land-grabbing', causing e.g.

- loss of agricultural land because, which may have negative socioeconomic impacts in countries all over the world
- loss of biodiversity
- climate change.

However, in two recent 2013 studies[43,44] it was concluded that that biofuel expansion between 2000 and 2010 is only limitedly associated with a decline in NHA (Net Harvested Area, crop area harvested for food, feed and fibre markets) available for food crop production.

5.2 Availability of biomass

5.2.1 Various end uses compete for biomass

Biomass can be used for multiple applications, e.g. electricity production, the chemical industry, industry heat generation, household heating and biofuels for mobility. Since biomass is only limitedly available, increasing the amount of biomass to be used for one application, decreases the amount available for others.

For some applications other low-carbon energy sources are available or are likely to become commercially viable in the near future. Some examples are light duty electric vehicles , sustainable electricity production by means of solar or wind. However, for industrial heat, household heating and the chemical industry, suitable alternative sources are for not expected in the short term. This is also the case for energy carriers for heavy duty vehicles and vessels.

In the end, the ways in which biogas is produced and used, depend on governmental incentives and the specific conditions at the sites where the biomass becomes available.

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[43] Land grabs for biofuels driven by biofuels policies. Carlo Hamelinck, 2013 July.

[44] Analysing the effect of biofuel expansion on land use in major producing countries: evidence of increased multiple cropping biomass research report 1301. Biomass Research, Wageningen, 1 July 2013

5.2.2 *Global availability of biomass*

The global biofuels production has increased significantly in the last decade ((figure 19). Ethanol is by far the most produced end-product, followed by biodiesel. Between 2010 and 2050 the production of biofuels is expected to grow significantly in all regions of the world (Figure 20). In this period the share of biodiesel and biomethane is expected to increase (Figure 21). The IEA expects that 50% of the feedstock for advanced biofuels and biomethane will be obtained from wastes and residues.

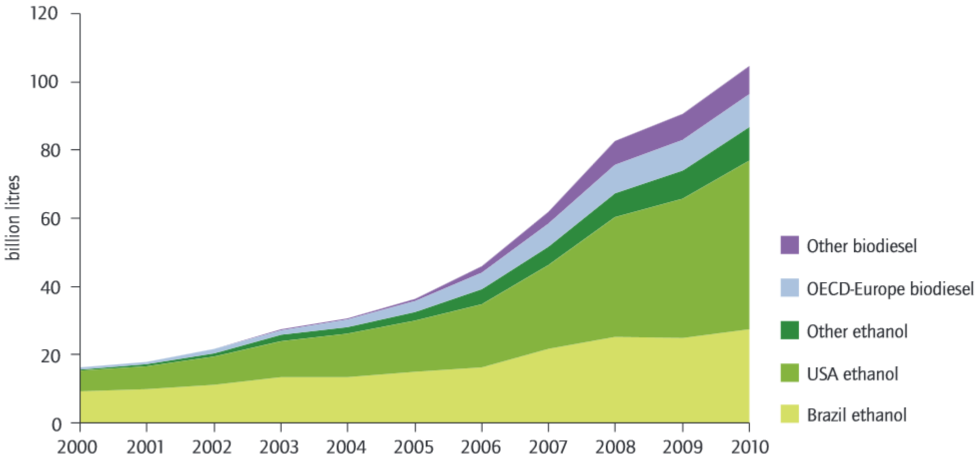

Figure 19 Global biofuel production between 2000 and 2010[45]

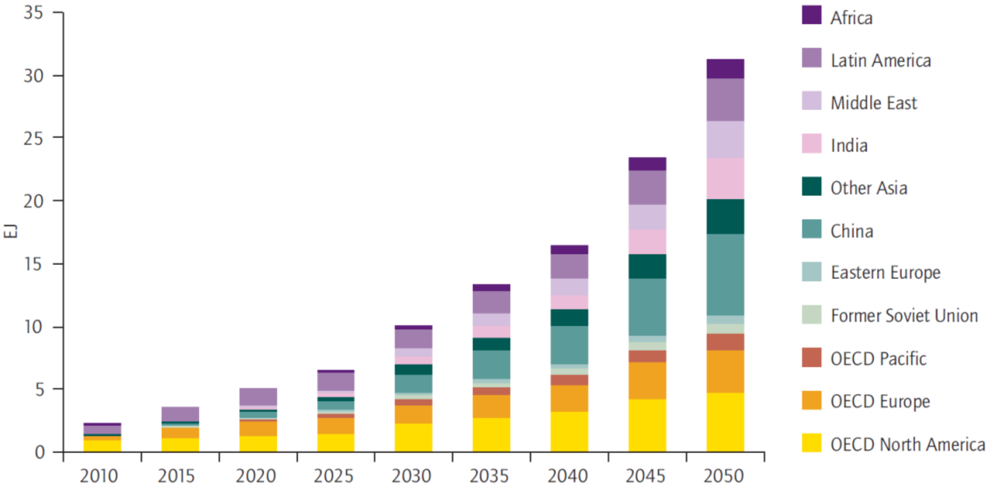

Figure 20 Biofuel demand by region between 2010 and 2050[45].

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[45] Technology Roadmap: Biofuels for Transport. IEA, 2011

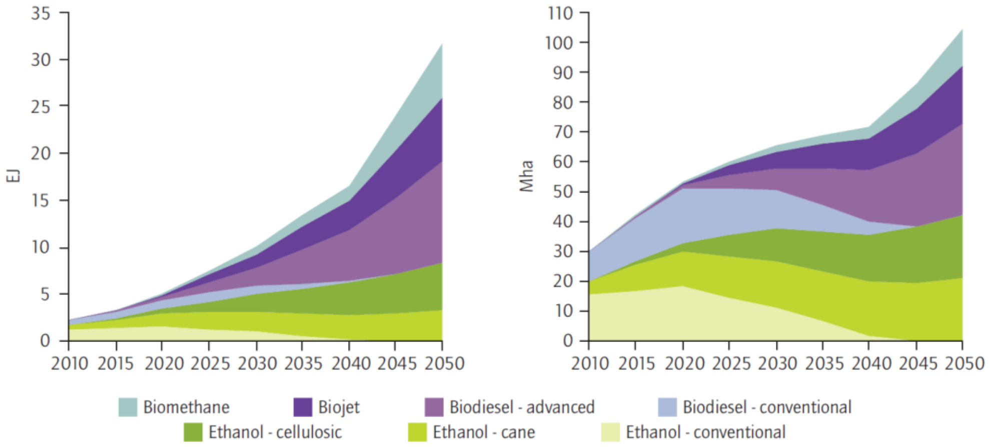

Figure 21: Demand for biofuels (left) and resulting land demand (right) [45].

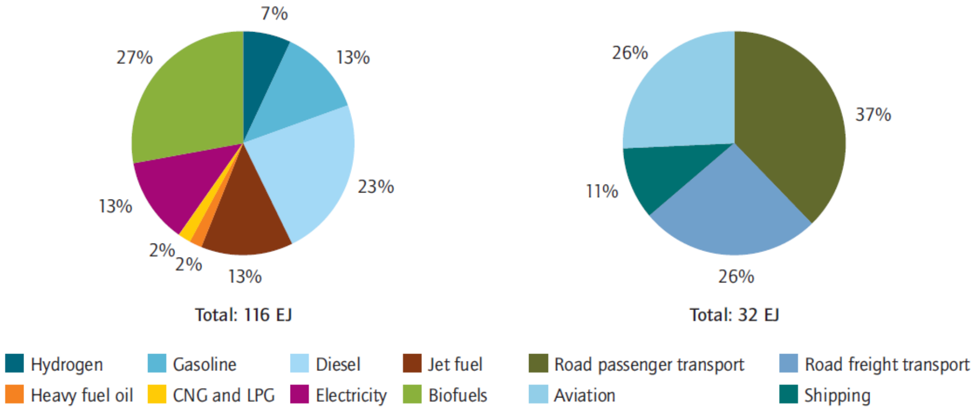

Figure 22: Global energy use in the transport sector (left) and use of biofuels in different transport modes (right) in 2050 (BLUE Map Scenario)[45].

5.2.3 *Availability of biomass in Europe*

As shown in Figure 20, the share of biofuels in the European energy supply for transport is expected to increase significantly. Part of this additional demand is likely to be produced within Europe. Therefore Eastern Europe has been identified as region in which approximately 40 Mha of underutilised and abandoned agricultural land could be cultivated to produce additional biomass feedstock[46]. In other parts of Europe, land availability is a potentially limiting factor and more efficient use of waste and residues will play an important role to enable further development of the biofuel sector.

Het IPCC Special Report on Renewable Energy[47] gives for Europe a biomass potential for non-food applications of 18 to 27 EJ in 2030. Refer to Figure 23, which

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[46] REFUEL (2008), Eyes on the track, Mind on the horizon. From inconvenient rapeseed to clean wood: A European road map for biofuels, REFUEL, Petten.

[47] IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

also shows production costs and supply quantities of first and second generation feedstock:

- 1e generation: plant oil, sugar and starch
- 2e generation: wood and grass

The first generation biomass includes Used Cooking Oil and waste streams from food production. The first generation biomass gives the natural feedstock for bio-diesel and bio-ethanol. Bio-ethanol, biodiesel (BTL) and bio methane can also be produced from the second generation feedstock, although these production routes are still in a research phase. So far ethanol production is the most developed one. Production of biogas from wood may be an option in order to produce large quantities of biogas from second generation feedstock.

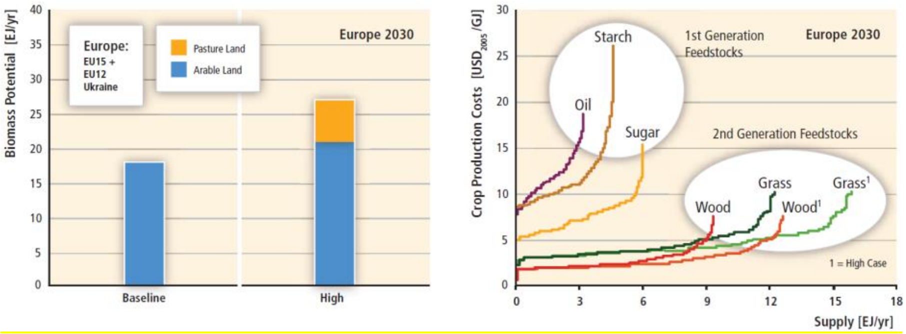

Figure 23 Left: European biomass potential for biomass
Right: cost-supply curves for specific biomass options for Europe and Ukraine
Source: IPCC (2011).

The IEA World Energy Outlook (2013)[48] presents an energy mix for Europe for 2013. Refer to Table 20. The table shows a (liquid) biofuels quantity of 13% to 25% depending on the scenario. Gaseous fuels are limited to 2% in these scenarios. The study also projects a 20% share of second generation biofuels for 2035, which means that for the coming decades first generation feedstock[49] and fuels may dominate. The European Commission and Dutch government want a faster transition to second generation biofuels. The question is whether policies will enter into force in time and whether R&D and up scaling of production are sufficient to make this transition faster.

Table 20. Energy mix for transport for EU in 2030 for two scenarios (IEA 2013).

	New policies scenario			450 scenario		
	Mtoe	PJ	%	Mtoe	PJ	%
Oil	212	8880	77%	137	5740	59%
Bio-fuels	35	1470	13%	58	2430	25%
Electricity	10	420	4%	16	670	7%
Other (incl. gas)	5	210	2%	5	210	2%
Total	275	11510		233	9760	

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[48] IEA World Energy Outlook 2013. International Energy Agency, Parish.

[49] NGO wants on short term to phase out 1^{e} generation biofuels that are not produced from waste

5.2.4 *Availability of biomass in The Netherlands*

In a Dutch fuel mix assessment in 2014, energy consumption projections for road transportation for 2030 and 2050 were made. The maximum availability was estimated as presented in table 21. For 2030 however a range was given of 5 to 80PJ[50].

Table 21 Estimated maximum available biofuel quantities, based on Dutch fuel mix assessment

PJ	**2030**	**2050**
Biofuel (liquid)	64	144
Biogas	16	36
Total (max)	80	180

The current energy use for transport in the Netherlands is currently about 500 PJ. So the estimated maximum biofuel availability for 2030 and 2050 correspond to respectively 15% and 35% of the current energy use.

According to a recent publication by the Dutch Biogas Forum[51], an increase of biofuels produced via fermentation is expected in The Netherlands up to 2030, because additional fermentable (wet) waste streams are likely to become available for biogas production:
- manure, in particular cattle manure because of changing market conditions and regulation; in addition, also pig and chicken manure;
- sewage sludge;
- grass;
- by 2030, an additional biomass stream is to be expected, i.e. seaweed.

Biogas could potentially generate approximately 13-20 PJ[52,51] by 2020, which would be between 4 and 7% of the Dutch renewable energy target.

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[50] G. Koornneef e.a. (TNO), H. van Essen e.a. (CE Delft), M. Londo e.a. (ECN): Verzamelde kennisnotities t.b.v. de visie duurzame brandstoffenmix (collected knowledge notes for Dutch fuel mix assessment). 27 June 2014

[51] Routekaart hernieuwbaar gas, juni 2014

[52] Breeuwer J. Deploying liquid biomethane in the Dutch transport sector Analysing economic, environmental and organisational sustainability

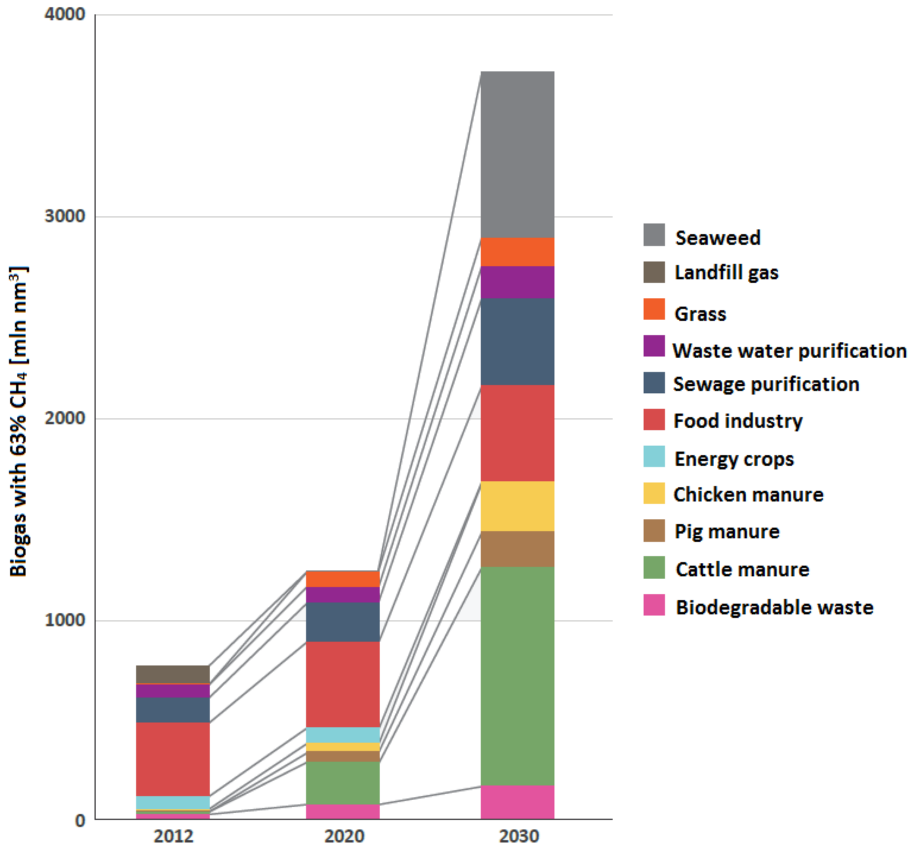

Figure 24 Potential energy from biogas obtained from anaerobic digestion in the Netherlands[51].

Compared to fermentation, gasification technology is still immature: further development of gasification technologies is required before large-scale applications become viable. In the end, strategic choices have to made on the final products produced via gasification. i.e. which existing intermediate and final products will be competed with. Prices of those competing products ultimately determine the route and determines the allowable costs of biomass conversion technologies.

5.3 Availability of LBM

As shown in Figure 21 the supply of biomethane is expected to increase significantly in the coming decades. This biomethane or biogas can be used for several different applications, e.g.

- heat generation: supplying biogas directly for heat generation has the lowest financial gap. However, this use for biogas results in very limited flexibility, i.e. the number of places where biogas produced and can be directly supplied to an end user with a constant and guaranteed demands for heat is limited.
- feed-in in the gas network: feeding into the natural gas network gives more certainty.
- Bio-CNG or bio-LNG (also known as Liquid Biomethane or LBM) in mobility: biogas can actually be compressed or liquefied to be used in mobility, but could also be fed into the gas network while the CO_2 credits are sold by means of certificates.

Each of these applications has financial, environmental and organisational advantages and disadvantages

Table 22 Advantages and disadvantages of various applications of biogas[53]

biomass option	Advantages	Disadvantages
anaerobic digestion	directly applicable, established technologies, solves methane emissions	limited potential and possible interference with food production
CHP	• provides electricity for the installation • guarantied marketing for electricity	• heat often not used effectively • relative low conversion efficiency
grid injected green gas	• extensive gas grid already present • guarantied marketing for green gas	• quality issues for produced gas • relative low environmental benefits
LBM	• high environment benefits per MJ • lowest production cost profile	• no significant market present • slow development of LNG vehicles
gasification	larger potential, better efficiency and applicable to coal	not commercially available before 2020, competition with other dry biomass use
incineration	• most cost-efficient option • multiple deployment options	• competition with coal power plants • limits green gas options
chemical processing	• dependent on type of processing	• dependent on type of processing
biodiesel	• can be mixed directly with diesel • certain marketing options	• lowest environmental benefits • higher energy loss
LBM	• low energy loss • best option to produce fuel	• uncertainty about costs • uncertain development LNG market

As indicated above the costs for using of biogas for (industrial) heating are lowest, partly because of low transportation costs and purification requirements compared to transport fuel use or grid injection. Therefore this application seems the most preferable use for biomethane. However, as the environmental benefits for this application are relatively limited, CO_2 credits could be transferred by means of certificates to the transport sector.

Moreover, liquefaction of biogas is more cost-effective when converted on large-scale. However, since biogas is likely to become available in relatively small amounts per production location, costs for converting biogas to LBM are somewhat higher than large scale liquefaction. According to Hochschule Emden/Leer 2014)[54]. Production costs of LBM in small units (1000 ton/year), is around 320 EUR/ton higher than large scale production with medium scale liquefactions (1400 → 1720 EUR/ton). .

Since direct use of biomethane in industrial heating is rather inflexible in terms of production and use location and supply and demand, injection of biogas in the grid may be a more viable option for certain production sites. This application would also allow for transferring CO_2 credits to sectors in which environmental benefits are higher. The advantage of not having to liquefy biomethane on a small-scale would also apply if biogas would be injected in the grid.

In case LNG technology for vehicles and vessels develops rather quickly in the coming decades and the demand for LNG increases accordingly, the price for LNG may rise sufficiently make the production of LBM economically feasible.

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[53] Deploying liquid biomethane in the Dutch transport sector Analysing economic, environmental and organisational sustainability. Jelco Breeuwer

[54] Prof. Dr. Sven Steinigeweg, Prof. Freerk Meyer, Wilfried Paul, EUTEC-Institut, Hochschule Emden/Leer: „Perspektiven und Potentiale von Low-Emission-LNG im Nordwesten“. Client: LNG Initiative Nordwest (Germany). Presentation 2014.

6 Discussion

6.1 Effect of future developments in engine technology

The reference period of this study is 2015 to 2020. So the technical solutions, performances and emission levels are related to products entering the market in this period. Manufacturers will continue to develop their engines which will likely lead to improvements in the future.
In this section an outlook is presented for future available products and technologies entering the market until 2030 / 2035.

Truck engines
The main technological direction is currently spark ignition with stoichiometric combustion, because this form the best basis to comply with the very stringent NOx, PM and methane emission requirements, with reasonable costs. The efficiency loss currently seems to be limited to10% - 20%, although it is recommended to monitor this in real life applications. Future developments will be focussed on a further reduction of the efficiency gap with diesel. Taking into account the small efficiency differences between large gas and diesel engines, closing the gap to some 5%-10% in the future may be feasible, especially with dual-fuel engines. This is however still in research phase.
Important will be to increase the power output to similar levels as for the more powerful diesel engines.

A dual-fuel engines with high-pressure direct gas injection is also under development by Volvo following the example of the Cummins engine with Westport injection system[55]. This engine will increase the power range and most likely also close the efficiency gap. Drawback may be the relatively high manufacturing costs.

Inland ships engines
Very stringent emission requirements for 2018-2020 has been proposed, but adaptation (levels and timing) is still considered uncertain. For NOx and PM the requirements are very similar to Euro VI truck engines. For gas engines (both pure gas as well as dual fuel) a 6.2 g/kWh[56] methane emission limit has been proposed for most engine types. This limit value makes sure that GHG emissions are not higher than for diesel engines.
Assuming that the stringent pollutant and methane requirements will be implemented around 2020-2025, more advanced gas dosage system are expected which could curtail the methane emissions. The gas (single or dual fuel) engines would also require specific emissions control systems such as EGR or SCR deNOx. Manufacturers which currently provide spark ignition (lean-burn) engines may make a transition towards stoichiometric running engines with 3-way catalyst, but EGR may be applied to prevent a loss in efficiency and to reduce thermal engine load. Still these are major changes which may eventually not be feasible due to impact on engine life time.

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[55] Westport 2003: Cummins Westport Spark-Ignited (SI) and High Pressure Direct Injection (HPDI) Natural Gas Engines. Natural Gas Vehicle Technology Forum (NGV-TF) 2003

[56] Formally it is max 6.18 g/kWh methane for engines with a higher gas share than 60%. Below 60%, there is a linear function with the gas %. The CO2 equivalent of 6.18 g/kWh methane is about equal as the advantage of gas due to the low carbon content.

The overall result will be that LNG will start to show a GHG emission advantage of some 15-20% compared to standard diesel engines.
It should be noted that the developments of such engine technologies are very costly, which has to be earned back in a relatively very small market. So it may not happen and availability of gas engines for inland shipping may stagnate. It would help if there would be similar requirements in other markets where these engines are used. These other markets are stationary power and auxiliary engines for sea vessels.
Sea ships
Most important developments for 2020 onwards are:

- Introduction of a global fuel sulphur limit of 0.5% in 2020 or 2025.
- Introduction of Tier III NO_x limit for new ships in European ECA (North Sea, Baltic Sea).

Especially the latter is uncertain. There are no signs yet that there will be IMO or European legislation which will limit methane emissions from the engine. Alternatively legislation to reduce GHG emissions of gas engines (or gas and diesel engines) can be considered. In that way a total optimisation of engine efficiency and methane emissions can be done which leads to lowest overall GHG emission.

Due to the pressure on GHG emissions, it is expected that the methane emission will slowly be reduced by improved gas dosage and combustion concepts. The challenge will be to realise this without sacrificing engine efficiency.

If methane emissions are reduced by voluntary measures or legislation, there will be a more general advantage in GHG emissions of some 15-20% of LNG compared to diesel engines. It is expected, that the year in which this may be realised could be somewhere around 2030 – 2035, provided the market develops in such a way that substantial investments in technology developments can be justified. It is recommended to develop a realistic time path with the industry.

6.2 Compatibility of biofuels and gas and diesel engines

LBM, Liquid Bio Methane, is a high quality fuel. Its methane number is often higher than for regular LNG, which may improve engine performance and reduce weathering risks of the stored fuel.
Biogas can however be produced for various applications. Apart from LBM, it can directly be used for heating or it can be used for heating or transportation via injection in the grid. Because of the additional energy loss and the relatively high costs of converting biogas to LBM, this is not the most logical application. When biogas is injected into the grid, CO_2 credits can be transferred to the transport sector, as is currently already done for CNG.

Biodiesel can be produced in several qualities, which makes it quite suitable to use it in a range of diesel engines. It can be used as pure fuel or as blend with regular diesel. The following types of biofuel for diesel engines can be distinguished:

- Pure Plant Oil or PPO is the simplest biofuel for diesel engines. It is just the oil pressed from oil containing crops such as from rapeseed, sunflower, etc. The viscosity is generally higher than for standard diesel fuel.
- Biodiesel or FAME, is one of the most economical options generally used as low blend for road transportation. The standard EN590 fuel specification allows for a blend up to 7%.

- Hydrotreatment Vegetable Oil or HVO. This is a very high quality diesel fuel which is can be used in rather high blends within the EN590 fuel specification (up to approx. 30%).

Depending on the engine manufacturer and engine type, higher blends than mentioned above and even pure biofuels can be used. This applies to HVO, FAME and PPO. For a broad overview of engine - biofuels compatibility, refer to Kampman, 2013[57]. It is recommended to use the highest quality biofuel for applications where pollutant emissions are important and where engines require a high fuel quality[58]. So this means, the highest quality (e.g. HVO) can best be used for trucks, high or medium quality (HVO or biodiesel) for inland shipping and the lowest quality for sea ships. The lowest quality, PPO, is still relatively clean if compared to the best marine fuels (such as ultra-low sulphur content). An issue is, that the specifications of marine fuels (ISO 8217) does not allow blending of biodiesel, but blending of FAME is currently being worked on. Possibly in the next update (2016), blending of FAME is allowed For HFO there is no specific limitation for biodiesel blending. In several studies the use of PPO has been proposed for sea ships[59]. There is experience with large engines running on PPO with stationary power generation.

6.3 ILUC emissions of biofuels

The environmental impact of biofuels strongly depends on the specific feedstock and production route. Certain routes result in much lower WTW GHG emissions than fossil fuels, while other routes result in comparable or even higher WTW GHG emissions due to ILUC. Therefore, biofuels from feedstock from production locations originally used for food and leading to unfavourable land use change elsewhere, should be avoided.

In this study, ILUC is taken into account. As a result the WTW (or WTP) GHG emissions of certain feedstock and biofuel production routes are relatively high. Especially for biodiesel from palm or rapeseed oil this is in many cases higher than for the fossil equivalent. For feedstock from waste, land use change is not a factor. As a result the gap between WTW GHG emissions from waste and biomass produced from new biomass (which is affected by ILUC) is large if ILUC is taken into account. This increases the attractiveness of waste to be used for biofuel production. A potential negative effect of this phenomenon is that the value of waste streams that can be used for biofuel production could increase. As a result certain material may be labelled as waste while it could have been used for material recycling and potentially have a more positive effect on total GHG emissions. This potentially negative effect of material use change is not accounted for in this study.

6.4 Likely applications for biogas and biodiesel

For biogas, it is more likely that this will be used directly for heating or injected into the gas grid. This is because of the relatively high costs of converting biogas to LBM. When injected into the grid, it can be considered to record CO_2 credits and

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[57] ‘Options to increase EU biofuels volumes beyond the current blending limits’. Bettina Kampman, Ruud Verbeek, Anouk van Grinsven, Pim van Mensch, Harry Croezen, Artur Patuleia. July 2013. Publication code: 13.4567.46 CE Delft. European Commission, DG Energy.

[58] Refer to MIF project: Biofuels for sea shipping. Verbeek 2011.

[59] Olav Andreas, Opdal and Johannes Fjell Hojem: Biofuels in ships: a project report and feasibility study into the use of biofuels in the Norwegian domestic fleet. ZERO-REPORT - December 2007

transfer them to the transport sector for LNG or even for diesel fuel such as is currently done for CNG.
Local production of LBM also has the advantage of reducing the safety issue of truck tanker distribution of LNG.

The use of liquid biofuel in diesel engines is considered a good and practical way to reduce GHG emissions of the commercial transport segments, provided high ILUC emissions can be avoided. Blending in fossil fuel is generally the most practical way to use large quantities of biofuel. For road transportation and inland shipping low blends of conventional biodiesel is possible within the fuel specification (up to 7%). HVO can be used in much higher blends. For maritime, biodiesel blends or PPO are not expected to create technical issues but the diesel specifications need to be adapted and a separate supply chain may be needed.

6.5 Global warming factors

The global warming factor used for methane to calculate the CO_2-equivalent GHG emissions plays a substantial role in the comparison of the natural gas and diesel fuel chains. In this study, the factor 25 is used. This is according to the official IPCC guidelines, to be used for National GHG emissions inventories for Europe and for the UNFCC (united Nations Framework Convention on Climate Change). Only this factor for 100 years global warming equivalent is used.
Apart from this official factor, also other values are published and additionally factors are published for 20 years and for 500 years equivalent. The ranges are:

- GWP: 100 years: 20 to 34
- GWP: 20 years: 56 to 86
- GWP: 500 years: 6 to 7.

Recently scientists asked the US government to use the highest global warming factors 34 (100 y) and 86 (20 y)[60]. It is clear that, when the high values are applied, such as the 86 for 20 years GWP, this is very disadvantageous for the ship engines with relatively high methane emissions. The GHG emissions would then increase to a level up to 50% higher than diesel engines. This emphasises the importance of reducing methane emissions of engines as well as methane leakages with production and distribution of natural gas.
In figure 25 below, the effect of different GWP factors is shown as a function of the methane emission of the gas engine. The methane emission of the engine would need to be below about 1.7 g/kWh in order to avoid an increase of GHG emission for the short term, 20 years period using the highest factor (86). For the long term, 100 years, the methane emission should be below 4 to 7 g/kWh depending on the precise GWP factor and the type of diesel fuel. In the context of this study, there was a lot of discussion on the importance of the different periods, the scientific uncertainty of the GWP factors and relevance of GTP (Global Temperature Factor). The latter is proposed as alternative to the GWP with a possible better relationship with the actual global temperature rise. It is concluded that GWP_{100} is the main parameter to consider, but that additionally GWP_{20} is important as well because adverse GHG emission effects will likely also substantiate in a shorter period than 100 years.

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[60] F. Stuart Chapin III, et.al.: Recommendation to accurately account for warming effects of methane. Letter, July 29, 2014

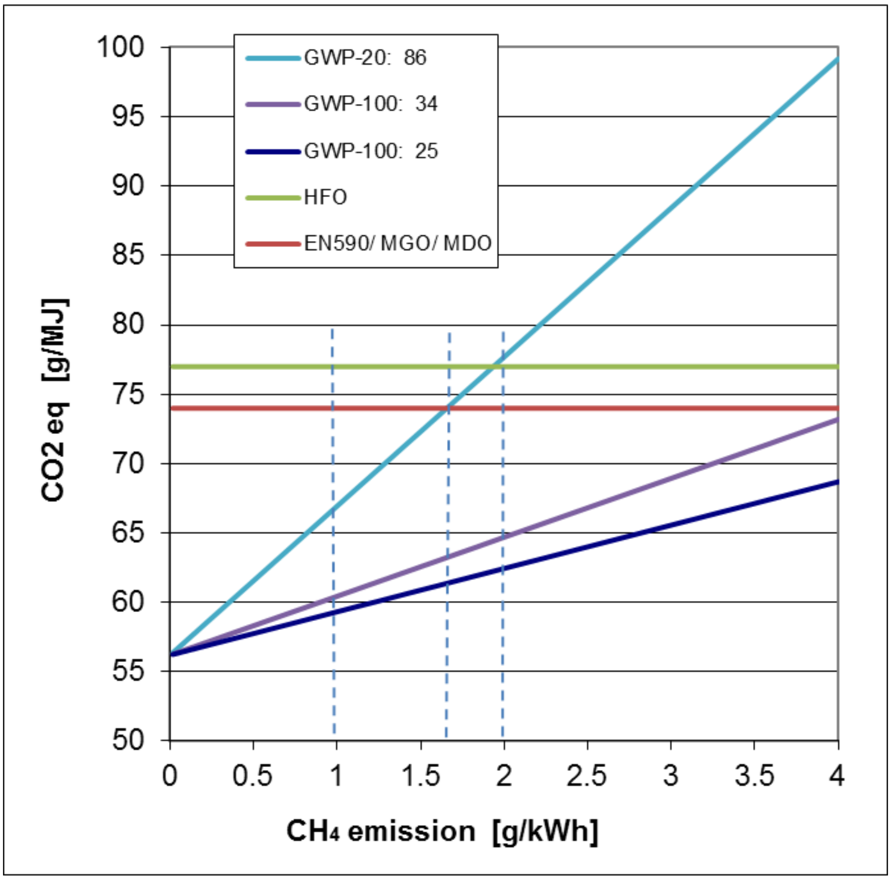

Figure 25. Comparison of Tank-to-Propeller GHG (CO_2 equivalent) emissions between diesel (EN590/MGO/HFO) and natural gas engine as a function of methane emissions of the gas engine. The effect of different GWP factors is shown.

6.6 Availability of biofuels

A significant share of the increase of biomass for biofuel production is likely to result from better use of residual and waste streams. Depending on the feedstock, a specific end product is most likely to be produced. Waste streams such as tallow and waste cooking oil can more easily be converted to biodiesel, while feedstock such as household waste and manure are more easily converted to biogas. It is therefore likely that the supply of both gas and ‘diesel type’ biofuels will increase in the coming decades.

Besides biomass from waste or residual streams, biomass is also grown on cultivated land. The choice for the feedstock grown on this land is a strategic choice depending on a number of criteria such as:

- GHG emissions for producing end product
- the demand and price for a specific end product
- amount land-use per energy unit of fuel
- chance of successful yield
- etc.

PBL uses a range of 50 to 150 EJ (50,000 to 150,000 PJ) for the global availability of biomass for biofuels and bio-chemical feedstock in 2030. IPCC even mentions a potential global amount of 170 EJ (without year). For the Netherlands a maximum potential amount for transportation is estimated of 80 PJ for 2030 and 180 PJ for 2050. The amount of liquid biofuel is generally a factor 3-5 larger than the amount of biogas. From the available projections, it can be concluded that up to 2030-2035 first generation biofuels will certainly dominate. After 2035, second generation biofuels may gradually take over.

The question is: can sufficient quantities of good biofuel be produced in the future and would that be biogas or liquid biofuel? If biofuel would be produced from second generation feedstock (wood, grass), the GHG emission of biogas and liquid biofuel may not deviate that much. Biogas (bio-methane) would have some advantages in production, while liquid biofuel would have some advantages with distribution and use in the vehicles. At the end it comes down to costs and practicality. The main challenges are probably the limitation of engine methane emissions for the biogas route and the feasibility of liquid biofuel production from second generation feedstock (or the avoidance of ILUC with first generation feedstock).

6.7 Lack of information

The most important gaps in information are the following:

- Engine methane emissions, especially for dual-fuel ship engines. Engine methane emission play a large role in the overall GHG emission for LNG.
- PM emissions data of ships diesel engines with different fuels (HFO, MDO, MGO and gas engines). PM results are currently based on a handful published measurement results and a linear regression with fuel sulphur content.

Also more data is desired for EURO VI heavy-duty vehicles in order to make a better comparison between gas and diesel fuelled vehicles. Especially information on engine efficiency, PM and NO_x emissions under real driving conditions is desired.

7 Conclusions and recommendations

The evaluation of pollutant and GHG emissions of different fossil and renewable fuels for different transportation segments leads to the conclusions below.

Application of LNG as fossil fuel option for GHG and/or pollutants reduction

- For trucks, GHG emissions will be reduced by 10-15% compared to diesel with LNG, provided that the increase in energy consumption compared to standard diesel engines can be limited to some 5-10%.
- Pollutant emissions will be very low for all fuels due to the stringent legislation and the high quality diesel fuel. Some data shows nevertheless lower NO_x emissions for spark-ignition gas engines than for diesel engines. In addition, gas engines have lower noise emission. Particulate mass and number emissions will be very low for both diesel and gas engines (diesel Euro VI with diesel particulate filter). Finally gas engines have lower noise emissions and therefore often qualify for reamer city delivery conditions
- For ship engines, the application of LNG generally does lead to more than 75% reduction of pollutant emissions, NO_x, PM and (for sea ships) SO_x.[61]. GHG emission reduction is generally not possible due to relatively high methane emission. Some engine types do have low methane emission showing that this is technically feasible[62]. In that case, a GHG reduction of 15-20% compared to diesel is possible. The applied fuel system and combustion technologies of these gas engines with low methane emission, should serve as example for developments and long term formal emission requirements (2025-2035).

For inland shipping, the emission requirements will likely develop in the same direction as for HD vehicles, although for methane emission this is still uncertain. The pollutant emissions advantage will then diminish compared to diesel.

Renewable fuel options

- Biofuels generally show the largest GHG emissions reduction (~ 80%) when residual or waste streams of feedstock are used (e.g. manure, municipal waste for biogas, and tallow, used cooking oil for biodiesel). The reduction will be in the range of 30-60% with dedicated agricultural crops. Liquid biofuels (biodiesel) from rapeseed or palm oil often have equal or higher GHG emissions than with fossil fuels due to ILUC. This will likely improve over time.
- The availability of biofuels, has been estimated to be between 50 and 150 EJ globally in 2030. For the Netherlands, the availability is expected to be around 80 PJ in 2030 and around 180 PJ in 2050. This corresponds to respectively about 15% and 35% of the current energy use for transportation. The amount of liquid biofuel (biodiesel, bio-ethanol) is in most projections a factor 3-5 larger than the amount of biogas. It is also concluded that even though the European Commission wants a fast transition to second generation biofuels, first generation biofuels may dominate up to 2030-2035.

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[61] Inland ships with diesel engines have already very low SOx emissions due to introduction of ultra-low sulphur fuel in 2011,

[62] Further substantial GHG reduction is possible, depending on the application, e.g. when LNG engine(s) are put into a hybrid or series electric configuration.

The following recommendations are done:

- In order to be able to realise a substantial GHG advantage with LNG for ships, it is recommended to come to an agreement between authorities and industry about a time path to reduce methane emissions to maximal 1 g/kWh and implement this in future legislation (e.g. by 2025-2035). Alternatively legislation can be considered to regulate total GHG emission of gas engines (combined result of engine efficiency and methane emission reduction).
- To obtain more measurement results on methane emissions of dual fuel gas engines for ships and particulates emissions of ship engines with all fuels, such that gaps in information can be filled in.

8 Signature

Delft,14 February 2015	TNO
Sam van Goethem Project leader	Ruud Verbeek Author

A Interpreting emissions

Interpreting GHG emissions

Before the previous decade, sales of new road vehicles and water vessels were dominated by ICE drivetrains using fossil fuels (mainly gasoline and diesel). Since then production and sales volumes of other drivetrain types and fuels have increased. This includes the introduction of biofuels (blended with fossil fuels) and with the increasing amount of vehicles with alternative drivetrain technologies, such as plug-in hybrid vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell vehicles (FCEVs) also energy carriers e.g. electricity and hydrogen.

The climate impact of fuels can be considered without taking the vehicle, in which the fuel is used, into account. For example, the greenhouse gasses emitted to produce a certain amount of useable energy from a specific source may be relatively high. However, if the drivetrain in which this energy is used, is very energy efficient, the climate impact may still be rather limited.

Analysing the climate impacts of various fuel types requires accounting for the greenhouse gasses emitted during the full production process. Besides the exhaust emissions (tank-to-wheel or TTW emissions) this also includes emissions during extraction, processing and distribution (well-to-tank or WTT emissions).

Tank-to-wheel and tank-to-propeller emissions
As explained above, TTW and TTP emissions are the actual emissions from the vehicle’s or vessel’s exhaust. The TTW and TTP emissions of a vehicle or vessel depend on its energy use and the GHG emissions resulting from combusting a certain amount of fuel. Since battery-electric vehicles (BEVs) and hydrogen vehicles (FCEVs) do not emit CO_2 directly from the exhaust, the TTW CO_2 emissions from these vehicles 0 g/km.

The CO_2 exhaust emissions of biofuels (such as biodiesel and biogas) are comparable to those of their fossil equivalents (respectively, diesel and natural gas). The TTW and TTP CO_2 emission factors of these biofuels are therefore very similar to those of their fossil equivalents.

IPCC emissions
In the definition of TTW and TTP CO_2 emissions described above, the use of biofuels does not result in lower CO_2 emissions than the use of fossil fuels. However, during the growth of the crops used for the production of biofuels, CO_2 is absorbed. Therefore, the IPCC (Intergovernmental Panel on Climate Change) has develop an alternative definition. According to this definition that all the emitted CO_2 is extracted from the atmosphere and absorbed by crops. In this definition the TTW and TTP CO_2 emissions are thus equal to 0 g/km.
GHG emissions released during the growing (e.g. harvesting) of crops and production of the fuels are allocated to the agricultural sector and the energy sector.

Besides emissions resulting from combustion, the use of certain (gaseous) fuels additionally results in emissions of the unburned gas into exhaust ports. In case of the use of LNG, which mainly consists of methane, this phenomenon is known as methane slip. As methane traps relatively much heat in the atmosphere, its Global Warming Potential is relatively high, i.e. 25 times that of CO_2. This factor can be used to convert methane emissions into CO_2 equivalents. Adding these equivalents to the TTW and TTP CO_2 emissions, results in the total GHG emissions expressed in CO_2 equivalents.

Well-to-wheel or well-to-propeller emissions

As explained above, the TTW and TTP CO_2 emissions are the direct result of burning fuels in vehicles or vessels. However, during the extraction, processing and distribution of these fuels greenhouse gases are emitted. This part of the energy chain is also referred to as well-to-tank (WTT). The WTT emissions express the amount of greenhouse gases emitted to produce a given amount of usable energy and transport it to the location where it is used. Besides CO_2 emissions two other greenhouse gases are generally also included in the WTT emission factors, i.e. methane (CH_4) and nitrous oxide (N_2O). These are converted into CO_2 equivalents based on their global warming potential (GWP). This is an indication for the degree to which different greenhouse gasses contribute to global warming.

By adding up the TTW (or TTP) and WTT emissions, the total GHG emissions over the entire fuel chain or energy chain can be determined, i.e. well-to-wheel (WTW) or well-to-propeller (WTP) emissions.

Well-to-wheel or well-to-propeller emissions of fossil fuels

Approximately 10% to 15% of the total greenhouse gasses resulting from the use of fossil fuels are emitted during production and distribution.

Well-to-wheel or well-to-propeller emissions for electricity

Currently, electricity is mainly produced by the burning natural gas and coal in power plants. During this process greenhouse gasses are emitted. This means that, given the current energy mix, greenhouse gasses are emitted to power BEVs. If all electricity would be generated from renewable sources, e.g. wind or solar energy, WTW CO_2 emissions of BEVs would be 0 g/km.

Well-to-wheel or well-to-propeller emissions for biofuels

Biofuels are produced from biomass. Liquid biofuels are currently mainly extracted from

- carbohydrates produced in sugar or starch crops such as corn or sugarcane,
- oils or fats using transesterification or from
- organic waste streams.

Since CO_2 is absorbed during the growth of crops, the greenhouse gas emissions from this part of the energy chain actually negative. However, during the growth, harvesting and transportation the crops and during the production and distribution of biofuels greenhouse gasses are emitted.

In case the biofuel is extracted from waste streams the WTW or WTP CO_2 emissions are very low and can even be negative. When for instance manure is not combusted (e.g. for energy production), methane (CH_4) is added to the atmosphere. Since this methane has a very high green global warming potential (GWP), the CO_2 emissions from the combustion can have a smaller contribution to the greenhouse effect than the greenhouse gases that would have been emitted if not burned.

Indirect Land Use (ILUC)
If existing agricultural land used for food production is used for growing biofuel feedstock, food production decreases. This reduction can be (partially) compensated by converting non-agricultural (e.g. forests) land into new cropland. This phenomenon is also called "Indirect Land Use Change" (ILUC) and can have negative impacts on biodiversity and the amount of greenhouse gases emitted. Accounting for ILUC therefore increases the WTW CO_2 emissions of biofuels.

Carbon capture and storage (CCS)
Carbon capture and storage is a technique for trapping carbon dioxide emitted from large point sources such as power plants, compressing it, and transporting it to a suitable storage site where it is injected into the ground

As the emitted CO_2 is stored underground and is therefore not added to the atmosphere, CCS reduces the WTW GHG emissions of fuels and other energy carriers. The cost of capture and storage remains an important barrier to the take-up of CCS. The capture component in particular is an expensive part of the process. As flue gas from coal or gas-fired power plants contains relatively low concentrations of CO_2, the amount of energy needed to capture the gas makes the process costly. CCS is currently in an experimental phase.

Well-to-wheel or well-to-propeller energy use
Vehicles and vessels consume energy when in use. This energy consumption of the vehicle itself is known as TTW or TTP. Besides this energy consumption, energy is also used during the production and distribution of the energy carriers, known as WTT or WTP energy consumption. Together the TTW (or TTP) and WTT energy consumption add up to WTW or WTP energy consumption.
Since the energy use during the production of energy carriers make up an important share of the total costs for the production of energy carriers, the WTW or WTP energy consumption is a proxy for the production costs of energy carriers. Since other costs such as facility costs and capital costs also differ significantly for different production routes, it cannot be concluded from the WTW and WTP energy which production route is most cost efficient. However, in most cases it is a good proxy.

Interpreting pollutant emissions

Besides emissions that have a negative climate effect (e.g. CO_2, N_2O and CH_4), vehicles and vessels emit substances that are harmful not so much because of their contribution to the greenhouse effect, but to air pollution. Air pollution is the emission of particulates or other harmful materials into the earth's atmosphere in such concentrations that they can be considered harmful to the environment, or human, animal and plant health.

Air polluting emissions mainly have an effect close to where they are emitted, since here the concentrations are highest. Therefore air quality is generally poorest in traffic intensive city streets, close to industrial areas or harbours and busy waterways. Since the pollutant emissions in the WTT stage are generally emitted at locations where they are relatively harmless, the focus is on the TTW (or TTP) pollutant emissions.

Just as with GHG emissions, the use of fuels result in different emissions when used in different drivetrain configurations. For instance, pollutant emissions of fuels with relatively high pollutant potential (e.g. with low sulphur concentrations) may still be relatively low when used in certain drivetrain configurations with effective aftertreatment. It is therefore important to evaluate the air pollution impact of combinations of fuels and the vehicles (given their specific drivetrain configuration) in which they are used.

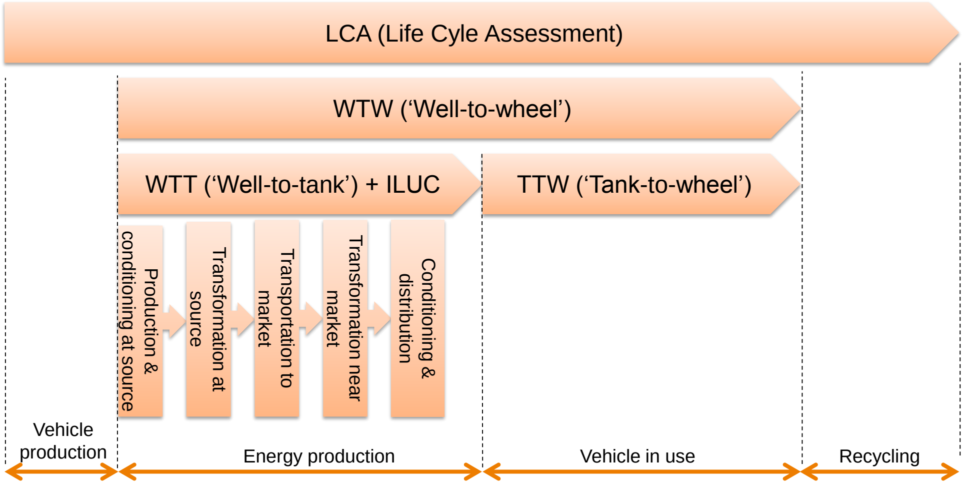

Figure 26 Overview of different ways to define vehicle emissions.

B Emissions legislation

Trucks

An overview of the European medium and heavy-duty vehicles emissions legislation is presented in Table 23 below. Heavy-duty engines are used in trucks and buses with a Gross Vehicular Mass above 3.5 tonnes. Euro VI is currently applicable for all new vehicles entering into the market.

Table 23. Overview European emission limits for heavy-duty CI truck and bus engines (GVM > 3,500 kg)

Date	Test cycle	Unit	CO	NMHC	NO_x	PM	PN (#/kWh)	CH_4 2)
Euro-IV-2005	ESC	g/kWh	1.5	0.46	3.5	0.02		
	ETC	g/kWh	4.0	0.55	3.5	0.03		
Euro-V-2008	ESC	g/kWh	1.5	0.46	2.0	0.02		
	ETC	g/kWh	4.0	0.55	2.0	0.03		
Euro-VI–2013 1)	WHSC	mg/kWh	1500	-	400	10	$8x10^{11}$	
	WHTC	mg/kWh	4000	160	460	10	$6x10^{11}$	500

1) Formal date is 31-12-2012 for new type approvals. 1 year later for all entries.

2) Only for gas engines (NG, LPG)

Inland ships

An overview of the generally applicable legislation for Rhine vessels is presented in Table 21 below. For NOx for engines with more than 560 kW engine power, a range is shown. The NOx level is dependent on max engine speed (n_{max}) using the following equations:

- CCNR1: NOx limit is $45\ n_{max}^{-0.2}$ (g/kWh)
- CCNR2: NOx limit is $45\ n_{max}^{-0.2} - 3$ (g/kWh)

The highest number in the table corresponds to an engine with a max speed of 600 rpm. The NOx limit goes down when max engine speed goes up.

Table 24: Overview of Rhine vessel 'RheinSchUO' emission limits

Date	Stage	Max Power (kW)	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	PM (g/kWh)
2003	CCNR 1	130 - 560 >560	5.0 5.0	1.3 1.3	9.2 9.2 -12.5	0.54 0.54
2007	CCNR 2	130 - 560 >560	3.5 3.5	1.0 1.0	6.0 6 - 9.5	0.2 0.2

In the future pollutant emissions of inland vessels will be set by the European Commission and they will be a part of the legislation for road mobile machinery.

For the future, the emission legislation for inland ships in Europe will be brought under the Directive 97/68/EC for non-road mobile machinery, within a separate paragraph. The limit values for IWT (Inland Waterway Transport) are labelled Stage

V. In September 2014, the Commission came with a proposal[63] for limit values and entry into force dates. Remarkable with the proposal are the strong dependency of limit values on engine size. For engines with a power output below 1000 kW, the limit values are in line with Euro V limits of trucks, while for engines larger than 1000 kW, they are in line with Euro VI for trucks.

Sea ships
The coordination of the pollutant emissions legislation for sea shipping is with the International Maritime Organisation (IMO). Marine Pollution is treated via MARPOL Annex VI.
The emissions legislation for sea shipping is focussed on reduction of sulphur oxide (SOx), particulates emission and nitrogen oxide (NOx). The legislation is in principle world-wide, but also special Emission Control Areas (ECA's) are put in place. In these areas the legislation is more stringent. This can be for SOx (SECA) and/or NOx (NECA). Examples are the East-Sea, North Sea and the US East and West coast.

The SOx and particulates emission control is implemented via limits of the sulphur content of the bunker fuel. In Figure 23 the limits are shown for both world-wide and the SECA areas.
The current maximum level of 1% sulphur for Emission Control Areas (ECA) will be reduced to 0.1% in 2015. For worldwide (including non-ECA EU waters), the next major step in sulphur reduction is planned for 2020: reduction from 3.5% to 0.5%.
There are basically three options to fulfil these requirements (ECA and worldwide):
The use of distillated diesel fuel or low sulphur diesel fuel
The use of LNG as a fuel, with either dedicated LNG or with dual-fuel (LNG/diesel) engines.
The application of a SOx scrubber in combination with HFO.

The NOx limits are presented in table 22. In 2011 Tier II entered into force. The NOx limits are 15% to 25% lower than Tier I, which entered into force in 2005. The NOx limits for Tier III are 80% lower than for Tier I. Tier III is planned for NECA's for 2016, although in 2013 IMO proposed to delay this by about 5 years . A NECA is currently considered for the Baltic Sea and the North Sea.
The NOx requirement for Tier II is not very stringent yet. For new diesel engines this can generally be met by using higher quality diesel fuel such as MGO (Marine Gas Oil). It can also be met by most, if not all, LNG fuelled engines. Tier III is much more stringent. For diesel (MGO, MDO, HFO) fuelled engines, it would mean that an SCR deNOx catalyst system is necessary. Some dedicated LNG engines, can meet this Tier III requirement without NOx aftertreatment, which is a large advantage.

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[63] Proposed: REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL: on requirements relating to emission limits and type-approval for internal combustion engines for non-road mobile machinery, COM(2014) 581 final, 2014/0268 (COD)

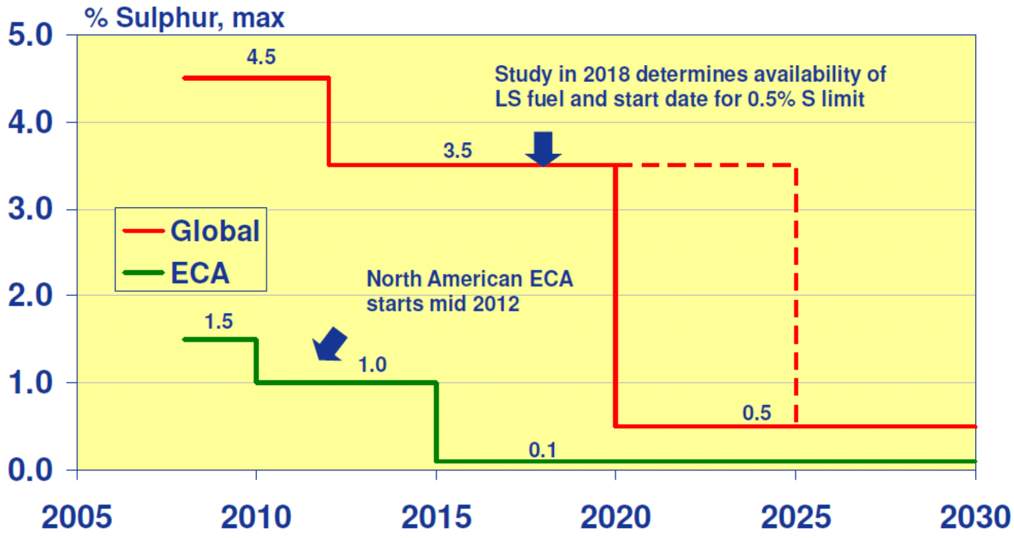

Figure 27. Fuel sulphur requirements, world-wide and in Emission Control Areas (ECA)

Table 25. NOx emission limits engines of sea ships.

NO_X (g/kWh)	**Tier I**	**Tier II**	**Tier III**
Year	**2005**	**2011**	**2016***
NO_X Emission Control Area (NECA)			2.0 - 3.4
Worldwide**	9.8 - 17	7.7 - 14.4	

* IMO considers delay of Tier III NOx until 2021, ref 65th MEPC meeting.
Also adaptation in Europe is quite uncertain.

** Range dependant on the maximum engine speed (Larger the engines have higher limit values).

C SOx emissions

The SO_x emissions are directly proportional to the fuel sulphur content and the quantity of fuel combusted. 90-95% of the fuel sulphur ends up as the gaseous SO_2. A small proportion, 5-10% ends up as particulate matter (SO_4, H_2SO_4). Refer to Duyzer (2007)[64].

An overview of the specific SO_2 emissions for different fuel types is presented in Table 26 below. Refer to Natural Gas in Transport (2013). For this calculation, it is assumed that 100% of the fuel sulphur is converted to SO_2.

Table 26 Projection specific SO_2 emissions for different diesel fuels and LNG

Fuel	S limit value	average S content [m/m]		SO2 emission		
				per kg fuel	per MJ fuel energy	per kWh power output*
		%	ppm	g/kg	g/MJ	g/kWh
HFO	3.5	2.7	27000	54	1.265	10.6
LSHFO 0.5%	0.5	0.5	5000	10	0.234	2.0
LSHFO 0.1%	0.1	0.08	800	1.6	0.037	0.3
MDO 0.5%	0.5	0.8	8000	16	0.375	3.1
MGO	0.1	0.08	800	1.6	0.0375	0.3
EN 590	0.001	0.0008	8	0.016	0.000375	0.003
LNG	(0.001)	0.0005	5	0.010	0.000204	0.002

* Based on engine efficiency of 43%

For the calculation of the SO_2 emission per MJ fuel energy, the following heating values are used:

- HFO, MDO, MGO, EN 590: 42.7 MJ/kg.
- LNG: 49 MJ/kg.

For dual fuel and pilot diesel gas engines, the SO_2 emission is calculated by adding up the SO_2 emissions of the diesel share and the LNG share on an energy contribution basis.

Methane emissions

Refer to Natural Gas in Transport 2013.
Methane emissions are not regularly made available by the engine OEMs.
The methane emission is multiplied by 30 in order to obtain the CO2 equivalent for the contribution to the GHG emissions. In the figure below the GHG emission of natural gas engines is plotted as a function of the methane emission. It can be seen that with approximately at 6 g/kWh methane emission, the GHG emission is equal to that of a diesel engine (with the same efficiency). Some years ago in Norway, the maximum methane emission level for ship engines was set to this 6 g/kWh in order to receive tax credits for

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[64] Duyzer J., Hulskotte J.: Luchtverontreinigng en scheepvaart. Tijdschrift 'Lucht', 2007, nb 5

CO2 emissions for gas engines. According to direct feedback from Dutch representatives of engine manufacturers (Wärtsilä, MAN and Caterpillar), dual-fuel and pilot diesel engines can comply with this. Also very large engines allegedly have much lower methane emissions. In Kryger et al. (2011), a methane emission of 0.2 g/kWh is reported for a large 2-stroke dual fuel engine. This source also mentions 4-8 g/kWh for other dual or mono fuel engines.

It is also emphasized that lowering methane emissions is an important development item for the coming decade. From governmental point of view, it is recommended to further follow this development and consider implementation of requirements in either an efficiency/CO2 design index or in pollutant emissions legislation.

For this study a value from the literature is used. This is based on the average methane emission of a large number of stationary gas engines (Engelen, 2009 and Olthuis and Engelen, 2007). In Verbeek (2011) these numbers are transferred to a g/MJ fuel energy value. This number is 0.53 g methane per MJ fuel energy, which converts to around 4 g methane emission per kWh mechanical energy and about 13 g CO2 equivalent per MJ fuel energy.

D WTW GHG emissions excluding ILUC

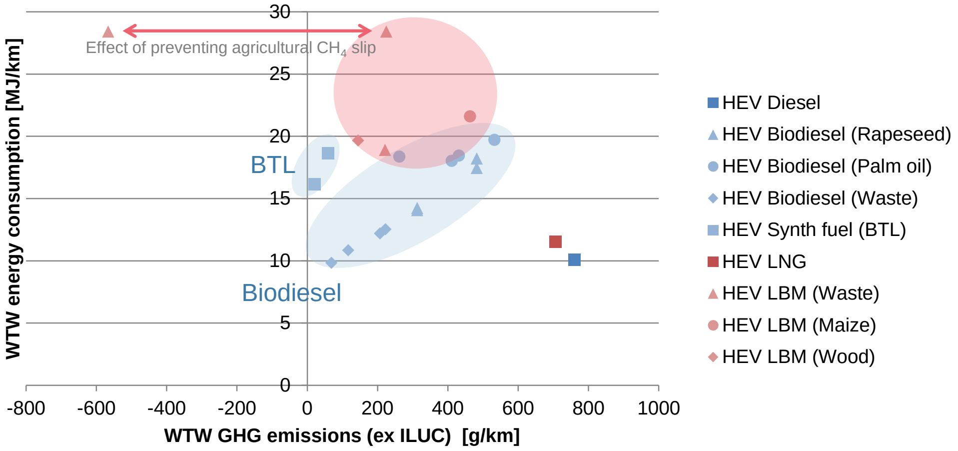

Figure 28: WTW GHG emissions and WTW energy use of a standard rigid truck with various drivetrain types using energy sources from various raw materials, excluding ILUC emissions and including methane slip.

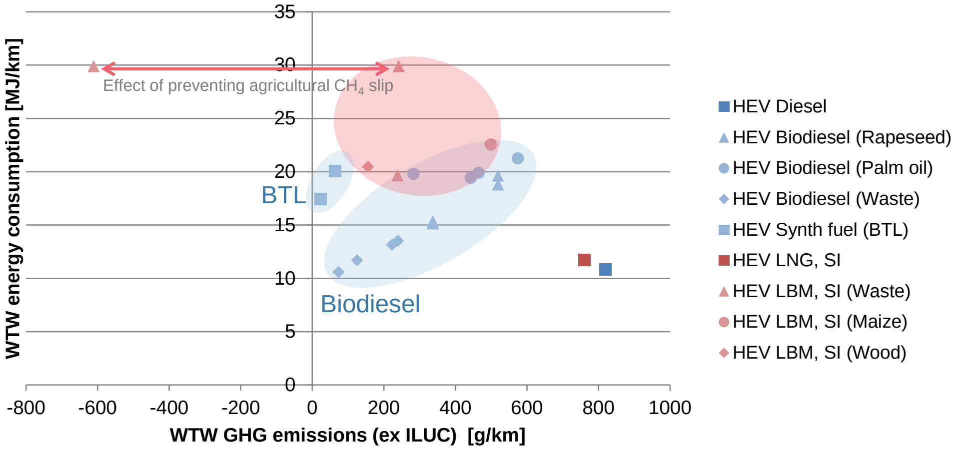

Figure 29: WTW GHG emissions and WTW energy use of a standard city bus with various drivetrain types using energy sources from various raw materials, excluding ILUC emissions and including methane slip.

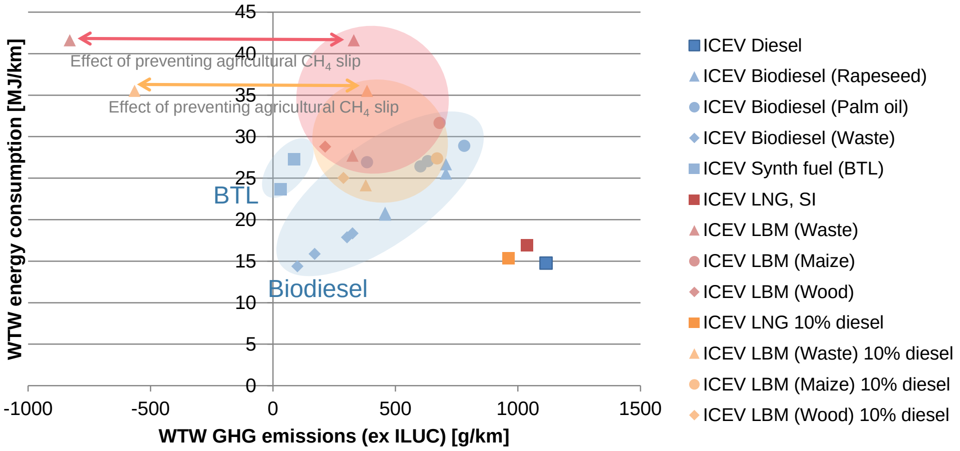

Figure 30: WTW GHG emissions and WTW energy use of a standard tractor trailer with various drivetrain types using energy sources from various raw materials, excluding ILUC emissions and including methane slip.

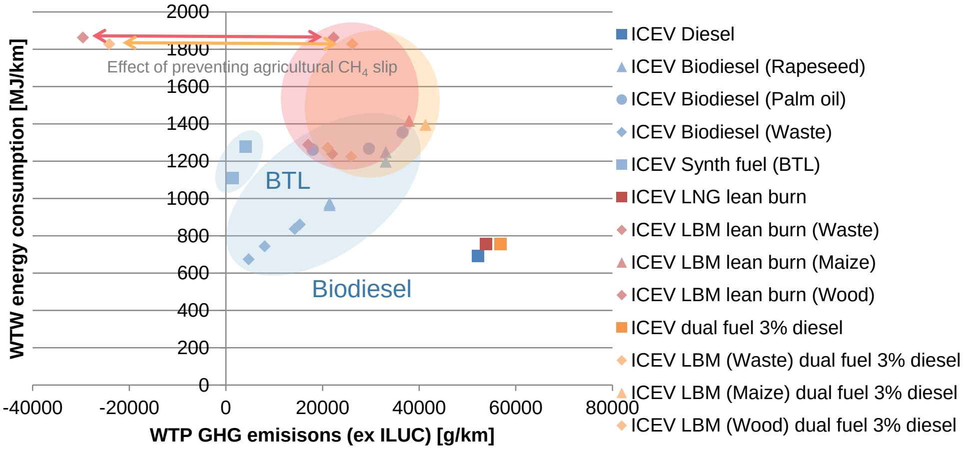

Figure 31: WTW GHG emissions and WTW energy use of a standard inland ship with various drivetrain types using energy sources from various raw materials, excluding ILUC emissions and including methane slip.

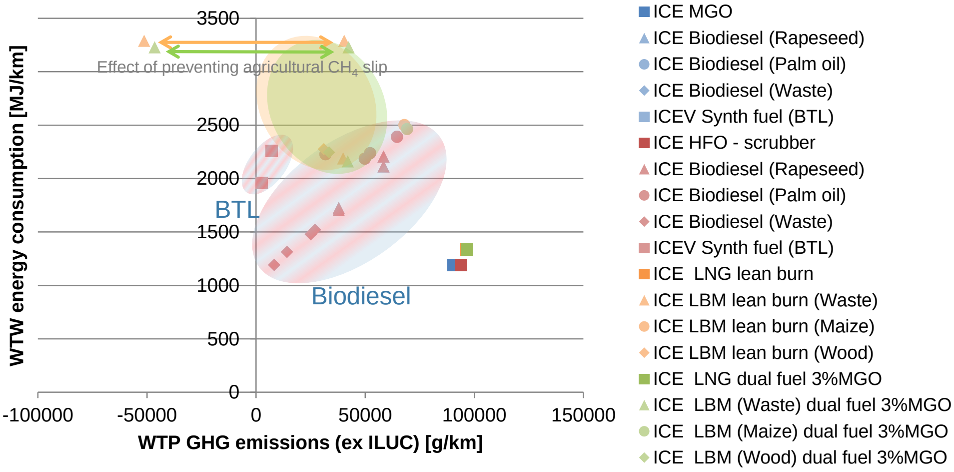

Figure 32: WTW GHG emissions and WTW energy use of a standard short sea ship with various drivetrain types using energy sources from various raw materials, excluding ILUC emissions and including methane slip.

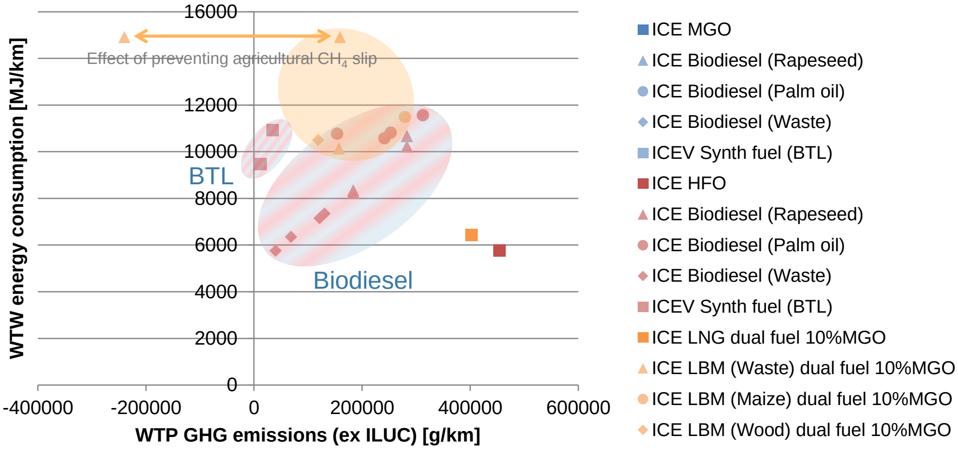

Figure 33: WTW GHG emissions and WTW energy use of a standard deep sea ship 5500TEU with various drivetrain types using energy sources from various raw materials, excluding ILUC emissions and including methane slip.

E Particle number and size emissions

This appendix include some references of particle size distributions using different fuels and engine technologies for HD vehicles.

Erkkilä 2004

Kimmo Erkkilä, Nils-Olof Nylund, Markku Ikonen and Juhani LaurikkoEvaluating: Exhaust emissions performance of urban bsuses using transient heavy-duty chassis dynamometer. 2004 DEER Conference
OC = oxidation catalyst
CRT = Continuously Regeneration Trap (wall flow particulates filters)

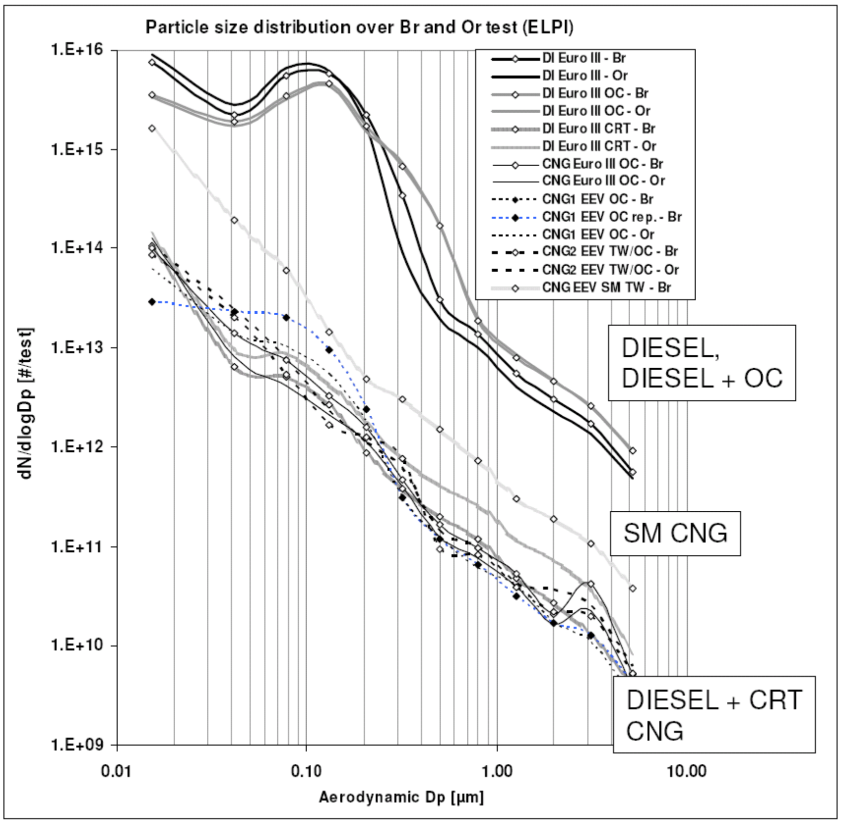

Figure 34. Particulate number size distribution for diesel and natural gas HD engines. Diesel engines include engines with oxidation catalyst (OC) and diesel particulates filter (CRT).

Nylund 2012
Fuel and Technology Alternatives for Buses. Overall Energy Efficiency and Emission Performance. IEA report (cooperation implementing agreements IEA Advanced Motor Fuels, IEA Technology Network and IEA Bioenergy). 2012.

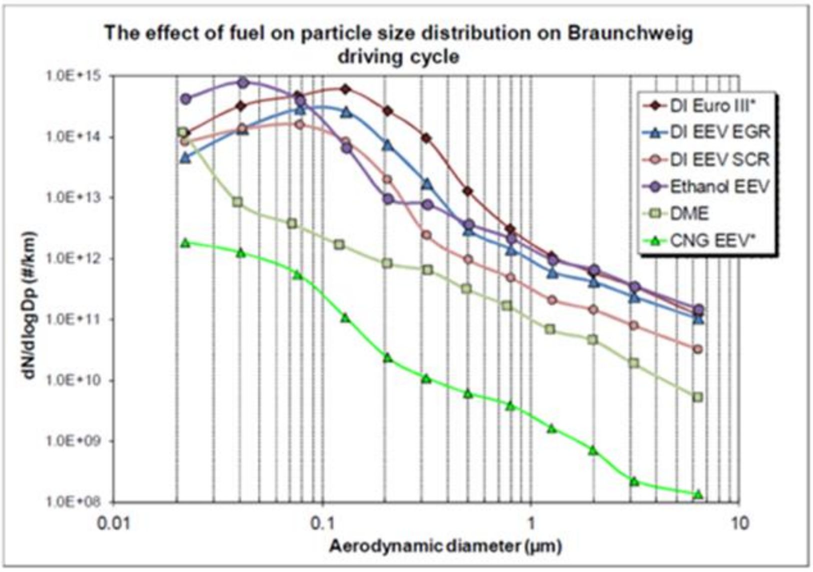

Figure 35. Particulate number size distribution for a number of fuel technology options. EEV: Environmentally Enhanced Vehicles (EURO V+) with either EGR or SCR
Ethanol EEV engine (diesel cycle with ignition improver)
DME: Diesel cycle DME engine: DME is Di-Methyl-Ether