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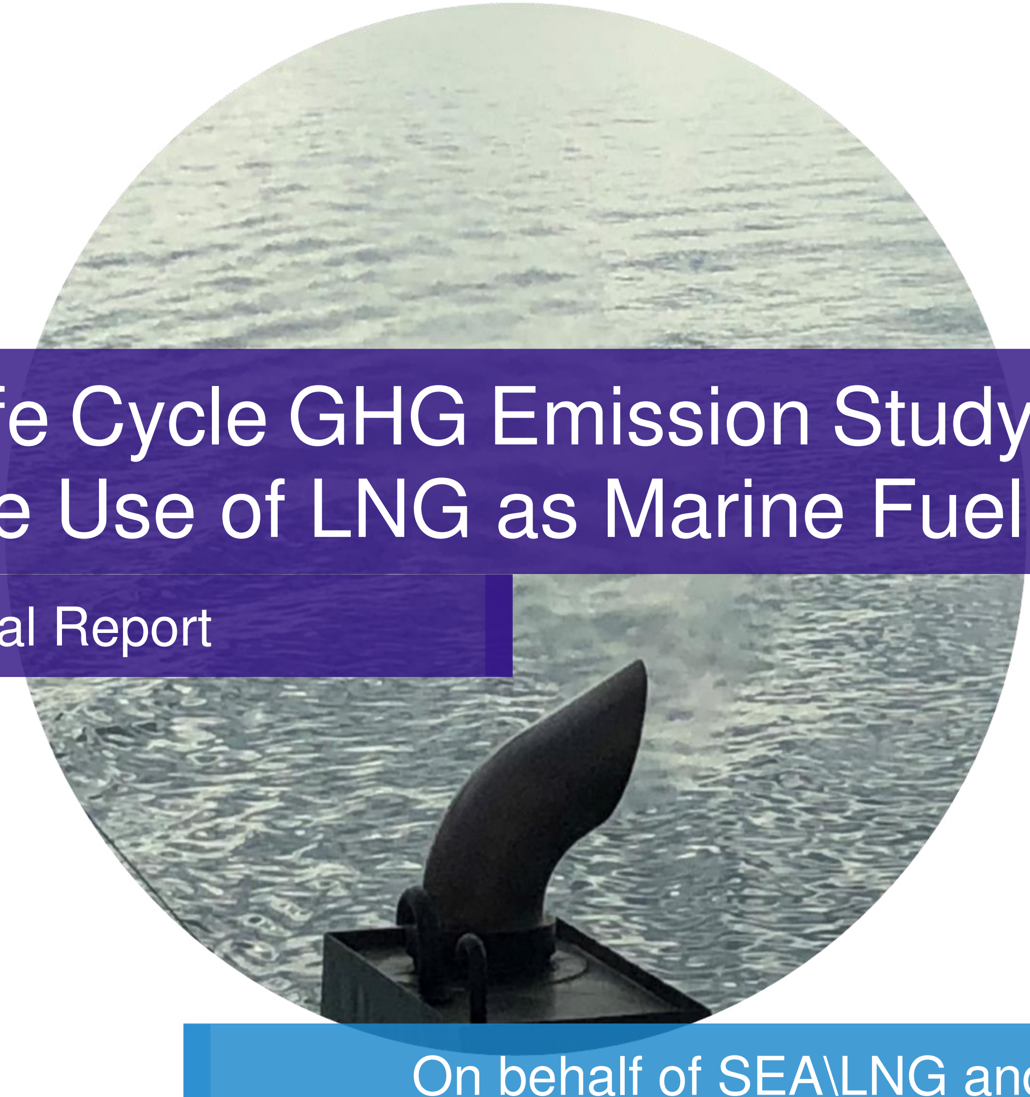
Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel

Final Report



On behalf of SEA\LNG and SGMF

thinkstep

Client:	**SEA\LNG Limited, and Society for Gas as a Marine Fuel Limited (SGMF)**
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On behalf of thinkstep AG and its subsidiaries

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Consortium Partners

SEA\LNG Consortium Partners

SEA\LNG

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sgmf sea change.

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WMT MARINE	woodside	WorleyParsons	YKIP	ZAITOUN GREEN SHIPPING		

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List of Acronyms

AR	Assessment Report
BC	Black Carbon
BOG	Boil-Off Gas
BAT	Best Available Techniques
BREF	Best Available Techniques Reference Document
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CF	Carbon Footprint
CH_4	Methane
CHP	Combined Heat and Power
CI	Compression Ignited Engine
Cm	Cubic Metre
CO_2	Carbon Dioxide
CO_2-eq.	Carbon Dioxide Equivalent
DF	Dual Fuel
DFDE	Dual-Fuel Diesel Electric Propulsion (e.g., installed at LNG Carrier)
DSI	Data Source Indicator (labelling primary, calculated, literature or estimated data)
E2 Cycle	Emission Test Cycles (ISO 8178)
E3 Cycle	Emission Test Cycles (ISO 8178)
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EGCS	Exhaust Gas Cleaning System (Scrubbers)
EGR	Exhaust Gas Recirculation
EoL	End of Life
EU	European Union
EU-28	European Union with its 28 Member States
FQD	Fuel Qualitative Directive
g CH_4	Gram Methane Emissions
g CO_2-eq	Gram Carbon Dioxide-Equivalent Emissions
GaBi	dt. “Ganzheitliche Bilanzierung”, engl. Life Cycle Engineering Software
GHG	Greenhouse Gas(es)
GTP_{100}	Global Temperature Change Potential at a 100-Year Time Horizon

GWP_{20}	Global Warming Potential at a 20-Year Time Horizon
GWP_{100}	Global Warming Potential at a 100-Year Time Horizon
HFO	Heavy Fuel Oil
$HFO_{2.5}$	Heavy Fuel Oil with a Sulphur Content of 2.5 wt.%
$HFO_{>2.5}$	Heavy Fuel Oil with a Sulphur Content of more than 2.5 wt.%
HHV	Higher Heating Value
HS	High Speed
HSD	High Speed Diesel
H_2S	Hydrogen Sulphide
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IGU	International Gas Union
ILCD	International Reference Life Cycle Data System (developed by European Commission)
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardisation
J	Joule
JEC	Consortium of JRC, EUCAR, and CONCAWE
JRC	Joint Research Centre of the European Commission
kWh	Kilowatt Hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
LNG	Liquefied Natural Gas
$LSFO_{0.5,\ Blend}$	Low Sulphur Fuel Oil; Index refers to “Blend of Residual and Distillate Marine Fuel”
$LSFO_{0.5,\ LScrude}$	Low Sulphur Fuel Oil; Index refers to “Based on Low Sulphur Crude Oil”
m^3	Cubic Metre
MAC	Methane Abatement Catalyst
MGO	Marine Gas Oil
$MGO_{0.1}$	Marine Gas Oil with a Sulphur Content of 0.1 wt.%
MDO	Marine Diesel Oil
MJ	Megajoule
MS	Medium Speedf
MSD	Medium Speed Diesel

MW	Megawatt
NGO	Non-Governmental Organisation
NGVA	Natural Gas & bio Vehicle Association
NO_X	Nitrogen Oxides
N_2O	Nitrous Oxide (Laughing Gas)
OEM(s)	Original Equipment Manufacturer(s)
PCF	Product Carbon Footprint
PM	Particulate Matter
PM_{10}	Particulate Matter with a Diameter of 10 Micrometres or less
$PM_{2.5}$	Particulate Matter with a Diameter of 2.5 Micrometres or less
ppmv	Parts per Million Volume
Q_{Flex}	Q-Flex is a Type of Ship Carrying Liquefied Natural Gas
rpm	Revolutions per Minute (referring to the Engine Speed)
S	Sulphur
SCR	Selective Catalytic Reduction
SFOC	Specific Fuel Oil Consumption
SEEMP	Ship Energy Efficiency Management Plan
SGC	Specific Gas Consumption
SI	Spark Ignited Engine
SO_X	Sulphur Oxides
SNG	Synthetic Natural Gas
SS	Slow Speed
SSD	Slow Speed Diesel
TFDE	Tri-fuel Diesel Electric Propulsion (e.g., installed at LNG Carrier)
TJ_{in}	Terajoule related to Input
ts	thinkstep
TtW	Tank-to-Wake
UHC	Unburned Hydrocarbon
vol.%	Volume Percentage
WtT	Well-to-Tank
WtW	Well-to-Wake
wt.%	Weight Percentage

Glossary

Carbon Footprint – Carbon Intensity – GHG intensity

Total emissions of greenhouse gases (GHG) using the life cycle approach. By characterising each single GHG emission with its individual characterisation factor, all GHG emissions can be aggregated to calculate the Global Warming Potential (GWP), also known as GHG intensity, Carbon Intensity or Carbon Footprint, and is expressed in CO_2-equivalents (CO_2-eq).

Life Cycle

A view of a product system as "consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal" (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water. [1]

Life Cycle Assessment (LCA)

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2006, section 3.2). [1]

Life Cycle Inventory (LCI)

"Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 14040:2006, section 3.3). [1]

Life Cycle Impact Assessment (LCIA)

"Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 14040:2006, section 3.4). [1]

Life Cycle Interpretation

"Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO 14040:2006, section 3.5). [1]

Functional Unit

"Quantified performance of a product system for use as a reference unit" (ISO 14040:2006, section 3.20). [1]

Critical Review

"Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the international standards on life cycle assessment" (ISO 14044:2006, section 3.45). [2]

Well-to-Tank (WtT), Tank-to-Wake (TtW) and Well-to-Wake (WtW) Analyses

A Well-to-Wake (WtW) analysis includes all process steps from the production of the fuel to its combustion in engines. WtW can be divided into Well-to-Tank (WtT) describing all process steps of the fuel supply and Tank-to-Wake (TtW) describing the combustion of the fuel. *[3]*

Life Cycle Assessment (LCA) versus Well-to-Wake (WtW) Analysis in this Study

This study is defined as a Life Cycle Assessment (LCA) excluding the efforts (energy and emissions) for manufacturing, maintenance and end of life of the infrastructure such as buildings or vessels. This definition is in line with the definition of a Well-to-Wake (WtW) analysis according to [3]. Therefore, both terms are used in this study.

Foreground System

The foreground system comprises all relevant processes within the scope of the study which are influenced by the producers or operators of the technologies under study. The goal is to model all relevant foreground processes using measured or calculated primary data. [4]

Background System:

The background system includes all processes within the scope of the study which are not directly influenced by the producers or operators of the technologies under study, like the supply of energy (e.g. electricity) or additives (e.g. urea). The goal is to represent all relevant background processes using average market consumption mixes (based on secondary data). [4]

Primary Data:

“Primary data” are measured, calculated or expert judged data based on primary information sources of the producer or operator of the technologies under study.

Secondary Data:

The term “secondary data” does include data from literature or from *thinkstep’s* GaBi LCI databases, which are mainly based on industry derived data and literature.

Consumption Mix

The fuel consumption mix of a region considers the indigenous fuel production of the member countries of the region (if applicable) as well as the fuel imports from producing countries to the region and fuel exports of the member countries to other countries out of the region.

Heating Value

All energy related numbers in this study are referring to the lower heating value (LHV).

Number Format

Very large and very small numbers are expressed in exponential notation in this report, e.g. 1.5E-3. In this example, the significand 1.5 is multiplied with a fixed base of 10 and an exponent of -3, i.e. $1.5 \times 10^{-3} = 0.0015$. Similarly, 3.5E6 refers to 3,500,000.

About thinkstep

thinkstep is a leading global consulting and software company in the field of sustainability and, in particular, life cycle thinking. Originally named PE International, *thinkstep* has grown over the past 25 years into a trusted resource for organisations worldwide. *thinkstep* draws on over 2,000+ person years of combined subject matter expertise to provide a solid foundation that informs all projects. *thinkstep* works with private and government clients around the world on technical, environmental, and economic solutions to increase the sustainability of products, processes and services.

The knowledge we have gained and the work we have performed for 8,000 clients worldwide, including some of the world's most respected brands, has led to new strategies, management systems, tools and processes needed to achieve leadership in sustainability. Our services and tools are used to drive operational excellence, product innovation, brand value and regulatory compliance.

thinkstep has created the world's leading Life Cycle Assessment (LCA) software and databases for use across all business sectors (www.gabi-software.com). Using international energy statistics, *thinkstep* has expertise in analysing and modelling the supply chain of Natural Gas to assess greenhouse gas emissions and other air and water pollutants. As a provider of LCA databases, *thinkstep* has gathered considerable experience in modelling emissions along the entire supply chain of Natural Gas in a multitude of countries and regions. Country-specific data for greenhouse gas relevant parameters can be used to perform benchmarks, consistency checks and closing data gaps when performing LCA assessments.

Our LCA data and tools are used by major engine manufacturers as well as major oil & gas companies. In addition, *thinkstep* works with many public authorities and national and regional governments, including the European Commission (EC). For instance, *thinkstep* has supplied a multitude of datasets to the European Commission's LCA data network (ILCD - see http://eplca.jrc.ec.europa.eu/) which are also used for the product environmental footprint (PEF) method currently being piloted by the EC.

thinkstep's vast experience in Life Cycle Assessment, carbon footprint and Well-to-X studies covers all relevant sectors in different geographic regions around the world, including the oil & gas industry, electricity generation, transportation and alternative fuels (biofuels, power-to-gas, hydrogen etc.) sectors. Numerous LCA, carbon footprint, and WtW studies, as well as economic market and technology analyses have been performed, and recommendations developed. These have focussed on different aspects such as conventional oil & gas production, CNG and LNG supply from various locations, shale gas production, oil sands, heavy oils, biomethane, power-to-gas etc.

thinkstep also prepared the "GHG Intensity of Natural Gas", study for the Natural Gas & bio vehicle Association (NGVA) in 2017. The report is available at: http://ngvemissionsstudy.eu/.

Our consulting teams consist of about 160 experts and practitioners and provide our clients with substantial knowledge and professional services. The project team provided for this study is well experienced and has a proven track record in analysing the Natural Gas life cycle.

thinkstep operates offices in Berlin, Boston, Copenhagen, Johannesburg, London, Lyon, Mumbai, Perth, Ravenna, Sheffield, Tokyo, Wellington, and Winterthur. Headquarters is in Leinfelden-Echterdingen, Germany (close to Stuttgart).

For further information, please visit: www.thinkstep.com.

Executive Summary

This study analyses the life cycle greenhouse gas (GHG) emissions of the use of Liquified Natural Gas (LNG) as marine fuel compared with current and post-2020 conventional oil-based fuels. In addition, air quality is assessed by comparing local pollutants from the operation of the vessels using these different fuels.

Key Messages from the Study

The collaboration and support from a large number of SEA\LNG and SGMF member companies working across the entire fuel supply chain and engine manufacturers enabled the collection of up-to-date, quality technical data. This has provided the basis for a complete and accurate life cycle analysis of the GHG intensity expressed in terms of CO_2-equivalents. For the main GHG emissions, the IPCC AR5 characterisation factors have been used (1 CO_2, 30 CH_4, 265 N_2O) to assess the global warming potential (GWP_{100}). Methane emissions from the supply chains as well as methane released at the ship combustion process (methane slip) have been carefully included. The comparison between LNG and oil-based fuelled engines is performed on a 1 kWh brake power specific unit (g CO_2-eq/kWh).

The study shows that LNG provides a significant advantage in terms of improving air quality which is particularly important in ports and coastal areas. Beyond the benefits associated with reducing air pollutants, LNG is a viable solution to reduce GHG emissions from international shipping and to contribute to the International Maritime Organization (IMO) GHG reduction targets. However, methane emission from the supply chain and engine slip need to be reduced further to maximise the positive impact on both air quality and GHG emissions.

The key messages are:

- The use of LNG as marine fuel shows GHG reduction of up to 21 % compared with current oil-based marine fuels over the entire life cycle from Well-to-Wake (WtW). The benefit is highly dependent on the engine technology installed and, to a certain extent, on the type of reference fuel (distillate or residual).
- On an engine technology basis, the WtW GHG emission reduction for gas fuelled engines compared with HFO fuelled engines are between 14 % to 21 % for 2-stroke slow speed engines, and between 7 % to 15 % for 4-stroke medium speed engines.
- On a Tank-to-Wake (TtW) basis, the combustion process for LNG as a marine fuel shows GHG benefits of up to 28 % compared with current oil-based marine fuels. On an engine technology basis, the TtW emissions reduction benefits for gas fuelled engines compared with HFO fuelled engines are between 18 to 28 % for 2-stroke slow speed engines and between 12 to 22 % for 4-stroke medium speed engines.
- Local pollutants, such as sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulate matter (PM), are reduced when using LNG compared with current conventional marine fuels. Due to the negligible amount of sulphur in the LNG fuel, SO_X emissions are reduced close to zero. NO_X emissions are reduced by up to 95 % to meet the IMO Tier III limits without NOx reduction technologies when using Otto cycle engines. Limited data on PM emissions is available, however reductions of up to 99 % are normal compared with heavy fuel oil (HFO).
- For post-2020 oil-based marine fuels (low sulphur fuel oil (LSFO) or the use of HFO in combination with an exhaust gas cleaning system) there is no significant difference in the WtW GHG emissions compared with current oil-based fuels. Post-2020 gas fuelled 2-stroke

engines have advantages in the order of 14 % to 22 % (current: 14-21 %), and 4-stroke engines between 6 % to 16 % (current: 7-15 %) compared with HFO fuelled engines.

- As a direct comparison if the global marine transport fleet for 2015 were to completely switch to LNG then there would be a GHG emission reduction of 15 % marine GHG emissions based upon engine technology alone.
- GHG reductions are reduced depending upon the degree of methane slip incurred during the combustion process. High pressure 2-stroke Diesel cycle engines and marine gas turbine propulsion units incur methane slip less than 1 % of the overall WtW GHG emissions. Low pressure 2-stroke and 4-stroke Otto cycle reciprocating engines are sensitive to methane slip with 10-17 % of the WtW GHG emissions resulting from unburned methane in the combustion process.
- This study presents the current status of the industry; ongoing optimisation in supply chain and engine technology developments will further enhance the benefits of LNG as a marine fuel. Methane slip reduction at combustion in the engines and methane emission reduction in the supply chain as well as further improving energy efficiency in combination with other measures such as enhanced operational methods and speed optimisation will make a major contribution to meeting the IMO's GHG emissions reduction target 2050 for shipping.
- An indicative analysis showed that bioLNG and synthetic LNG can provide an additional significant (up to 90 %) benefit in terms of WtW GHG intensity. Bio and synthetic LNG are completely fungible with LNG derived from fossil feedstocks. For example, a blend of 20 % bioLNG as a drop-in fuel can reduce GHG emissions by a further 13 % compared with 100% fossil fuel LNG.
- GHG emissions of fuel supply chains differ from region to region due to a large number of variables. Therefore, specific supply chain analyses as applied in this study have been key in order to get to a global average GHG intensity.

Context

The international shipping industry, as other industry sectors, are under pressure to reduce emissions. The International Maritime Organization (IMO) has announced the ambition to reduce the GHG emissions from international shipping by at least 50% by 2050 compared with 2008. More stringent air quality regulations, such as the IMO 2020 global sulphur cap, are also approaching.

In the light of the IMO 2020 global sulphur cap, conventional oil-based residual marine fuels will need to either change in their specification or be replaced by alternative fuels like LNG.

While the environmental benefits of LNG as the most promising alternative marine fuel are clear in relation to local pollutants such as sulphur oxides (SO_X), nitrogen oxide (NO_X), and particulate matter (PM), various studies have demonstrated different GHG impacts from the use of LNG. These differences have resulted from the studies using different assumptions, methodologies and data. Most important, the studies have used different data and assumptions about methane emissions in the LNG supply chain, and methane slip in ship engines. The end result is that there are divergent opinions about the GHG benefits of LNG as marine fuel which in turn influence views on whether LNG is a viable option to address GHG emissions.

Life cycle analysis of GHG emissions of LNG and oil-based marine fuels and their use is a complex topic due to different engine technologies in operation, the different fuels bunkered and their geographically specific supply chains. In addition, fuels and their supply chain GHG emissions may change over time, e.g. due to the introduction of the low sulphur standards.

The marine engine market, in contrast to the road transport market for instance, comprises of a multitude of different engine technologies for different shipping applications and power requirements. This results in the use of different engines with 2-/4-stroke, single/dual fuel, combustion cycle, efficiency, exhaust gas cleaning system, etc.. Hence, gas fuelled vessels cannot be summarised by one representative technology and propulsion and power provision system, and more differentiation is necessary when drawing further conclusions, particularly by ship type, size and operational parameters. Large container ships for instance, are used to transport goods from one continent to another, and hence mainly operate in deep-sea regions, mostly with a constant engine load after leaving the harbour. In contrast, ferries or cruise ships mainly operate in coastal areas, and may change engine load more frequently. For smaller ships such as support vessels and tug boats, engine response with many engine load changes is crucial. There is therefore not one single gas engine to be considered, but rather different engines with different performance, fuel consumption and emission characteristics.

For ocean-going shipping outside Emission Control Areas (ECAs), the fuel sulphur limit is currently 3.5 wt.%, changing to 0.5 wt.% from 2020 onwards. For shipping inside ECAs, the sulphur limit has been 0.1 wt.% since 2015. For NO_X emissions, different Tier limits (Tier I-III) apply based on the construction date of the ship and the engine speed. For engines build from 2016 onwards, Tier III limits apply inside Emission Control Areas (ECA). Outside these areas, Tier II limits apply.

Study Objectives

SEA\LNG and SGMF commissioned *thinkstep* to perform a comprehensive, industry-wide Well-to-Wake (WtW) GHG emission analysis on the use of LNG as marine fuel. The intention was to reduce the uncertainty regarding the GHG benefits of LNG as marine fuel as mentioned above. Special focus was given to methane emissions. The study also investigated air quality aspects. By collecting primary, state-of-the-art data and by the integration of an external critical review the main study objectives were achieved.

While the analysis has been performed on a global level, it considers:

- the most common ship engine technologies in operation, taking into account the specific fuel consumption and methane slip.
- a global average LNG supply inventory, based on ‘bottom-up’ calculations of different regional consumption mixes, and LNG production countries.
- a differentiated view on various oil-based marine fuels, taking into account different fuel types and specifications, as well as post-2020 sulphur limits (including exhaust gas cleaning systems). Different regional analyses have also been carried out, analogous to the LNG supply analysis.

In 2018, the most common marine fuels were oil-based Heavy Fuel Oil (HFO) with a global average sulphur content of 2.5 wt. % and Marine Gas Oil (MGO) with 0.1 wt. % sulphur, which is primarily used in ECAs. HFO made up more than 75 % of the marine fuels followed by MGO with around 20 %. As mentioned, the upcoming more stringent air quality regulations relating to SO_X and NO_X, will change the marine fuel portfolio.

Today, it is not known how refiners will provide marine fuel that will comply with the IMO 2020 sulphur regulations for global fuels with a maximum of 0.5 wt.% sulphur. Fuel makers are likely to treat the fuel to reduce the sulphur, or blend it with ultra-low sulphur fuel oil, e.g. blending hydro-treated residuals, heavy fractions from hydrocrackers and lighter hydro-treated fractions or blending it with low sulphur MGO. Other options to obtain a 0.5 wt. % sulphur content fuel include the usage of a low sulphur crude oil feedstock. There will be a wide variability of fuel oil quality depending on input crude, refining process, blend strategy, and region.

Based on the available information and considerations of likely future actions, the project consortium defined the following current and “post-2020” fuels for consideration in this study:

Current fuels considered:

- Liquefied Natural Gas (LNG)
- Marine Gas Oil (MGO) as distillate marine fuel with a sulphur content of 0.1 wt. %
- Heavy Fuel Oil (HFO) as residual marine fuel with an average sulphur content of 2.5 wt. % (global average)

Post 2020 fuels considered:

- Liquefied Natural Gas (LNG)
- Marine Gas Oil (MGO) as distillate marine fuel with a sulphur content of 0.1 wt. %
- Heavy Fuel Oil (HFO) as residual marine fuel with an average sulphur content of >2.5 wt. % with scrubbers as approved exhaust gas cleaning system (EGCS)
- Low Sulphur Fuel Oil ($LSFO_{0.5,\ LScrude}$) as residual marine fuel with a sulphur content of 0.5 wt. %, using low sulphur crude oil as feedstock in refineries
- Low Sulphur Fuel Oil ($LSFO_{0.5,\ Blend}$) as blend of residual and distillate marine fuels with a sulphur content of 0.5 wt. %.

Other alternative fuels, e.g. Liquified Petroleum Gas (LPG), methanol, bioLNG, and synthetic LNG are also analysed in this study.

Approach and Methodology

The analysis distinguishes between the following ship engines and their specific characteristics when operating on different fuels:

- 2-stroke slow speed dual fuel engines
- 4-stroke medium speed single and dual fuel engines
- 4-stroke high speed single fuel engines
- Gas turbines in simple and combined cycle.

These engine technologies are further distinguished by combustion cycle, i.e. Otto combustion cycle (low pressure gas injection) and diesel combustion cycle (high pressure gas injection). Steam turbines as a main fuel oil engine are not analysed in this context due to the small number of vessels in operation with this technology. However, within the LNG supply chain analysis, steam turbines are considered as engine technology in LNG carriers in this study.

The data collection in particular focussed on ship engine data provided by eight major engine manufacturers (OEMs) incorporating the latest engine technologies and performance attributes. Main data providers were Carnival, Caterpillar MaK, Caterpillar Solar Turbines, GE Aviation, MAN Energy Solutions, MTU Friedrichshafen, Winterthur Gas & Diesel and Wärtsilä. On the fuel supply chains, ExxonMobil, Shell and Total were engaged in this study.

The study details the complete Well-to-Wake GHG emissions analysis of the LNG supply and use as marine fuel. The results of this analysis are compared with the WtW GHG emissions of other marine fuels in order to show the advantages and disadvantages. The study also includes a summary indicative outlook looking at the integration of bioLNG and synthetic LNG into the LNG supply chain. In addition, scenarios of potential future developments and technical improvements are investigated such as more efficient technologies which would reduce methane emissions.

The study is based on steady-state test-bed data using standard test cycles. GHG emissions based on actual operational fuel consumption and measured emissions data will differ due to load cycles and duration and could be considered as further analysis. However, this is the case for both LNG and fuel oil engines.

This assessment considers global warming as an environmental impact category only. However, the study assesses the supply and use of LNG as a marine fuel according to ISO 14040/44 and compares the GHG results with values for other marine fuels.

Air quality related local pollutants of sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulate matter (PM) of the fuel combustion are also presented in the results.

The focus of this study is on the data collection and calculation of the GHG emissions of ship engines for LNG and oil-based fuels. For both, primary data has been provided by the OEMs.

In general, the chosen approach regarding GHG emissions can be seen as conservative from a LNG perspective (i.e. not favouring LNG) compared with oil-based fuelled ships, because a) for oil-based engines black carbon emissions are not considered (though potentially contributing to the global warming potential), b) for oil-based fuelled engines low mark-up values for EGCS operation are used, c) GHG impacts occurring as a result of a chemical reaction of used EGCS cleaning water (at open loop EGCS) and sea water are neglected and d) it is assumed that up to 90 % of the measured total hydrocarbon tailpipe emissions of the LNG engine are pure methane (recent studies show lower numbers). The key findings are:

Well-to-Wake Results

As described above, the total WtW GHG emissions of marine engine are highly dependent on the engine technology and fuel type. The overall Well-to-Wake GHG emissions of the marine engines operating on current oil-based HFO, MGO and LNG have been calculated based on fuel consumption and emission data provided by eight different engine manufacturers and members from SEA\LNG and SGMF. All data is related to compliance with the IMO Tier III NO_X limits, and are given in brake power specific units (kWh) per engine technology weighted according to the IMO E2/E3 cycle. The following tables shows the technical parameters (all primary data are provided by engine manufacturers) that are used for the calculation of the Well-to-Wake GHG emissions of the 2-stroke slow speed and the 4-stroke medium speed engines. Please note that all energy related numbers in this study are referring to the lower heating value (LHV).

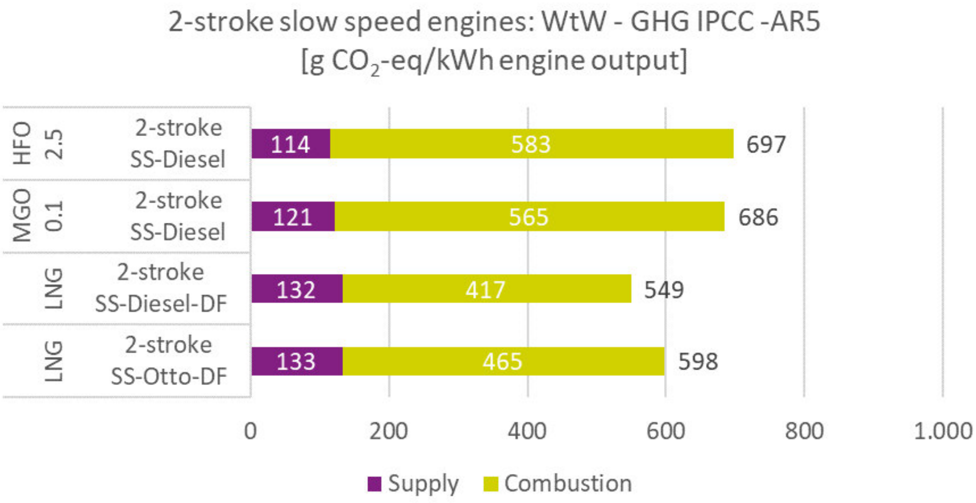
g/kWh	Oil-based fuels		Gas-based fuel	
	$HFO_{2.5}$	$MGO_{0.1}$	LNG	LNG
2-stroke slow speed	Diesel		Diesel-DF	Otto-DF
Main fuel consumption	184.8	174.0	141.3	145.1
Pilot fuel consumption	-	-	6.4	1.5
Urea solution consumption	20.7	20.7	-	-
Methane slip	-	-	*0.1 %*	*1.5 %*

g/kWh	Oil-based fuels		Gas-based fuel	
	$HFO_{2.5}$	$MGO_{0.1}$	LNG	LNG
4-stroke medium speed	Diesel		Otto-SI	Otto-DF
Main fuel consumption	197.5	184.7	155.8	156.5
Pilot fuel consumption	-	-	-	2.8
Urea solution consumption	15.7	15.7	-	-
Methane slip	-	-	*1.3 %*	*2.5 %*

2-stroke slow speed engines are the most common engines in shipping and burn more than 70 wt. % of the fuel used in the industry. Due to their high efficiency and high power, these engines are mainly used in large ocean-going cargo ships. LNG is used in two engine technologies which differ in their underlying combustion cycle and gas injection system.

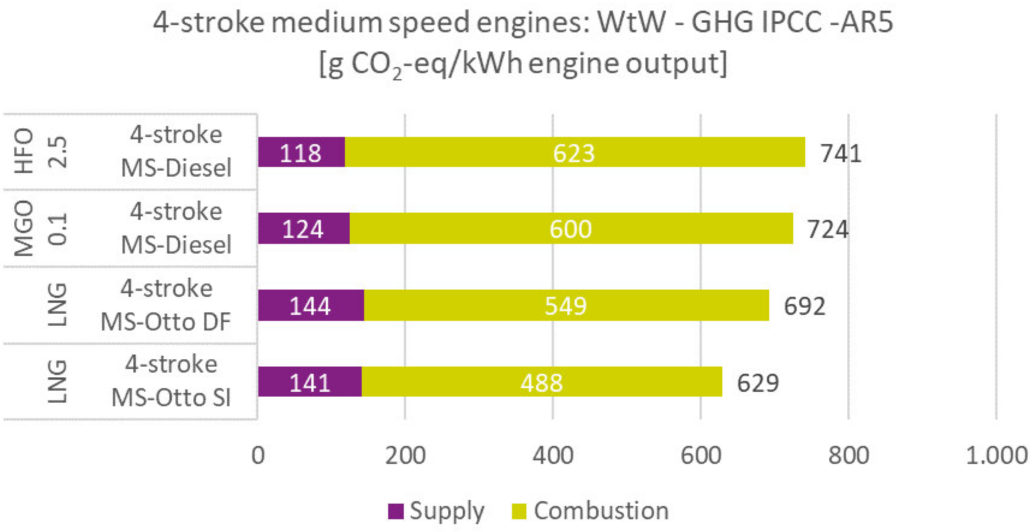
a) The WtW GHG emissions of the 2-stroke slow speed Diesel dual fuel engine (high pressure gas injection) are 549 g CO_2-eq/kWh when using LNG which is 21 % less compared with the same engine operating on HFO (697 g CO_2-eq/kWh) as shown in the figure below.
b) The WtW GHG emissions of the 2-stroke slow speed Otto dual fuel engine (low pressure gas injection) are 598 g CO_2-eq/kWh when using LNG which is a reduction of 14 % compared with HFO operation.

For these LNG fuelled engines, the WtT GHG emissions of the supply chain contribute about 22-24 % of the entire life cycle emissions (WtW). For oil-based fuels, the supply chain accounts for 16-18 %.



4-stroke medium speed engine are the second most common engine (18 wt. % of fuel burned) used in shipping. They typically have a lower engine power and are mainly used in car and passenger ferries as well as cruise ships. Both engines investigated in the study are Otto cycle engines and can be differentiated according to their ability to run on single (SI) or dual fuel (DF).

a) The WtW GHG emissions of the 4-stroke medium speed Otto-DF engine are 692 g CO_2-eq/kWh running on LNG which is a 7 % reduction compared with operation on HFO (741 g CO_2-eq/kWh).
b) The WtW GHG emissions of the 4-stroke medium speed Otto-SI engine which is a single fuel, pure gase engine, are 629 g CO_2-eq/kWh resulting in a 15 % reduction compared with HFO.



4-stroke high speed engines only account for 6 wt.% of the fuel burned in shipping, with gas turbines in simple and combined cycle operation having a minor share of 2 wt.%. Nonetheless, these engines are also analysed in the study and described in detail in the report. The high speed engines and gas turbines only run on $MGO_{0.1}$ and LNG. 4-stroke high speed engines show a potential GHG reduction of 5 % compared with $MGO_{0.1}$.

Gas turbines in simple and combined cycle have a methane slip during the combustion accounting for only 0.3 % of the overall WtW GHG emissions. Simple operation gas turbines using LNG give a benefit of 16 % compared with $MGO_{0.1}$, or 20 % in combined cycle operation.

The comparison of LNG fuelled engines with post-2020 oil-based fuelled engines shows similar GHG results as for the current situation, depending on the post-2020 fuel type and engine technology. For 2-stroke engines the advantages of gas fuelled engines are calculated to be 14-22 % (current fuels: 14-21 %) and for 4-stroke engines 6-16 % (current fuels: 7-15 %).The main reason for the high range of GHG reduction potential is the methane slip during the combustion phase which is mainly dependent on the combustion cycle of the engine and evaluated in more detail below.

Methane Emissions Contribution Analysis

Methane emissions can have a significant impact on the total WtW GHG emissions of marine engines. For oil-based marine fuels, methane emissions are limited to the supply chain of the fuel. In LNG operation, the methane slip in the engine (combustion) plays an important role in addition to the emission from the supply chain. The following tables show an analysis along the life cycle of the fuel and the contribution of supply and combustion. GHG emissions resulting from methane account for around 3 % of the total WtW GHG emissions of oil-based fuels ($HFO_{2.5}$ and $MGO_{0.1}$ in the following tables) and can be considered as insignificant whereas this goes up to 22 % for certain engines combusting LNG (to be considered as significant).

Methane emissions in the supply chain are mainly fugitive emissions. Methane emissions from the combustion of the fuel show a strong dependency from the combustion cycle.

Due to the high gas injection pressure and the combustion in a Diesel cycle, methane emission in the combustion of the 2-stroke slow speed Diesel-DF engine are about 4 g CO_2-eq/kWh representing less than 1 % of the total WtW GHG emissions. The data of the 2-stroke slow speed Otto cycle engine shows that methane slip accounts for 63 g CO_2-eq/kWh which is equal to 11 % of the total WtW GHG emissions.

g CO_2-eq/kWh	Oil-based fuels		Gas-based fuel	
	$HFO_{2.5}$	$MGO_{0.1}$	LNG	LNG
2-stroke slow speed	Diesel		Diesel-DF	Otto-DF
Total WtW GHG emissions	697	686	549	598
- of which methane	23	24	37	96
- supply	*23*	*24*	*33*	*33*
- combustion	*-*	*-*	*4*	*63*

The same characteristics apply for 4-stroke medium speed engines with the two engine technologies investigated using an Otto combustion cycle. The data indicates that pure gas engines (Otto-SI) are less sensitive to methane slip. It accounts for 10 % (60 g CO_2-eq/kWh) of the total WtW GHG emissions of the Otto-SI engine. The dual fuel engines covered in the study show GHG emissions resulting from methane slip of 115 g CO_2-eq/kWh which is equal to 17 % of the total WtW GHG emissions.

g CO_2-eq/kWh	Oil-based fuels		Gas-based fuel	
	$HFO_{2.5}$	$MGO_{0.1}$	LNG	LNG
4-stroke medium speed	Diesel		Otto-SI	Otto-DF
Total WtW GHG emissions	741	724	629	692
- of which methane	24	25	96	151
- supply	*24*	*25*	*36*	*36*
- combustion	*-*	*-*	*60*	*115*

Well-to-Tank Results

Focusing on the Well-to-Tank analysis, results from the study are as follows:

- The carbon footprint of the global LNG supply is calculated at 18.5 g CO_2-eq/MJ (LHV) from Well-to-Tank. The global LNG supply is based on the analysis of five LNG consuming regions (Europe, North America, Asia Pacific, China, and Middle East) which are based on the LNG supply chains of the nine most important and emerging LNG producing countries (Algeria, Australia, Indonesia, Malaysia, Nigeria, Norway, Qatar, Trinidad & Tobago and the USA), covering more than 72 % market share per region.
- Contributions to GHG emissions over the total life cycle are:
    - Gas production, processing and pipeline transport to the liquefication plant (33 % contribution, caused by energy consumption and methane emissions)
    - Gas liquefaction and purification (50 % contribution, caused by energy consumption)
    - LNG carrier transport (13 % contribution, defined by the distance travelled and the utilisation (in terms of time) of the LNG carrier)
    - LNG terminal operations and bunkering (4 % contribution, caused by energy consumption and methane emissions).
- For the LNG supply, carbon dioxide is the major GHG contribution at 74 %, followed by methane at 25 %. N_2O is negligible. The CO_2 emissions mainly come from fuel combustion, with small amounts of CO_2 vented during processing and purification of Natural Gas (CO_2-removal) if no carbon capture and storage is applied in the corresponding country. The main sources for the CH_4 emissions are fugitive emissions.
- The Well-to-Tank analyses of the current and post-2020 oil-based fuels are in the same order of magnitude, ranging from 13.2 to 14.4 g CO_2-eq/MJ (LHV) fuel. The calculation of the WtT GHG results of refinery products is associated with a range of uncertainties. Different crude

oil properties and refinery settings, different levels of desulphurisation and blending ratios, and assumptions made, as well as methodological differences such as different allocation methods can lead to different results. This means that interpretation of results and comparison between studies needs to be undertaken with care. However, the global supply of oil-based marine fuels has a lower WtT GHG intensity compared with LNG.

- For both, LNG and oil-based fuel supply chains, GHG emissions differ from region to region due to different natural reservoir characteristics, and hence production technologies applied, ambient temperatures at liquefaction (LNG supply only), transport distances, etc. Technology consideration as well as specific supply chain analyses to get to a global average are key for the assessment of the supply chains.

Air Quality and Local Pollutants

Although the focus of the study is on GHG emissions of the supply and use of LNG compared with other marine fuels, the influence of the fuel combustion on air quality is investigated but limited to the Tank-to-Wake stage of the life cycle. Sulphur oxide (SO_X), nitrogen oxide (NO_X) and particulate matter (PM) emission data were reported by the engine manufacturers for the operation with LNG, HFO and MGO. Based on these data, the following conclusions are drawn:

- Due to the absence of sulphur in LNG, sulphur oxide emissions of LNG are zero for pure gas engines, and negligible for dual fuel engines where a small amount of sulphur oxide emissions occur due to the use of pilot fuel. Oil-based pilot fuel is self-ignitable and is needed in dual fuel engines to function as a spark plug for the gas. Because it accounts for only 1 to 5 % of the fuel used in normal engine operation, LNG has a clear advantage compared with oil-based fuels.
- NO_X emissions are mainly dependent on the underlying combustion cycle. Most gas fuelled engines utilise the Otto cycle and comply with the strict IMO Tier III NO_X limits (e.g. for ECAs) without any NO_X after-treatment system. The 2-stroke slow speed Diesel-DF engines complies with Tier III by incorporating exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) systems.
- PM measurement data was provided for gas turbines and 4-stroke medium speed engines. Based on these data, LNG can deliver a PM reduction of up to 99 % compared with oil-based marine fuels.

1. Introduction

1.1. Background

The international shipping industry is under pressure to reduce atmospheric emissions. Greenhouse Gas (GHG) emissions as well as local pollutants, like sulphur oxides (SO_X), nitrogen oxide (NO_X), and particulate matter (PM) are in focus of most governmental environmental agencies, public health organisations and non-governmental environmental groups.

In 2018, the most common marine fuels were Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO), with a maximum sulphur limit of 3.5 wt. % outside the Emission Control Areas (ECAs)[1] respectively 0.1 wt. % inside the ECAs. As a result of the external pressures, as well as foreseeing the impending more stringent air quality regulations relating to SO_X and NO_X, the marine fuel portfolio will change.

The International Maritime Organization (IMO) has already introduced different measures to reduce GHG emissions from shipping (e.g. the Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan (SEEMP) and announced, subsequent to the Paris Agreement, a commitment to reduce the GHG emissions from shipping by at least 50 % by 2050, compared with 2008 [5], [6]

MARPOL Annex VI, Regulation for the Prevention of Air Pollution from Ships, limits the sulphur content of marine fuels used in Emission Control Areas (ECAs) to a maximum of 0.1 wt. % from January 1, 2015 and globally to 0.5 wt. % from January 1, 2020 [7]. Hence, ships will have to use marine fuels with a sulphur content of no more than 0.5 wt. % unless using an approved exhaust gas cleaning system (EGCS), such as a scrubber. An additional benefit of reducing SO_X emissions is a decrease in the level of PM, especially an advantage for ports and coastal areas with high shipping traffic.

As mentioned, the IMO 2020 global low sulphur cap with its 0.5 wt. % global sulphur cap, may lead to changes in the marine fuel market in 2020. However, it is currently unknown how refiners and fuel makers will provide marine fuel that will comply with the global 2020 requirements. There will be a wide variability of fuel oil quality depending on crude, refining process, blend strategy, and region. In general, the following main fuel options are possible [8]:

- Marine Gas Oil ($MGO_{0.1}$) → low sulphur distillate fuel
- Marine Diesel Oil (MDO) → blend of distillates with small amounts of residual fuel
- Low Sulphur Fuel Oil ($LSFO_{0.5}$) → specification not known (low sulphur residual fuel), either desulphurised HFO or HFO produced by using low sulphur crude oil as feedstock [2].
- Heavy Fuel Oil in combination with an Exhaust Gas Cleaning Systems (i.e. scrubbers)[3]
- Liquified Natural Gas (LNG)
- Other alternative fuels, e.g. Liquified Petroleum Gas (LPG), methanol, bioLNG[4], synthetic LNG, etc.

[1] ECAs are: the Baltic Sea, the North Sea, the North American and the US Caribbean Sea area.
[2] According to [8], the sulphur content of crude oil in different parts of the world ranges from 0.1 wt. % to 4.1 wt.%. As a rule of thumb 2 to 3 times the S content in the crude ends up in the residual fuel, which means a crude having a S content of 0.3 wt. % would translate to a residual fuel sulphur content of approx. 0.6 wt. % to 0.9 wt. %. Hence to meet the IMO regulations the refiners have to either treat the fuel or blend it with ultra-low sulphur fuel oil. Other options to obtain a 0.5 wt. % S content HFO include blending with hydro-treated residuals, heavy fractions from hydrocrackers and lighter hydro-treated fractions.
[3] No sulphur limit in HFO.
[4] For details regarding bioLNG and synthetic LNG please see section 7.

To control NOx emissions new vessels, based on their date of construction, are required to use Tier II compliant engines outside Emission Control Areas (ECAs) and Tier III compliant engines within ECAs. For explanations regarding the emission limit regulations, please see Annex B. Where these emission limits cannot be met by the engine itself, either exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) technologies may be applied.

Both the IMO GHG emission reduction ambition as well as the IMO 2020 global sulphur cap are challenging the shipping industry. While emission reduction may be achieved by efficiency improvements at the vessels, the industry is searching for alternatives to comply with the upcoming regulations. Liquified Natural Gas (LNG) is seen as the most promising alternative low carbon fuel on a short to medium term.

1.2. Motivation

The use of LNG as a marine fuel continues to gain the attention of the shipping industry as the benefits from the reduction of local air pollutants like SO_X, NO_X, and PM are widely accepted. However, the actual greenhouse gas emissions of LNG in this use are unclear for various reasons. Data availability of conventional oil-based fuelled engines is much greater than for LNG based vessel propulsion. There is also the issue that methane emissions from incomplete combustion could play a major role in GHG emissions from LNG use. The diverse engine technologies and engine characteristics used in shipping further complicate the issue, especially with regard to methane slip. The resulting paucity of data and complexity of systems mean that it is very difficult to make valid general statements of the GHG emissions of LNG in shipping.

For this reason, SEA\LNG and SGMF commissioned a comprehensive Well-to-Wake (WtW) GHG analysis on the use of LNG as marine fuel. While the analysis has been performed on a global level, it considers different regions for the LNG supply, and distinguishes between different ship engines technologies. Primary, up-to-date data from engine manufacturers (OEMs), incorporating the latest technologies and performance attributes, have been used to calculate the Well-to-Wake GHG emissions. The results of this analysis, the WtW GHG emissions, are compared with the WtW GHG emissions of other marine fuels in order to show the advantages and disadvantages.

The Life Cycle Assessment (LCA) method has been applied for the analysis. LCA is a method to evaluate the potential environmental impacts of a product, a system or services throughout its entire life cycle, from raw material extraction to end of life, by quantifying the material and energy inputs and outputs of all unit processes that comprise the product system under study.

LCA is standardised in ISO 14040/14044 [1], [2] and consists of four steps:

- Goal and Scope Definition (sets the objectives and boundaries of the study)
- Life Cycle Inventory Analysis (includes data collection and quantifies the inputs and outputs)
- Life Cycle Impact Assessment (evaluates the potential environmental impacts of resource consumption and emissions)
- Interpretation (discusses the results in relation to the stated goal and scope).

The report is structured as follows: Section 2 outlines the goal of the study and section 3 the general scope of the study. In the subsequent sections 4, 5 and 6, the Well-to-Tank, Tank-to-Wake, and Well-to-Wake analyses are described. Section 7 gives an outlook on renewable LNG sources. Section 8 addresses the interpretation of the results and section 9 details the conclusions and recommendations.

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2. Goal of the Study

2.1. Goal of the Study

The main goal of the study is to provide an accurate report of the life cycle GHG emissions on the use of LNG as a marine fuel compared with conventional marine fuels. An objective is to resolve the existing uncertainty of the overall life cycle GHG emissions of LNG and hence clarify its potential benefit compared with oil-based fuels.

In addition, the study is aimed to provide information on local pollutant emissions of the combustion of fuels in the marine engines.

The goals are reached by using state-of-the-art Well-to-Tank data and performing an industry-wide Tank-to-Wake analysis including data from the most up-to-date marine engine technology available on the market.

An intensive data collection effort was initiated to gather primary industry information about the fuel consumption, methane emissions and pollutant emissions of marine engines. Based on the data collected, the GHG intensity (carbon footprint) is calculated.

2.2. Reasons for Carrying out the Study

While the benefits of LNG in terms of air quality are widely accepted, there is considerable uncertainty regarding the level of greenhouse gas emissions. A number of studies have produced varying results creating further uncertainty[5].

To clarify the potential benefits and barriers of LNG compared with conventional marine fuels, especially as the fuel market changes due to the IMO 2020 sulphur regulations, primary, up-to-date data from engine manufacturers incorporating the latest technologies and performance attributes has been used to calculate the Well-to-Wake GHG emissions from the use of LNG compared with oil-based marine fuels.

2.3. Intended Application

This report is mainly prepared to support open and transparent communications with external stakeholders such as investors, ship owners and ship operators. It is intended to provide transparent information of the benefits of, as well as barriers to LNG as a marine fuel. This includes its GHG intensity along the whole life cycle (Well-to-Wake) as well as emissions of local pollutants during the combustion of the fuel. The results are intended to support the decision-making process of investors and ship operators.

The results of the study are intended to be disclosed to the public. Therefore, the study was subjected to a critical review by a panel of independent experts according to ISO 14044.

[5] This is especially true for the amount of methane being released during the combustion of the fuel (also known as methane slip). Sometimes, general statements have been made regarding the benefit of LNG, even the methane slip and hence GHG performance is highly dependent on the engine technology, analysed.

2.4. Intended Audience

The report has been prepared to be used for public dissemination and the dialogue with external stakeholders, particularly investors, ship owners, operators, governmental agencies, NGOs and regulators.

3. General Scope of the Study

This section outlines the general scope of the project. A detailed description of the scope of the WtT and TtW part is found in sections 4 and 5. The general scope includes an overview on the considered product systems of the study, the selection of the impact category, the interpretation to be used, data quality requirements and the type and format of the report, as well as software and databases used and addresses critical reviewer needs.

The detailed scope in section 4 and 5 includes, the product system, product function and functional unit, the specific system boundary, the handling of multifunctional processes and allocation rules as well as cut-off criteria.

3.1. Overview on Different Product Systems

The study is divided into three main parts, the:

- Well-to-Tank (WtT) analysis (section 4) describes the fuel supply
- Tank-to-Wake (TtW) analysis (section 5) describes the combustion of the fuel
- Well-to-Wake (WtW) analysis (section 6) combines the WtT and TtW analyses.

An overview on the system boundary of LNG is displayed in Figure 3-1.

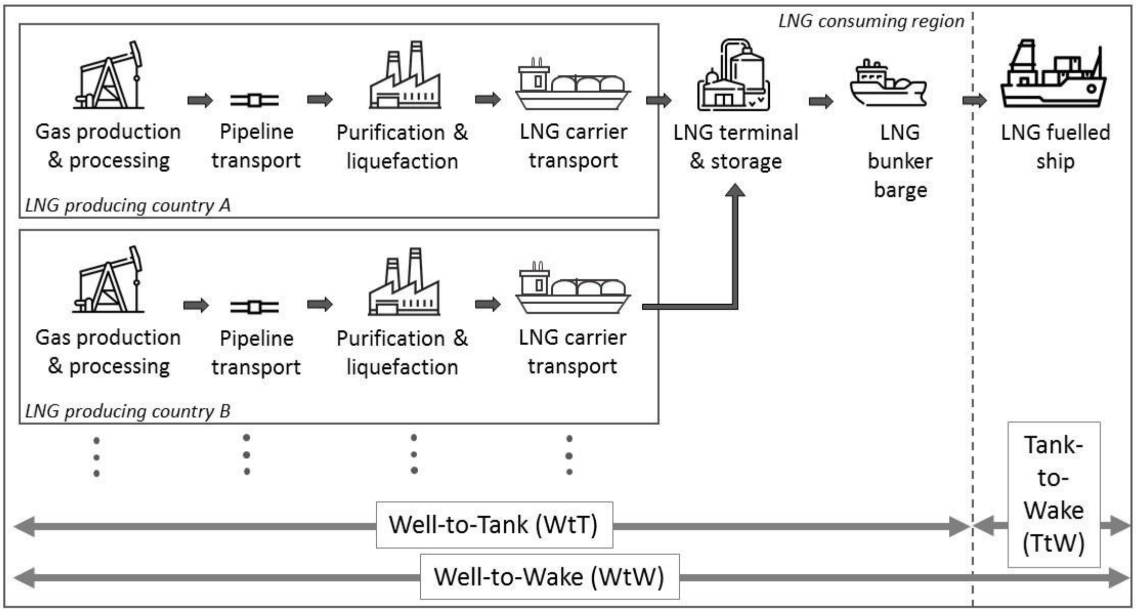

Figure 3-1: Overview – Well-to-Tank, Tank-to-Wake and Well-to-Wake analysis of LNG [9]

The fuel consumption mixes of five main bunker regions (Europe, North America, Asia Pacific, China and Middle East) defined by the project consortium are analysed in this study as well as a global fuel consumption mix which is calculated based on these five regions.

As indicated there is a large number of marine fuels from different sources, different levels of desulphurisation and blending ratios. Table 3-1 gives an overview on the marine fuels which have been defined by the project consortium and considered in this study.

Table 3-1: Overview on current and post-2020 marine fuels considered in this study

Marine fuel	Description
Current fuels	
LNG	Liquefied Natural Gas (LNG) is produced from Natural Gas through liquefaction.
Heavy fuel oil ($HFO_{2.5}$)	The maximum sulphur content limit of this residual marine fuel is 3.5 wt. % [7]. The worldwide average sulphur content for $HFO_{2.5}$ is assumed to be 2.5 wt. % and is used in this study [10]. No EGCS used in ships outside ECAs.
Marine gas oil ($MGO_{0.1}$)	Distillate marine fuel with an average sulphur content of 0.1 wt. %. Fuel used mainly in ECAs.
Post -2020 fuels[6]	
LNG	Liquefied Natural Gas (LNG) is produced from Natural Gas through liquefaction.
Heavy fuel oil ($HFO_{>2.5}$) with EGCS	Residual marine fuel with an average sulphur content of >2.5 wt. %[7]. An SO_x exhaust gas cleaning system at the ships is used to meet the 0.5 wt.% sulphur limit. It is assumed that the fuel is produced in the same way as today $HFO_{2.5}$.
Marine gas oil ($MGO_{0.1}$)	Distillate marine fuel with an average sulphur content of 0.1 wt. %. It is assumed that the fuel is produced in the same way as today.
Low sulphur heavy fuel oil ($LSFO_{0.5,\ Blend}$)	$LSFO_{0.5,\ Blend}$ is a blend of 50:50 residual and distillate marine fuels with an average sulphur content of 0.5 wt. % produced from a crude oil with an average sulphur content. In general, different blending ratios are possible. Additional CO_2 emissions for the production of the fuel are assumed to be in the range of 2 to 10 % of refinery CO_2, depending on the blending ratio between residual and distillate fuels [11]. After intensive discussions with a representative of CONCAWE [12], 4 % additional GHG emissions for the production are assumed in this study for a 50:50 blend.
Low sulphur heavy fuel oil ($LSFO_{0.5,\ LScrude}$)	Residual marine fuel with an average sulphur content of 0.5 wt. %. $LSFO_{0.5,\ LScrude}$ can be produced using low sulphur crude oils as feedstock in refineries. No further direct modifications in the existing refinery are assumed.

Other marine fuels such as LPG and methanol are also analysed, as well as renewable supply sources of LNG. The WtT, TtW and WtW analysis for LPG and methanol can be found in Annex G. Section 7 analyses the WtW GHG emissions of renewable supply sources of LNG.

[6] According to [8], the sulphur content of crude oil in different parts of the world ranges from 0.1 wt. % to 4.1 wt.%. As a rule of thumb 2 to 3 times the sulphur content in the crude ends up in the residual fuel, which means a crude having a sulphur content of 0.3 wt. % would translate to a residual fuel sulphur content of approx. 0.6 wt. % to 0.9 wt. %. Hence to meet the IMO regulations the refiners have to either treat the fuel or blend it with ultra-low sulphur fuel oil. Other options to obtain a 0.5 wt. % sulphur content HFO include blending with hydro-treated residuals, heavy fractions from hydrocrackers and lighter hydro-treated fractions [8].

[7] It is very likely that the sulphur content will increase post-2020. CONCAWE, for instance, estimates an increase of the average sulphur content of post-2020 HFO to potentially 4.2 wt. % for European refineries [12].

Based on the global fuel supply, different ship engines are analysed. Table 3-2 provides an overview of the engines investigated. A detailed explanation of the technologies can be found in section 5.1.3.

Table 3-2: Overview of engines technologies and fuels investigated

	Oil-based fuels		Gas-based fuel[redacted]
	HFO$_{2.5}$, HFO$_{>2.5}$, LSFO$_{0.5, Blend}$, LSFO$_{0.5, LScrude}$	MGO$_{0.1}$	LNG
2-stroke SS-Diesel-DF or Otto-DF[8]	x	x	x
4-stroke MS-Diesel-CI	x	x	
4-stroke MS-Diesel DF or Otto DF	x	x	x
4-stroke MS-Otto-SI			x
4-stroke HS-Diesel-CI		x	
4-stroke HS-Otto-SI			x
Gas turbine simple cycle (GT)		x	x
Gas turbine combined cycle (CCGT)		x	x

Steam turbines are not analysed in this context due to the small number of vessels in operation and less common technology. However, within the LNG supply chain analysis, steam turbines are considered as engine technology at LNG carriers in this study. The usage of natural gas in fuel cells is not common in shipping today and is therefore not investigated here.

This study is a Well-To-Wake analysis, however the data collection focuses more on the Tank-to-Wake analysis than the Well-to-Tank analysis because the majority of the Well-to-Tank primary data were already collected within the NGVA study [13]. These data are supplemented by *thinkstep*'s LCI databases [14] and literature and have been validated by energy suppliers. Tank-to-Wake primary data have been collected intensively for the combustion of the fuels in ship engines.

3.2. Tasks

The assessment of the GHG emissions (carbon intensity) of LNG is carried out on a full life cycle basis. This includes the following life cycle phases: production & processing, pipeline transport, liquefaction, LNG carrier transportation (for imports), LNG terminal operations (for imports), bunkering (dispensing) and the final combustion in the engine. Several LNG pathways are analysed, including LNG from Algeria, Australia, Qatar, Indonesia, Malaysia, Nigeria, Norway, Trinidad & Tobago and the USA. In addition to the life cycle GHG emissions, local pollutants, like SO_X, NO_X, and PM are considered for the use phase of the fuels. The main reason why the local pollutant emissions are considered for the use phase only, is that adding all air pollutants along the fuel supply chains in different global regions and locations may give wrong conclusions of air quality impacts, especially for coastal areas, harbours and ECAs.

The following tasks are performed:

- Literature survey to identify relevant documents and studies
- Data collection and validation
  - Primary data for the marine engines from engine manufacturers (OEMs) of SEA\LNG and SGMF members for both operation on LNG as well as on oil-based fuels

[8] Low pressure engines (all 4-stroke engines considered and the 2-stroke SS-Otto-DF) run in the Otto cycle while using LNG and in the Diesel cycle when using oil-based fuels. The high-pressure engine (2-stroke SS-Diesel-DF) run in a Diesel cycle when using both LNG and oil-based fuels.

  - Use (and update were necessary) existing supply chain models (mainly from NGVA study [13]) by collecting primary data from LNG suppliers
  - Secondary data for the oil-based fuels
- Development of specific life cycle GHG models including the fuel supply and combustion
- Calculation of life cycle GHG emissions using established midpoint metrics (e.g. Global Warming Potential)
- Comparison of the life cycle GHG results of LNG marine fuel with the use of oil-based fuels used today ($HFO_{2.5}$, $MGO_{0.1}$), and fuels that will mostly likely enter the market due to the introduction of the IMO 2020 global sulphur cap, e.g. low sulphur fuels
- Comparison of the local pollutants, like SO_X, NO_X, and PM for the use phase of the fuels
- Scenario analysis to quantify GHG impact from different EGCS technologies, e.g. open loop, closed loop[9]
- Consideration of future LNG supply sources, including biomethane and synthetic gas (based on results from other publicly available reports)
- Sensitivity and uncertainty analyses on technical parameters and different midpoint metrics, e.g. GHG characterisation factors referring to different IPCC reports and/or targeted years.
- Third-party critical review of the study / report.

3.3. Selection of the Impact Category

As this study focuses to understand the influence of the fuel usage on the global warming potential, GHG emissions and their impact to the global warming potential are investigated. The global warming potential is of major relevance to climate change, of high public and institutional interest, and deemed to be the most pressing environmental issue of our time. The marine transport sector is currently being driven by policy makers, NGOs, the shipping industry and the public towards carbon reduction to mitigate the effects and consequences of climate change as far as possible.

This study is not a complete LCA as limited to GHG. LCAs typically consider various other environmental impact categories at the midpoint level with respect to different environmental compartments such as air, water and soil. Instead, the study focuses exclusively on the impact category called “climate change” which is caused by a number of substances emitted into the air, mainly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). By characterising each single greenhouse gas (GHG) by its individual characterisation factor, all GHG emissions can be aggregated to the global warming potential (GWP), also known as greenhouse gas (GHG) intensity or Product Carbon Footprint (PCF), and expressed in CO_2-equivalents (CO_2-eq). The impact category climate change is assessed based on the current IPCC (Intergovernmental Panel on Climate Change) characterisation factors taken from the 5th Assessment Report (AR5, 2013) for a 100-year timeframe (GWP_{100}), as this is currently the most commonly used metric [15] and also in accordance with ISO 14067 “Carbon Footprinting of Products” [16].

Black carbon (BC) is part of the particulate matter emissions and another contributor to the global warming potential. It absorbs the energy of the sun leading to atmospheric warming. Compared with the greenhouse gases mentioned above, the location of the emission and the deposit of BC is of importance. In addition to the absorption of solar radiation, BC reduces the albedo of the surface when it deposits on snow or ice. Hence the global warming impact of BC is especially significant in the arctic where its presence leads to increased melting of the artic sea ice[10] [17]. The IPCC AR5 collected information from different studies indicating a range of characterisation factors for GWP_{100}

[9] ECGS systems typically use either sea water or fresh water to wash of pollutant emissions. Sea water is used in open-loop systems and discharged into the sea without any further treatment (the high water flow ensures that the IMO guidelines are met). Fresh water is used in closed-loop systems and only discharged after special after treatment. [57]

[10] More detailed information on BC (especially BC from shipping) and its special importance for the artic regions can be found in [80].

of BC from 100-1.700 g CO_2-eq/g BC [15]. The International Council on Clean Transportation (ICCT) [17] estimated using a characterisation factor of 900 g CO_2-eq/g BC that GHG emissions of shipping resulting from black carbon emissions account for 5-8 % of the global GHG emissions of shipping. The range of characterisation factors researched by the IPCC, however, shows a high level of uncertainty with respect to the quantitative influence of black carbon emissions on GWP. Considering the estimations used by ICCT [17] and the range of characterisation factors presented by IPCC [15], the GHG emissions resulting from black carbon emissions would add between 0.3 and 15 % to the total WtW GHG emissions of the oil-based fuelled engines. Due to this high uncertainty, GHG emissions resulting from black carbon are not included in this study. This represents a conservative approach with respect to the potential benefits of LNG, as CO_2-eq emissions resulting from black carbon would increase the GHG emissions mainly of oil-based fuels.

In order to increase the comparability of the results of this study with the results of other studies, the factors from the 4th Assessment Report (AR4, 2007) for a 100-year timeframe (GWP_{100}) are applied in a sensitivity analysis to check the influence of any changes to the different factors on the overall GHG results [18]. Additionally, the short-term climate effects (20-year timeframe) which are described by the GWP_{20} and the global temperature potential[11] on a 100-year timeframe (GTP_{100}) are investigated. For a complete listing of the characterisation factors used, refer to Annex B.

It must be noted that impact categories represent impact potentials, i.e., they are estimates of environmental impacts that could occur if the emissions (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach). GHG results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

Optional elements of the ISO 14040/14044 standard include normalisation, grouping and weighting factors. Normalisation is not applied. Weighting and grouping are also not included, because only one impact category is chosen for the present study.

3.4. Selection of Local Pollutants – Air Quality

In addition to the GHG emissions, the following selected local pollutant emissions that are released during the combustion of the fuel (hence Tank-to-Wake emissions) are analysed:

- **Nitrogen oxides (NO_X):**
  "Nitrogen oxides" is a collective term for binary compounds of nitrogen and oxygen, mainly nitrogen monoxide and nitrogen dioxide. NO_x are a significant source of air pollution. There are three different types of NO_x emissions released during combustion: thermal NO_x, fuel NO_x and prompt NO_x. Thermal NO_x emissions result from the combustion of fuels at high temperatures. Fuel NO_x emissions are related to the nitrogen content of the combusted fuel and released during combustion. Prompt NO_x emissions are caused by atmospheric nitrogen but is considered to be negligible. NO_x emissions are responsible for the formation of acidic rain and the eutrophication of the environment. They have a negative effect on the respiratory tracts of humans when occurring in high concentrations in the ambient air and tend to produce

[11] Compared with the GWP, the Global Temperature Change Potential (GTP) goes one step further down the cause-effect chain and is defined as the change in global mean surface temperature at a given point in time in response to an emission pulse, and expressed relative to that of CO_2. Compared with the GWP, the GTP puts much less emphasis on near-term climate fluctuations caused by emissions of short-lived species (e.g., CH_4). The GWP and GTP are different by definition, and different numerical values can be expected. In particular, the GWPs for near-term climate forcers are higher than GTPs over the same timeframe due to the integrative nature of the metric. The GTP values can be considerably affected by assumptions about the climate sensitivity and heat uptake by the ocean. Thus, the relative uncertainty ranges are wider for the GTP than for GWP.

low-lying atmospheric ozone in the presence of UV-radiation causing summer smog (photochemical ozone formation).

- **Sulphur oxides (SO_X):**
  Sulphur oxide emissions are not dependent on the temperature of the combustion process but are a product of the reaction of sulphur in the fuel with oxygen, and hence directly linked to the sulphur content of the fuel.
  Sulphur oxides are another major reason for the occurrence of acidic rain and its consequences [19]. SO_X emissions are also main constituents for PM, and its related health impacts and contribute to summer smog.
- **Particulate matter (PM):**
  Particulate matter emissions consist of solid and liquid particles and result from the combustion of fuels. They are mainly classified according to their size ($PM_{2.5}$-PM_{10}). The data used in this study refers to total PM emissions from marine engines and is not distinguished into different particle sizes due to data availability.
  The effects of PM emissions range from health issues for humans mainly in the respiratory tracks, to other environmental effects [20]. Black carbon is part of the fine particulate matter ($PM_{2.5}$). Health impacts is listed as the main driver for reduction at IMO (MEPC 70/INF.34).

3.5. Interpretation to be used

The results of the life cycle inventory analysis and the GHG impact assessment are interpreted according to the goal and scope. The interpretation addresses the following topics:

- Identification of relevant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data
- Conclusions, limitations and recommendations.

The interpretation is provided in section 8, and the conclusions and recommendations in section 9.

The interpretation does include the evaluation of the differences of the results according to their significance. Whether differences between the results are environmental significant or not varies from case to case. Differences in the results of the Well-to-Wake (WtW) GHG analysis of 3 %[12] and more are already considered as environmental significant, while differences in the results of the Well-to-Tank (WtT) GHG analysis are considered as environmental significant from 15 % onwards. For local pollutants differences more than 30 % can be considered as significant.

3.6. Data Quality Requirements

The data used to create the inventory model must be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study.

- Measured primary data are considered to be of the highest precision, followed by calculated (or extrapolated) data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data and all relevant LCA stages/activities.

[12] The Well-to-Wake (WtW) results are mainly defined by the fuel consumption of the engine, and to a certain extend by the methane slip.

- Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties are able to approximate the reported results. This ability may be limited by the exclusion of confidential primary data and access to the same background data sources.
- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope. The goal is to use the most representative specific respectively industry-average data. Whenever such data were not available (e.g., no industry-average data available for a certain country), best-available proxy data were used. An overview on the proxy data used is given in Annex E.

An evaluation of the data quality with regard to these requirements is provided in section 8.3.

3.7. Software and Databases

The LCA software system GaBi 8.7[13] is used to synthesise the collected data and information and to build the basis for the GHG model. The associated LCI databases (GaBi databases 2018, service pack 36) [14] provide the life cycle inventory data for the background datasets, like country-specific electricity grid mix data and data for urea solutions. A list of the key background datasets is given in Annex E.

3.8. Critical Review

The results of the study are intended to be disclosed to the public. The study was therefore subjected to a critical review by a panel of independent experts according to ISO 14044, section 6 [2].

The critical review statement can be found in Annex I. The critical review report containing the comments and recommendations by the independent experts as well as the practitioner's responses is available upon request from the study commissioner in accordance with ISO/TS 14071 [21].

The members of the critical review panel are introduced in Table 3-3.

Table 3-3: Members of critical review panel

Reviewer	Organisation, Location, Position	Role
Philippe Osset	Solinnen, Paris (France) *CEO, member of the ISO 14040/14044 working group*	Chair of Review Panel
Prof. Dr. Atsushi Inaba	Kogakuin University (Japan) *Department of Environmental and Energy Chemistry*	Reviewer
Prof. Dr. Friedrich Wirz	Hamburg University of Technology (Germany) *Head of Department of Marine Engineering*	Reviewer
Dr. Michael Wang	Argonne National Laboratory (USA) *Head of Systems Assessment Department*	Reviewer

The panel has expertise of the different technical systems and applied methodologies and, in consideration of the global nature of the shipping industry, has an international membership.

[13] GaBi is an LCA software and one of the largest consistent LCA databases on the market. The databases offer >10,000 LCA datasets (all compliant with ISO 14040/44 standards in the ILCD data format of the European Commission [22]), based on collected primary data during *thinkstep* global work with companies, associations and public bodies including all relevant industry sectors. The datasets are updated annually. More than 2,000 professionals work with GaBi on a daily basis.

4. Well-to-Tank Analysis

4.1. Well-to-Tank – Scope of the Study

The following sections describe the scope of the Well-to-Tank analysis in detail to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function, functional unit and reference flows, the system boundary, handling of multifunctional processes, and cut-off criteria of the study.

4.1.1. Product System

The Well-to-Tank (WtT) section analyses the following product systems:

- the fuel supply of Liquefied Natural Gas (LNG)
- the fuel supply of current oil-based fuels: $HFO_{2.5}$, $MGO_{0.1}$
- the fuel supply of post-2020 oil-based fuels: $HFO_{>2.5}$, $MGO_{0.1}$, $LSFO_{0.5,\ Blend}$ and $LSFO_{LScrude}$.

The focus of the study is on the supply and use of LNG as the main fuel. Therefore, the WtT section for LNG is highlighted. However, the section on the oil-based fuels is outlined as well.

4.1.2. Product Function and Functional Unit

The product function is the provision of the fuel to be used for engines. The lower heating value (LHV) of the fuels is the main property to be used to describe the functional unit. The functional unit is to provide 1 MJ (LHV) of fuel, in tank. The reference flow related to the defined functional unit is 1 MJ (LHV) of fuel, in tank.

The technical characteristics of the different fuels are stated in Annex B.

The system boundaries of the LNG and the oil-based fuel engines are described in the following.

4.1.3. System Boundary of the LNG Supply

The system boundary of the product system includes the whole supply chain from the production and processing of Natural Gas up to the provision of LNG (see definitions on Natural Gas and LNG in Annex A) to LNG fuelled ships:

- Natural Gas production & processing (including well drilling)
- Natural Gas pipeline transport
- Natural Gas purification and liquefaction
- LNG carrier transport
- LNG terminal and storage,
- Maritime bunkering by LNG bunker barge.

Figure 4-1 shows the Well-to-Tank system boundary of LNG.

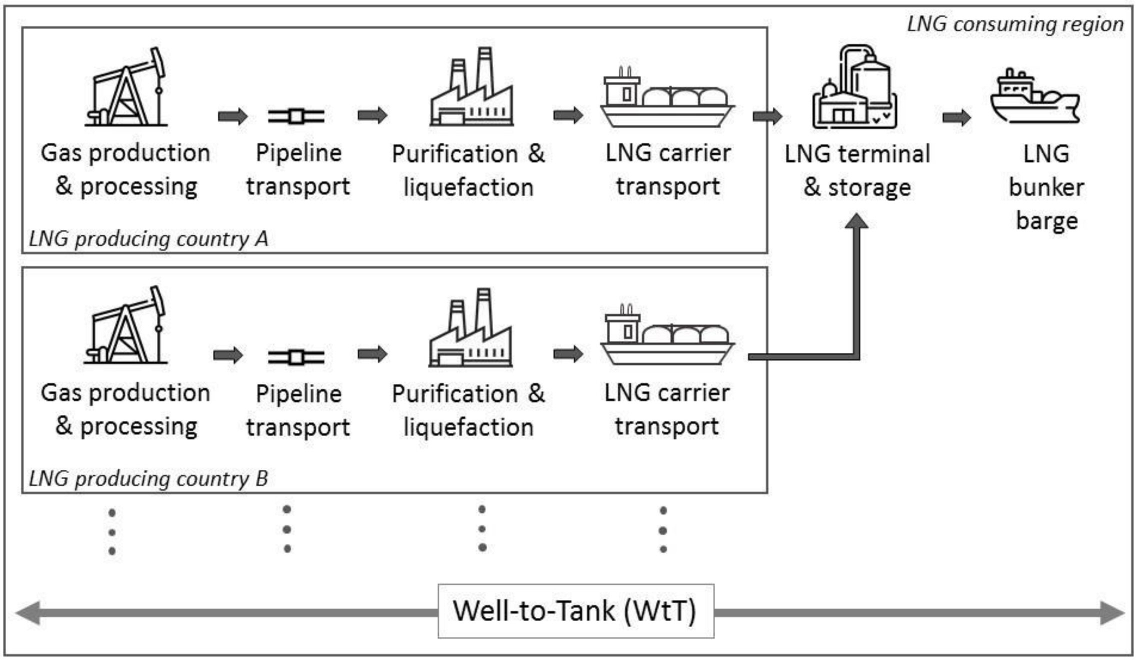

Figure 4-1: Well-to-Tank analysis – LNG supply [9]

The global LNG consumption as well as five LNG consumption regions are considered in the Well-to-Tank Analysis. Data is collected for each process step of the LNG supply chains from each LNG producing country to each considered region. The considered regions as well as the LNG producing countries are addressed more precisely in the Geographical Coverage section below.

The following paragraphs describe the product system. Corresponding data used for the modelling are displayed in section 4.2. and Annex D.

Natural Gas Production & Processing (including Well Drilling)

After drilling and well installation, raw Natural Gas is produced from gas fields. It is sometimes mixed with other hydrocarbons such as crude oil. The raw Natural Gas is separated and processed to remove Natural Gas liquids (NGL) and impurities such as carbon dioxide, hydrogen sulphide, and water. These process steps include the following GHG emissions relevant processes respectively emission sources:

- Extraction of the hydrocarbons itself (e.g. conventional gas, unconventional gas like shale gas, tight gas and coal bed methane (CBM) and associated gas) at the reservoir, considering data on the latest analyses of fugitive emissions associated with hydraulic fracturing ("fracking")[14],
- Separation facilities (including separators as well as washing tanks)
- Natural Gas processing (including heat exchanger, scrubbers, compressors, gas dehydration and glycol regeneration unit, Claus processing of H_2S to elemental sulphur)
- Energy supply units (diesel generator, gas turbine, gas engines, electricity from the grid)
- Waste water treatment facilities (e.g., for the treatment of produced water)
- Natural gas flaring, venting (if any) and other methane emissions (fugitives)
- Well drilling and well installation efforts, such as flaring and venting during installation (scaled by the natural gas production over well lifetime).

[14] Conventional natural gas is extracted by drilling vertical wells and can be produced without further technical measures. The extraction of unconventional natural gas requires the drilling of horizontal wells and pumping of chemicals and water to create fractures in the rock of the reservoir around the well. This process is called hydraulic fracturing or fracking.

Natural Gas Pipeline Transport

Natural Gas is transported by onshore and/or offshore pipelines from the Natural Gas production and processing units to the liquefaction plant. All necessary processes are included: energy supply units (diesel generator, gas turbine, electricity from the grid), and fugitive methane emissions.

Natural Gas Purification and Liquefaction

Before liquefaction, Natural Gas needs to be purified. Different liquefaction technologies have been developed which use different cooling cascades and different refrigerants. The following process steps and emission sources are taken into account for Natural Gas purification and liquefaction:

- Purification process, including removal of acid gas and sulphur recovery unit, gas dehydration, removal of mercury, liquefied petroleum gas (LPG) recovery, carbon capture and storage (CCS) technology to sequester the CO_2 separated in the purification process (at the considered countries, CCS is only applied in Norway)
- Liquefaction process itself, including heat exchanger, refrigerant cycles, etc.
- Onsite storage and loading facilities
- Energy supply units (diesel generator, gas turbine, electricity from the grid)
- Natural Gas methane emissions

LNG Carrier Transport

Liquefied Natural Gas is transported by dedicated LNG carriers. These vessels are equipped either with steam turbine, dual-fuel diesel electric (DFDE), tri-fuel diesel electric (TFDE), M-type electronically controlled gas injection (ME-GI), dual-fuel (X-DF) or slow speed Diesel (SSD) propulsion systems. Due to the high outside temperature (compared with the LNG at -162°C), LNG is warmed leading to some LNG evaporating to gaseous Natural Gas (called boil-off gas). This boil-off gas either is used as propulsion fuel at steam, DFDE, TFDE, ME-GI, X-DF vessels or is re-liquefied on-board (SSD). The “LNG carrier transport” includes:

- Transportation process, specifying the fuel demand
- Boil-off rates
- Energy supply processes ($HFO_{2.5}$, $MGO_{0.1}$, BOG)
- Fuel demand of the vessels due to loading and unloading operation (harbour operations)
- Natural Gas methane emissions

The propulsion type, fuel type, distance (round trip), boil-off rates, and usage of the boil-off gas (re-liquefied or used as fuel) as well as the utilisation of the LNG carrier are taken into account. The time the vessels spend both sailing and in port depends on the trip distance, the speed of the vessel, and the time required for loading and unloading the tanks.

LNG Terminal Operations and Storage

This includes the storage and unloading activities, energy supply units (diesel generator, submerged combustion vaporisers, boilers, electricity from the grid) and methane emissions.

Maritime LNG Bunkering

LNG terminals are marine terminals where LNG carriers unload or load the LNG. Often after storage, the LNG can be either warmed-up to its gaseous state and fed into the Natural Gas transmission network, or provided by means of pipelines, trucks, trains or LNG bunker barges to LNG consumers. The focus of the study is on the provision of LNG to LNG fuelled ships.

Three general pathways for maritime LNG bunkering operations are possible:

- ship-to-ship
- shore-to-ship
- truck-to-ship

This study focuses on ship-to-ship since it is the seen as the most common pathway, but a scenario analysis is assessed for the alternative maritime bunkering pathways (please see section 6.7). The following emission sources are considered: energy supply units (diesel generator, gas turbine, electricity from the grid) and methane emissions.

Table 4-1 provides an overview on the elements and activities included and excluded from the system boundary.

Table 4-1: System boundary – included and excluded elements or activities

Included	Excluded
✓ Well drilling and well installation	× Seismic exploration and exploratory drilling
✓ Production and processing (CO_2-removal, water removal, H_2S removal)	× Infrastructure and maintenance efforts for infrastructure (e.g., pipeline, LNG carriers, liquefaction plants)
✓ Pipeline transport	× Auxiliary materials, like lubricants
✓ Purification and liquefaction	× Overhead of production plants, e.g., personnel lodging and transport, employee commute, administration
✓ LNG carrier transport	× Accidents
✓ LNG terminal and storage	
✓ Maritime LNG bunkering	
✓ Energy supply: gas turbine, gas engines, diesel generators, grid electricity	
✓ Methane emissions	
✓ Consideration of co-products (crude oil, NGLs, and LPG)	

Previous work conducted demonstrated that the excluded data do not have a relevant influence on the overall GHG results [14]. Seismic exploration and exploratory drilling activities may have an impact resulting from methane emissions, but there is no useable information available, as exploration activities may vary considerably from case to case, and from year to year. Because of this variability, only data covering multiple years would make sense. Additionally, most of the other studies used for benchmarking also did not take exploratory drilling into account, so it is excluded from consideration. However, well drilling and well installation efforts are considered. Accidents are excluded since “LCA only accounts for impacts related to normal and abnormal operation of processes and products, but not covering, e.g., impacts from accidents, spills, and similar[15]", as outlined in the European Commission's ILCD handbook on LCA [22]. Infrastructure is assumed to be negligible.

Time Coverage

The intended reference year for all primary data collected for the LNG supply is 2017, and 2016 if 2017 data are not available. The detailed reference years are given in Annex C and Annex D. The reference period of the background data is from 2014 to 2017.

Technology Coverage

The technology covered in the study is described in detail in section 4.2 for all processes and for all LNG supply chains under consideration. It is intended to cover all relevant technologies.

Geographical Coverage

The LNG consumption mix of a region considers the indigenous LNG production of the member countries (if applicable) as well as the LNG imports from producing countries and LNG exports of the member countries. The LNG consumption mixes of the five main bunker regions (Europe, North America, Asia Pacific, China and Middle East) are analysed in this study, as well as a global LNG consumption mix which is calculated based on these five regions. The approach for the calculation of the consumption mixes is explained in Annex C.

4.1.4. System Boundary of the Oil-based Marine Fuel Supply

Figure 4-2 shows the Well-to-Tank system boundary for oil-based marine fuels $HFO_{2.5}$, $HFO_{>2.5}$, $MGO_{0.1}$, $LSFO_{0.5, Blend}$ and $LSFO_{0.5, LScrude}$. After production and processing, the crude oil is transported by pipeline and/or oil tanker from the crude oil producing country to the consuming region for the production of the oil-based marine fuels in a refinery. The fuels are distributed by pipeline to the bunkering terminal to be used as fuel for ships.

[15] "Accidents and accident-type leakages and spills shall not be inventoried as part of the normal life cycle inventory since they are fundamentally different in nature from the production or operation related to normal and abnormal operating conditions that LCA relates to (other than e.g., fugitive emissions through seals and other "engineered losses" that are included in LCA). Accident modelling necessarily requires dealing with frequencies and with cause-effect chains (to assign them to the causing unit processes). Work on this Life Cycle Accident Assessment is still under methodological development, while a number of exploratory case-studies have been published." [22].

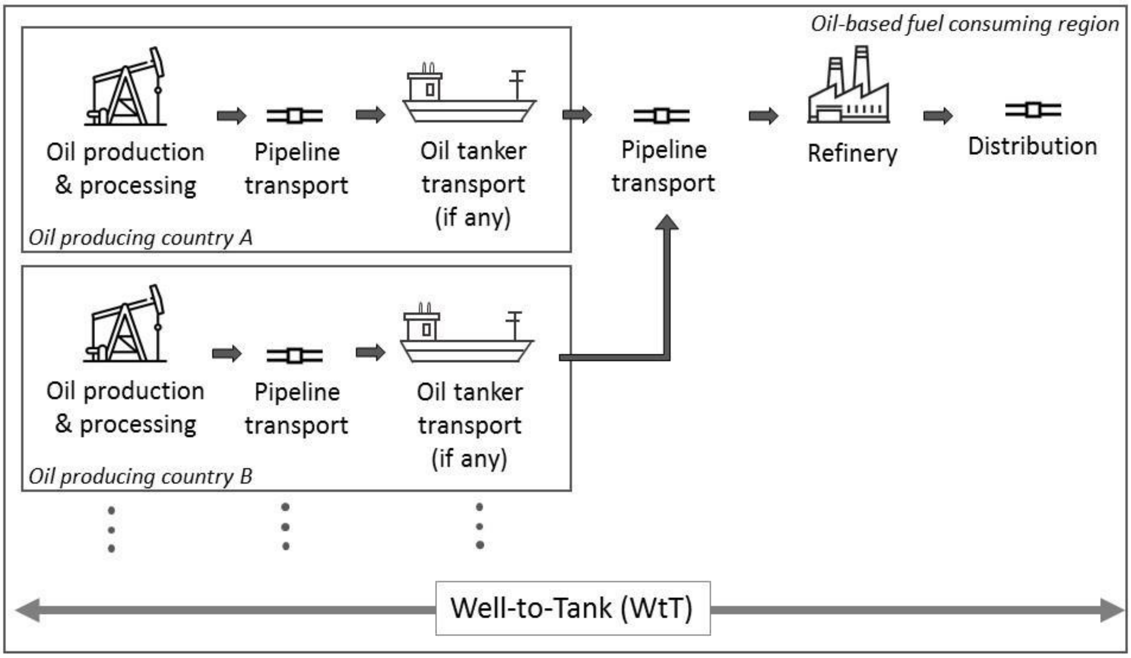

Figure 4-2: Well-to-Tank analysis – Oil-based marine fuel supply [9]

Analogue to LNG, the global consumption as well as five consuming regions are considered in the Well-to-Tank Analysis of the oil-based fuels. Data are collected for each process step of the supply chains from each producing country to each considered region. The considered regions as well as the producing countries are addressed more precisely in section Geographical Coverage below.

Time Coverage

The intended reference year for all data collected for the oil-based fuel supply chains is 2017, and 2016 if 2017 data are not available. The detailed reference years are given in Annex C and Annex D. The reference period of the background data is from 2014 to 2017.

Technology Coverage

The technology covered in the study is described in detail in section 4.2 for all processes and for all oil-based fuel supply chains under consideration. It is intended to cover all relevant technologies.

Geographical Coverage

Analogue to LNG, the oil-based fuel consumption mix of a region considers the indigenous oil-based fuel production of the member countries (if applicable) as well as the oil-based fuel imports from producing countries and oil-based fuel exports of the member countries. The oil-based fuel consumption mixes of the five main bunker regions (Europe, North America, Asia Pacific, China and Middle East) are analysed in this study as well as a global oil-based fuel consumption mix which is calculated based on these five regions. The approach for the calculation of the consumption mixes is explained in Annex C.

4.1.5. Multifunctional Processes and Allocation Rules

Multi-output allocation generally follows the requirements of ISO 14044, section 4.3.4.2. The main products and co-products occurring in the given product systems are listed below:

- Products and co-products of "Crude Oil and Natural Gas production":
  - Crude oil
  - Natural Gas
  - Natural Gas Liquids (NGL, i.e., mix of ethane, propane, butane, and higher hydrocarbons)
- Products and co-products of "Natural Gas purification" (LNG supply chain):
  - Natural Gas
  - Liquefied petroleum gas (LPG, i.e., mix of propane, butane)

The allocation was applied on the basis of the energy content (MJ LHV) as is common practice in modelling oil and gas supply chains.

In Table 4-2, an example of the sensitivity on the allocation factors is displayed for the "Natural Gas Purification" step. Applying allocation by either energy or mass does not lead to different results due to the nearly equal LHVs (~45-49 MJ/kg) of the different products. In both cases, the majority of the environmental burdens is allocated to Natural Gas.

Table 4-2: Allocation factors for purification step based on energy content (based on mass for comparison) [23]

Energy carrier	Allocation factor (energy)	*Allocation factor (mass)*
Natural Gas (after treatment)	96.23 %	*95.95 %*
Propane (C3)	1.76 %	*1.87 %*
Butane (C4)	1.37 %	*1.48 %*
Pentane (C5)	0.64 %	*0.70 %*

For the "Crude Oil and Natural Gas production", the choice of the allocation method is also of minor significance due to the similar LHVs of the different products. Hence, no further sensitivity analysis was performed.

Allocation of the refinery efforts and background data (energy and materials) taken from *thinkstep*'s LCI databases is documented in [24].

Relevant for this study, the products and co-products of "combined heat and power generation (CHP) units", namely: thermal energy and electricity, are allocated based on exergy in accordance with the IPPC - BREF document on large combustion plants [25], one of the Best Available Techniques (BAT) reference documents related to the Industrial Emissions Directive. CHPs are used during drilling, well installation, production and processing of natural gas.

4.1.6. Cut-off Criteria

No cut-off was applied within the system boundary, apart from the infrastructure which is assumed to be negligible. The system boundary was defined based on the relevance to the goal of the study (all included and excluded processes are listed in Table 4-1). For the processes within the system boundary, all available energy, material and activity data have been included in the model.

In cases where no matching life cycle inventories were available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts. The choice of proxy data is documented in the report and an overview on the proxy data used is given in Annex E.

4.2. Well-to-Tank – Inventory Analysis

4.2.1. Data Collection Procedure

Existing primary data from the NGVA study prepared by *thinkstep* [13] and information from *thinkstep's* GaBi LCI databases [14] and literature were used for the development of the fuel supply chains. The data used were circulated among the consortium partners who were invited to validate the data and to provide feedback and remarks. Additional primary data were collected for maritime LNG bunkering using customised data collection templates, which were sent out by email to the respective data providers in the participating companies. Upon receipt, each questionnaire was crosschecked for completeness and plausibility. If gaps, outliers, or other inconsistencies occurred, *thinkstep* engaged with the data provider to resolve any open issues. The following companies were actively engaged in the data collection process and gave advice based on their individual expertise:

- Exxon Mobil Corporation
- Shell International B.V.
- Total S.A.

All three companies are major LNG as well as oil-based marine fuel suppliers operating globally.

The general data collection procedure is displayed in Figure 4-3.

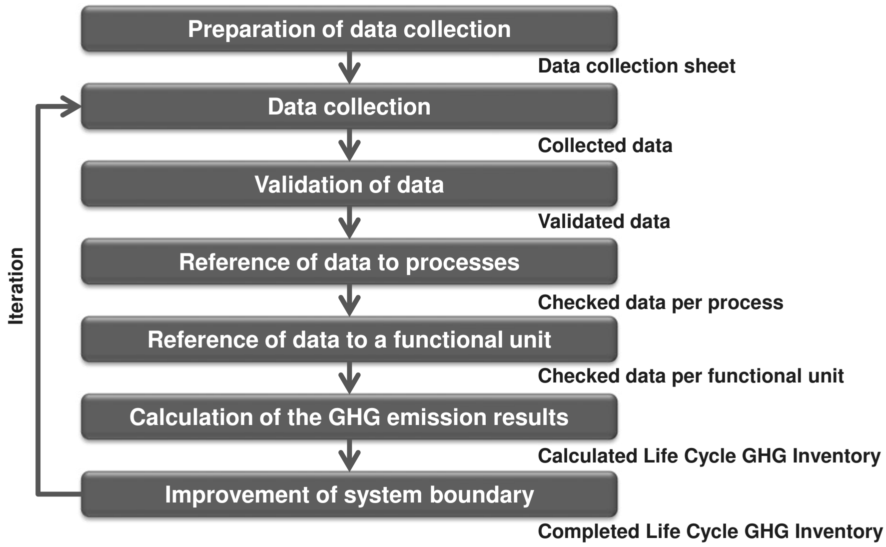

Figure 4-3: Data collection procedure applied by *thinkstep* [26]

The inventory analyses for the LNG supply and the oil-based marine fuel supply are described below.

4.2.2. Inventory Analysis of the LNG Supply

Data for the Natural Gas production and processing of Algeria, Nigeria, Norway and Qatar are the main sources of primary data from the NGVA study prepared by *thinkstep* [13]. The Natural Gas production and processing data for Australia, Indonesia, Malaysia, Trinidad & Tobago are sourced from *thinkstep's* GaBi LCI databases [14]. US data for US unconventional gas production and processing, including data on the latest analyses of fugitive emissions associated with hydraulic fracturing ("fracking"), are provided by Exxon Mobil [27] and literature [28] [29], and data gaps closed by *thinkstep's* GaBi LCI databases [14]. However, all data used in the model were circulated among respective data providers in the participating companies (i.e. Shell [30], Total [31] and Exxon Mobil for the US LNG supply chain [27]) for validation and adapted, if necessary.

The life cycle inventories for the Natural Gas pipeline transport from the gas production and processing fields to liquefaction plants as well as the liquefaction are sourced from *thinkstep's* GaBi LCI databases [14].

The composition of the fleets for the LNG carrier transport is calculated based on the distance and the vessel capacities based on a study published by the International Gas Union (IGU) [32]. Data on fuel consumption and methane emissions of the LNG carrier transport are taken from the NGVA study [13] and *thinkstep*'s GaBi LCI databases [14], crosschecked with [33], [34] and additionally crosschecked with primary data provided by representatives of Shell and Total [30] [31]. The fuel consumption values were crosschecked with [32]. The distances for the LNG imports are calculated based on [35].

Data for LNG terminal operations are taken from the NGVA study [13] and *thinkstep*'s GaBi LCI databases [14]. Shell provided primary data for maritime LNG bunkering [36], [30].

A detailed description of the inventory analysis of the LNG supply and the data sources and data quality can be found in Annex D and Annex E.

4.2.3. Inventory Analysis of the Oil-based Marine Fuel Supply

The GHG emissions data on the country-specific crude oil supply are taken from the study "Global carbon intensity of crude oil production" [37], published in 2018, as it is considered to be the most up-to-date and most reliable public source currently available. The data are calculated based on the "Oil Production Greenhouse Gas Emissions Estimator" (OPGEE) model v2.0 developed by the Stanford University [38] and include all GHG emissions from the exploration, drilling, development, production and extraction, surface processing, and transport to the refinery gate considering onshore and offshore production as well as conventional and unconventional oil. In [37], default values have been used for the crude oil transport and are included in the crude oil production data. Since this study at hand, intends to represent the actual transports from the production country to the region of consumption, the GHG emissions of the transport are subtracted from the total GHG emissions for the crude oil supply [39] and life cycle inventories from *thinkstep's* GaBi LCI databases [14] are used to calculate the GHG emissions associated with the actual crude oil transport by pipeline and oil tanker from the oil production and processing fields to the refinery.

The GHG emissions of the refining and distribution of the oil-based fuel by pipeline from the refinery to the terminal to be used as fuel for ships are sourced from *thinkstep's* GaBi LCI databases [14]. The refinery key parameters[16] are crosschecked with the PRELIM: Petroleum Refinery Life Cycle Model developed by the University of Calgary [40].

4.2.4. Background Data

Background data (e.g., fuels, electricity, materials) are taken from *thinkstep's* GaBi LCI databases [14]. A list of the key background datasets is given in Annex E.

4.2.5. The GHG Models in the GaBi Software System

Based on the collected data from the NGVA study [13], information from *thinkstep's* GaBi LCI databases [14] and literature, the GHG model was developed and set up in the LCA software system GaBi 8. It follows a modular approach. Each module consists of several single underlying processes or other modules. The modules are connected via materials and energy flows, resulting in a hierarchical system of modules representing the complete supply chain with each relevant process step. Each module can be set up and maintained independently. As an example, a screenshot of the

[16] E.g. refinery configuration, conversion rate, crude oil spec, energy use, etc.

module “Liquefied Natural Gas (LNG) Mix” is shown in Figure 4-4 (Sankey diagram) with each box representing another module.

The GHG model:

- allows modular model set-up
- enables the hierarchical structuring of processes
- provides comprehensive analysis functionalities
- provides access to all necessary background data needed.

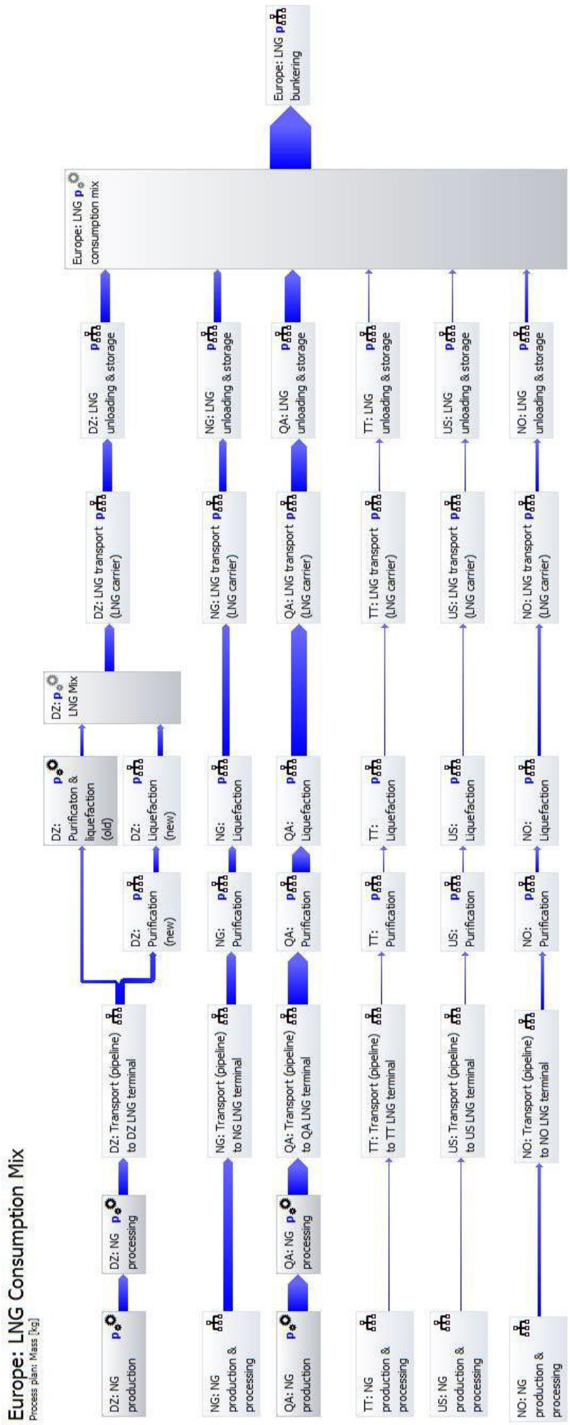

Figure 4-4: GaBi screenshot of the Liquefied Natural Gas Mix (LNG) Mix as modelled (Sankey diagram) (Example: Europe) [26]

The GHG model of the global LNG supply chain consists of 5 modules representing the 5 region-specific LNG supply chains. Each of these region-specific LNG supply chains include the supply chains of 4 to 6 LNG producing countries. Each of these country-specific LNG supply chains countries include modules covering all relevant process steps of the LNG supply chain from Natural Gas production and processing, pipeline transport, purification and liquefaction, LNG carrier transport, LNG terminal operations and storage to LNG bunkering. These modules are set-up generically and allow an easy transfer of the collected region-, country- and process-specific data into the GHG models.

The GHG models of the oil-based marine fuel supply chains are set up in the same way.

4.3. Well-to-Tank – GHG Emissions

4.3.1. Well-to-Tank GHG Emissions of LNG

This section presents the results for the Well-to-Tank GHG emissions of the LNG supply.

It is important to note once again that the reported impact category "Global Warming Potential GWP_{100}" represents impact potentials and not actual observed impacts. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit chosen (relative approach). GHG results are therefore relative expressions only and do not predict actual impacts, exceeding of thresholds, safety margins, or risks. Furthermore, they do not express an effect on any other environmental impacts apart from global warming. As mentioned in section 3.3, the following IPCC AR5 characterisation factors have been used for the main GHG emissions. 1 CO_2, 30 CH_4, 265 N_2O.

The GHG results are displayed for the global LNG supply. The GHG results for the five LNG consumption regions can be found in Annex E. An overview of the GHG results in grams of CO_2-eq per MJ of lower heating value (LHV) delivered to the tank is provided in Figure 4-5. The results are broken down by the main process steps of the LNG supply chain.

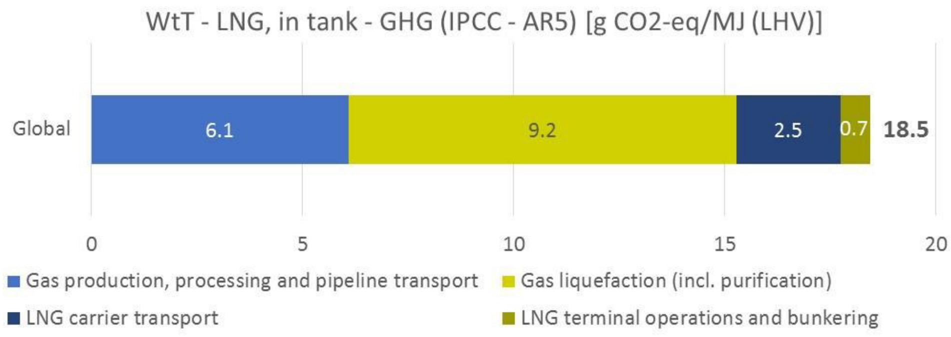

Figure 4-5: Well-to-Tank – GHG Emissions: Global LNG supply – breakdown by main process steps [23]

Table 4-3 presents GHG emissions of the global LNG supply in a corresponding table.

Table 4-3: Well-to-Tank – GHG Emissions: Global LNG supply – breakdown by main process steps [23]

GHG IPCC - AR5 [g CO_2-eq/MJ (LHV)], in tank	Global LNG supply
Gas production, processing and pipeline transport	6.1
Gas liquefaction (including purification)	9.2
LNG carrier transport	2.5
LNG terminal operations and maritime bunkering	0.7
TOTAL LNG	**18.5**

Figure 4-6 displays the same overall results as Figure 4-5 and Table 4-3, but are broken down into the main individual emissions CO_2, CH_4, and N_2O. CO_2 is the main contributor to the GHG emissions, followed by CH_4. N_2O only contributes to a very small extent, and the contributions of other greenhouse gases also included in the life cycle inventory data are orders of magnitude smaller and therefore not shown in the Figure and the Table.

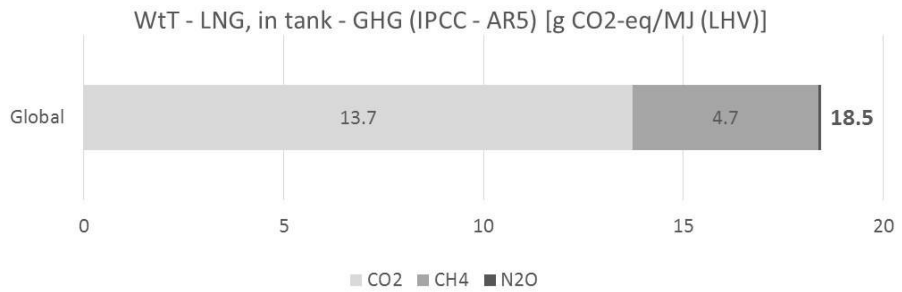

Figure 4-6: Well-to-Tank – GHG Emissions: Global LNG supply – breakdown by main individual emissions [23]

Table 4-4 presents results of the global LNG supply broken down by main individual emissions in a corresponding table.

Table 4-4: Well-to-Tank – GHG Emissions: Global LNG supply – breakdown by main individual emissions [23]

GHG IPCC - AR5 [g CO_2-eq/MJ (LHV)], in tank	Global LNG supply
CO_2	13.7
CH_4	4.7
N_2O	0.1
TOTAL LNG	**18.5**

The key findings of the LNG supply are stated in the following:

- The carbon footprint of the global LNG supply, in tank is 18.5 g CO_2-eq/MJ (LHV).
- The GHG emissions are dominated by gas production, processing and pipeline transport (33 %) and gas liquefaction (including purification) (50 %), followed by LNG carrier transport (13 %) and LNG terminal operations and bunkering (4 %).

- Carbon dioxide is the major contributor to LNG supply chain GHG emissions (74 %), followed by methane (25 %). N_2O only contributes to a very small extent (0.5 %)[17]. Other GHG emissions are taken into account but can be ignored. The CO_2 emissions mainly come from fuel combustion at gas turbines, with small amounts of CO_2 vented during processing and purification of Natural Gas (CO_2-removal) if no carbon capture and storage is applied. The main sources for the CH_4 emissions are fugitive emissions.
- The contributions of other greenhouse gases also included in the life cycle inventory data are orders of magnitude smaller (<0.02 % in total) and therefore excluded from the chart.
- This study focuses on ship-to-ship maritime LNG bunkering. The possible alternatives shore-to-ship and truck-to-ship are also analysed (see section 6.7).

4.3.2. Well-to-Tank GHG Emissions of Oil-Based Marine Fuels

An overview of the GHG results of the current oil-based marine fuels in g CO_2-eq/MJ (LHV) fuel delivered to the tank is provided in Figure 4-7. The results are broken down by the main process steps of the fuel supply chains. The fuel supply chains of $HFO_{2.5}$ and $MGO_{0.1}$ show similar GHG emission profiles. The global GHG emissions for the $HFO_{2.5}$ supply are 6 % less compared with the $MGO_{0.1}$ supply. Compared with the $HFO_{2.5}$ supply, the supply of $MGO_{0.1}$ requires more crude oil feedstock (causing higher GHG emissions for the oil production, processing and transport) as well as more energy intensive refinery processes (causing higher GHG emissions for refining) per MJ (LHV) of fuel. Similar results for $HFO_{2.5}$ and $MGO_{0.1}$ are confirmed by the study "Life Cycle Assessment of greenhouse gas emissions from marine fuels", published in 2018 [41]. The global GHG results are dominated by oil production, processing and transport (67-68 %) and refining (29-31 %). The marine fuel distribution has a low impact on the results (3 %).

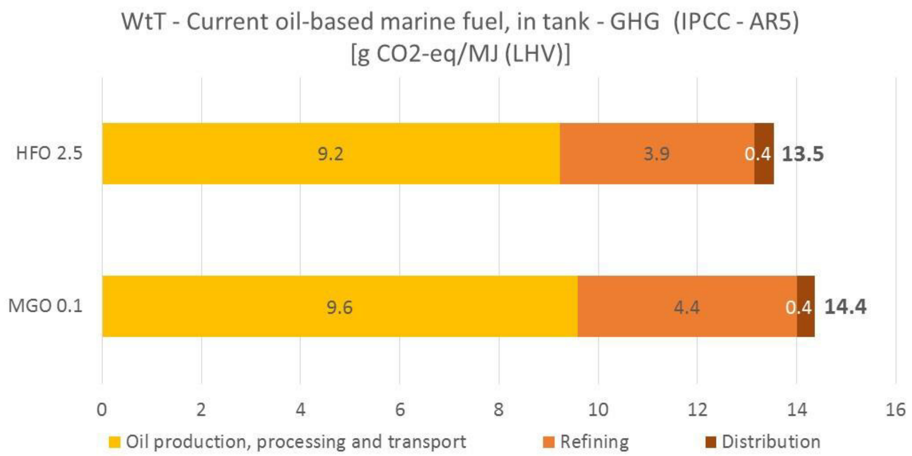

Figure 4-7: Well-to-Tank – GHG Emissions: Current global oil-based marine fuel supply - breakdown by main process steps [23]

Figure 4-8 provides the GHG results for the considered post-2020 scenarios for oil-based marine fuels in g CO_2-eq/MJ (LHV) fuel delivered to the tank. It should be noted that there is a large number of fuels which could be considered for post-2020 regarding different levels of desulphurisation and blending ratios. This study considers the fuels defined by the project consortium (please see Table 3-1). The results are broken down by the main process steps of the fuel supply chains. The GHG emission profiles of the post-2020 scenarios are in the same range. The global results are dominated

[17] N_2O emissions occur during combustion processes within the LNG supply chain and they are included in the background data used. Other GHG emissions, like halogenated organic emissions, are included in the background data (e.g. electricity supply) and thus taken into account.

by oil production, processing and transport (67-68 %) and the refining (29-31 %). The marine fuel distribution has an impact of 3 % on the results. Depending on the amount of crude oil feedstock and the specific refinery processes, the contributions of the main process steps of the fuel supply chains vary per MJ (LHV) of fuel. The GHG result for $MGO_{0.1}$ is the same for post-2020 and today because it is produced in post-2020 in the same way as today. $HFO_{>2.5}$ shows the same GHG emissions as for the current fuel $HFO_{2.5}$, since it is produced in the same way as $HFO_{2.5}$[18]. Exhaust gas cleaning systems at the ships are used for $HFO_{>2.5}$ to meet the SO_x limit. The GHG profile of the $LSFO_{0.5,\ Blend}$ supply is insignificant higher compared with the supply of $HFO_{>2.5}$ due to the additional desulphurisation needed. The supply of $LSFO_{0.5,\ LScrude}$ shows a insignificant better performance than the supply of $HFO_{>2.5}$ due to less desulphurisation within the whole refinery.

A further scenario analysis is conducted on the additional GHG emissions for $LSFO_{0.5,\ Blend}$ which are estimated to be in the range of 2 to 10 %, depending on the blending ratio between residual and distillate fuels [11]. For details, please see section 6.7 "Scenario Analysis on the GHG Emissions for the Supply of $LSFO_{0.5,\ Blend}$".

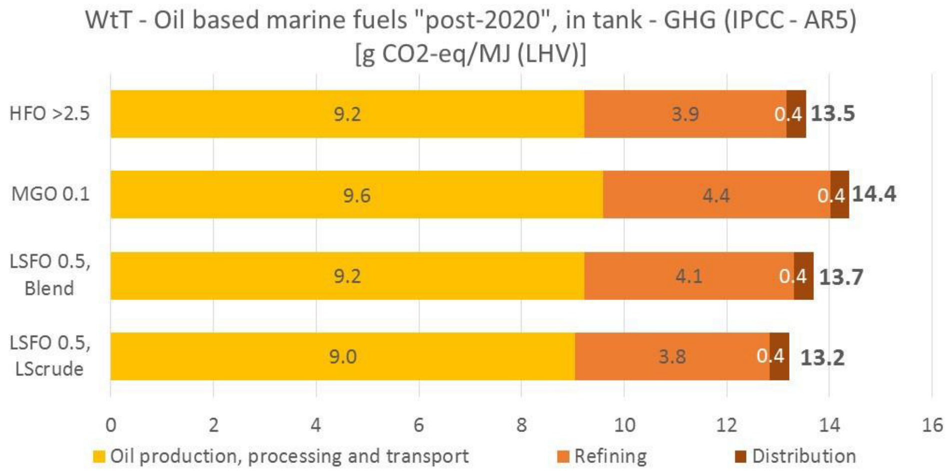

Figure 4-8: Well-to-Tank – GHG Emissions: Global oil-based marine fuel supply "post-2020" - breakdown by main process steps [23][19]

In summary, the calculated global results of the current oil-based marine fuel supply chains and the post-2020 scenarios on oil-based marine fuel supply chains are quite similar, ranging from 13.2 to 14.4 g CO_2-eq/MJ (LHV) fuel. The calculation of the WtT GHG results of refinery products is associated with uncertainties. Different crude oil properties and refinery settings, different levels of desulphurisation and blending ratios, and assumptions made, as well as methodological differences such as different allocation methods can lead to different results. This uncertainty is addressed in a sensitivity analysis in the context of the entire Well-to-Wake life cycle, see section 6.8.3. However, the GHG emissions for oil-based marine fuel supply chains will not change significantly after 2020.

[18] It is very likely that the sulphur content will increase post-2020. CONCAWE, for instance, estimates an increase of the average sulphur content of post-2020 HFO to potentially 4.2 wt. % for European refineries [12]. This is expressed by $HFO_{>2.5}$.

[19] Remember that $LSHO_{0.5,\ Blend}$ and $LSFO_{0.5,\ LScrude}$ are two sample options (scenarios) of many.

4.4. Well-to-Tank – Comparison with Other Studies

Comparison of the WtT GHG Emissions LNG with Other Studies

The GHG results of the global LNG supply presented above were compared with the GHG intensity reported in other public studies. Since some results relate to GHG IPCC AR5 and others to GHG IPCC AR4 (for details of AR4 vs. AR5, see Annex B), the GHG benchmarking is split into two tables for comparability. Table 4-5 shows a comparison of the results with other studies evaluated according to GHG IPCC AR5, while Table 4-6 shows the results based on GHG IPCC AR4. It is important to note that the scopes of the studies differ and therefore the results of the studies are only comparable to a certain extent and with care.

Table 4-5 shows the comparison with the GREET model [42] developed by the Argonne National Laboratory based on GHG IPCC AR5. The GREET model considers the LNG supply (as a transportation fuel) of the United States including LNG from indigenous Natural Gas production (conventional and unconventional Natural Gas) but no LNG imports. Reference year of the data is mainly 2016. Compared with the GREET model, this study at hand calculates 6 % lower GHG emissions for the global LNG supply. After adapting the North American LNG supply of this study (representing the consumption mix of Canada, Mexico and the United States) to 100% US LNG supply, the differences between GREET and this study are smaller, showing 3 % lower GHG emissions for the US LNG supply chain compared with the GREET result. The differences are within acceptable limits considering small differences in the scope, e.g. this study analysis only large-scale LNG production. Summarized, excellent consensus with GREET

Table 4-5: WtT - GHG Emissions: LNG supply - benchmarking (GHG IPCC - AR5) [23]

LNG supply	[g CO_2-eq/MJ (LHV)]
This study (global LNG supply)	**18.5**
This study (100% US LNG supply without imports)	**19.2**
GREET 2018 [42] (US LNG supply)	19.7

Table 4-6 shows the comparison with other studies based on GHG IPCC AR4.

The similarity of the results between this study at hand and the NGVA study is not surprising as data from the NGVA study served as a basis for this study. Small differences in the scope (reference year, LNG consumption mix and distribution) do not have a notable impact on the results for the European LNG supply chains.

The GHG emission results for the European LNG supply in this study are 19 % lower than the GHG emissions of the Exergia study [43]. The Exergia study is based mainly on literature data from 2012. Differences between the results are mainly related to different kind of data for the LNG supply chains (primary data derived from NGVA study versus data from public sources in Exergia) and differences in the scope (reference year, LNG consumption mix and distribution). More detailed information on the debate can be found in the NGVA study in chapter 5.4: Well-to-Tank – Comparison with other Studies. [13].

The JEC-WtW study [3] is based on data mainly from 2010 and considers the European LNG supply for use in vehicles, explaining the differences of 3 % between the results for the European LNG supply (JEC-WtW 19.4 vs. this study 19.9 g CO_2-eq/MJ (LHV).

The TNO - CE Delft study [44] considers the supply of LNG for road transport from Qatar to Europe in 2025. For comparability, the European LNG supply of this study (representing the consumption mix of Europe) is adapted to 100% European LNG supply from Qatar. The GHG emissions of the

European LNG supply in this study are 9 % lower than the results of the TNO - CE Delft study which could be explained by differences in the methodology, scope, data, assumptions, etc.

Eight different pathways for the LNG supply in the United States were analysed in a study published by the ICCT [45] analysing indigenous and imported LNG and differences in LNG liquefaction (small scale and large scale), distribution and storage. The results of the considered pathways vary significantly. More detailed information can be found in the ICCT study, in chapter 2: Analysis of LNG Pathways [45]. The GHG emissions for the North American LNG supply of this study and for the adapted North American LNG supply with 100% LNG supply from the USA are within the range of these results.

Table 4-6: WtT - GHG Emissions: LNG supply - benchmarking (GHG IPCC – AR4) [23]

LNG supply	[g CO_2-eq/MJ (LHV)]
This study (global LNG supply)	**17.7**
This study (North American LNG supply)	**17.9**
This study (100% US LNG supply, without imports)	**18.1**
This study (European LNG supply)	**19.9**
This study (European LNG supply from Qatar)	**15.4**
NGVA 2016 [13] (European LNG supply)	19.9
Exergia 2015 [43] (European LNG supply)	24.6
JEC-WtW 2014 [3] (European LNG supply)	19.4
TNO - CE Delft 2013 [44] (European LNG supply from Qatar)	17.0
ICCT 2013 [45] (US LNG supply)	13.1-33.3

The comparison with other studies reveals that the results are in the same order of magnitude. Differences can be explained by differences in the scope of the studies.

5. Tank-to-Wake Analysis

5.1. Tank-to-Wake – Scope of the Study

The following sections describe the scope of the Tank-to-Wake analysis to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function, functional unit and reference flows, the system boundary, handling of multifunctional processes, and cut-off criteria of the study.

5.1.1. Product System

The product system of the Tank-to-Wake section is the combustion of the fuels described in section 4.1 and its related emissions. It is described in more detail in the following paragraphs.

5.1.2. Product Function and Functional Unit

The function of the Tank-to-Wake product system is the power to serve the transport of goods and/or people by marine ships. The engine energy output expressed in kWh is the property to be used to describe the functional unit. The functional unit is to provide 1 kWh brake power. The reference flow related to the defined functional unit is 1 kWh brake power specific unit. For instance, GHG emissions are expressed in g CO_2-eq/kWh.

The relation to kWh ensures that the main objective of the study, the evaluation of GHG emissions of LNG as marine fuel compared with conventional oil-based fuels is achieved. The evaluation of GHG emissions of the transportation itself (e.g. emissions per cargo and nautical mile) is not within the scope of this study as well as the consideration of different ship applications, e.g. cargo, ferries, cruises.

5.1.3. System Boundary

The Tank-to-Wake process includes the combustion of the defined fuels in marine engines and all auxiliary services needed to run the engine excluding services that are ship specific (such as cabin heating, electricity generation on board, cooling/heating of cargo, etc.). This includes the energy consumption for fuel, gas, oil and coolant pumps and the energy and material needed for the treatment of exhaust gases to comply with emission regulations within and outside ECA regions. These treatment systems are:

- Exhaust Gas Cleaning System (EGCS) (also called: scrubber) to decrease sulphur oxide emissions if needed.
- IMO Tier III-NO_X limit compliant after-treatment systems if needed. This can include Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR).

The Tier III NO_X limit is chosen because it is the most onerous regulation (the direction in which regulation is likely to travel). In addition, Tier II results are also calculated and presented in Annex G.

The study assesses the global warming potential as defined in section 3.3 and the local pollutants described in section 3.4, that occur during the regular operation of the engines. All emissions from the engines are considered including gases from the complete or incomplete combustion process, as well as unburned gases and emissions.

For clarification, the production and end of life (EoL) of the ship are not within the system boundary since this study compares different marine fuels on an engine basis. In general, it can be assumed that the manufacturing and EoL of ships for the different engine technologies are very similar. The GHG emissions of the manufacturing and EoL of the engine themselves is estimated be of minor relevance for the total life cycle Well-to-Wake GHG emissions, considering that ship engines are typically 20-30 years in operation. Table 5-1 summarises the elements that are included and excluded in the Tank-to-Wake part of the analysis.

Table 5-1: System boundary for Tank-to-Wake analysis

Included	Excluded
✓ Use of fuel in marine engines ✓ Emissions from combustion (complete and incomplete) ✓ Auxiliary material needed for the exhaust gas cleaning system (e.g. urea solution for SCR systems) ✓ Emissions that may occur due to the use of exhaust gas cleaning systems (EGCS) ✓ Fuel consumption needed to run fuel, gas, oil and coolant pumps ✓ Fuel consumption needed to run exhaust gas after-treatment systems such as scrubber (only for HFO operation) and SCR or EGR	× Efficiencies of the propulsion system from engine shaft to propeller × Manufacturing and EoL of the engines and exhaust gas cleaning systems × Potential CO_2 emissions occurring from the dilution of SO_X-emissions and their chemical reactions in sea water (when operating an open loop EGCS)[20] × Energy (and related emissions) needed for the removal of waste products (e.g. HFO sludge, sludge from closed loop EGCS, etc.) × Emissions that occur during the switch of LNG to fuel oil operation of dual fuel engines (and vice versa)

Time Coverage

The data considered in this study reflect existing technologies that are available on the market today or within the near future. Potential future improvements are considered as a scenario (see section 6.7). The intended reference year for all primary data collected for marine engines is 2018. As engines entering the market today are typically in operation for several years, the data collected today can be seen as valid for the upcoming years, especially for the considerations with post-2020 fuels.

Technology Coverage

The engine technology covered in the study is described in detail in section 5.2 for all fuels under consideration, including specific characteristics regarding fuel consumption and emissions.

For all applications, a share of 100 % fossil fuels is considered. This enables an equal starting point for comparison with other studies. Hence, the possible bio-shares of existing fuels are not taken into consideration.

The following section provides an outline of the relevant engine technologies. The study includes the most important engine technologies for marine ships. Figure 5-1 shows an overview of the engines and fuels used in shipping in 2015 [17]. More than 70 wt.% of the fuel used in shipping (267 million tons in total including residual and distillate fuel as well as LNG) is burned by 2-stroke slow speed Diesel engines (SSD: 68 wt. % residual fuel, 4 wt. % distillate fuel)[21] followed by 4-stroke medium speed Diesel engines (MSD: 10 wt. % residual fuel, 8 wt.% distillate fuel). The two engine

[20] For more details see section 5.1.5
[21] Residual fuel is mainly HFO, distillate fuel mainly MGO.

technologies hence burn 90 wt. % of the overall fuel. 4-stroke high speed engines (HSD) running on distillate fuels have a share of 6 wt. %. The amount of fuel burned in gas turbines and steam turbines is low compared with the reciprocating engines and accounts for only 2 wt. %.

Due to the high proportion of 2-stroke slow speed and 4-stroke medium speed engine for the marine market, the study focuses on these engine technologies. Nevertheless, high-speed engines and gas turbines are included for completeness.

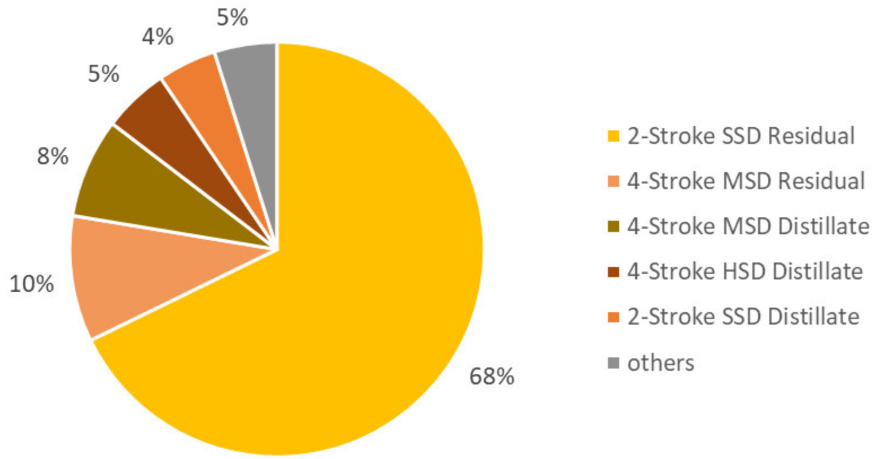

Figure 5-1: Fuel used in marine engines in the year 2015; breakdown by residual and distillate fuels and different engine technologies, based on [17]

2-stroke engines:

2-stroke engines are mainly slow speed engines with engine speeds below 300 revolutions per minute (rpm) [46]. They have the highest efficiency among marine reciprocating engines and are the most common engine in marine propulsion. Due to the high engine efficiency and high power, 2-stroke engines are mainly used for large ocean-going cargo ships. The engines considered in the study are dual fuel engines (DF) that can run on oil-based fuels (HFO, LSFO, or MGO) and on LNG, and can also be differentiated between a high and low-pressure injection systems. Depending on the size of the bore and number of cylinders, 2-stroke engines cover a range from below 5 up to 75 MW. When running on oil-based fuel, the combustion is based on a Diesel combustion cycle[22]. In LNG operation engines can either of two different combustion cycles:

- Engines running in a Diesel cycle (SS-Diesel-DF) inject the gas in the compression stroke (hence a high-pressure injection system is needed) and ignite it with a small amount of pilot fuel. The most prominent engine in the market is the MAN ME GI engine. [47]
- Engines running in an Otto cycle (SS-Otto-DF) mix the gas with the air prior to the cylinder and ignite it with a small amount of pilot fuel. Win GD offers Otto cycle dual fuel engines that use a low-pressure injection system (e.g. the X-62 DF, X-72 DF etc).

The high-pressure engines have a good fuel economy. However, after-treatment systems are needed to be able to comply with the IMO Tier III NO_X limits in both oil-based fuel and LNG operation. The low-pressure Otto-DF engine complies with the Tier III limits without after-treatment when using LNG [47].

[22] A more detailed description of the differences between Diesel and Otto cycle combustion in marine engines can be found in [47].

4-stroke engines:

4-stroke engines can be distinguished by different characteristics. Medium speed (MS) engines normally range between 300 and 1000 rpm, while high speed (HS) operate above 1000 rpm [46]. MS engines typically cover the power range up to 20 MW whereas HS engines are provided for the lower one-digit MW range.

The latter usually have lower efficiencies but tend to be used in applications where engine response is more important. 4-stroke engines have a different ship design/dimensions and are more operational flexible compared with 2-stroke engines. 4-stroke medium speed engines are typically used in cruise ships and ferries. Within medium speed engines, there are single and dual fuel (DF) engines. Dual fuel engines can run on oil-based fuel and on LNG. Depending on the fuel used, the engines run on a Diesel combustion cycle (oil-based fuel) or on an Otto cycle (LNG) (see also Table 5-2). The most prominent manufacturers of 4-stroke medium speed dual fuel engines are MAN, Wärtsilä, Caterpillar and HiMSEN [47]. Single fuel engines are either designed for operation with oil-based fuels (CI = compressed ignition, Diesel combustion cycle) or LNG operation (SI = spark ignited combustion, Otto combustion cycle). The high-speed engines investigated in this study are limited to single fuel engines (CI for oil-based fuel and SI for LNG).

When running on oil-based fuels, all engine technologies need after-treatment systems to comply with the Tier III limits. When running on LNG, no treatment system is needed as the formation of NO_X is lower.

In modern reciprocating engines (2-stroke and 4-stroke), part of the heat produced by the engine is used for fuel treatment. Additionally, the heat in the exhaust gas can be used by waste heat recovery systems for the generation of electricity for on-board services. However, as the study is focused on the main engine only and not on the ship, waste heat recovery systems are not included [23].

Simple cycle gas turbines (GT):

Gas turbines can burn either low sulphur oil-based fuel (assumed as $MGO_{0.1}$) or LNG. Due to the combustion relying on the Brayton cycle, the efficiency of gas turbines is lower than that of the reciprocating engines described above. Due to the high energy density, gas turbines are mainly used in applications where installation space is limited, e.g. fast ferries. For both LNG and $MGO_{0.1}$, Tier III limits can be met without additional after-treatment.

Combined cycle gas turbines (CCGT):

Combing a gas turbine with a steam turbine increases the overall efficiency of the system. Hence combined cycle gas turbines have an efficiency similar to that of reciprocating engines. Again, compliance with the IMO Tier III limit is achieved for both MGO and LNG operation.

Engines and marine fuels considered:[24]

As presented, Table 3-2 shows the engine technologies explained above in combination with the fuel which can be burned in these engines. The relevant combinations are marked with x and are mainly related to the technical capabilities of the systems at hand. E.g. high-speed engines as well as gas turbines have higher restrictions regarding fuel quality and can only run on MGO or LNG. Therefore, HFO operation is not considered for these engines.

To be able to adequately compare oil-based fuel operation to gas operation the engines are clustered as shown in Table 5-2 based on the underlying combustion cycle. Running on oil-based fuels, the 2-stroke slow speed engines both (low-pressure and high pressure) run on a Diesel combustion cycle

[23] A paper by MAN suggests that the overall efficiency (engine + waste heat recovery system) could be increased by 5 % [79].
[24] Steam turbines are not analysed in this context due to the small number of vessels in operation and less common technology. However, within the LNG supply chain, steam turbines are considered as engine technology in LNG carriers in this study. The use of natural gas in fuel cells is also not investigated within this study.

and are hence aggregated to one reference value[25]. When running on LNG, the combustion cycle is different as mentioned above and the engines are distinguished accordingly. As both 4-stroke medium speed DF and CI engine run on a Diesel combustion cycle when using oil-based fuels, efficiencies are comparable and hence the consumption and emission data are aggregated to one reference value which can be compared with LNG SI and DF engines. 4-stroke HS engines as well as GT and CCGT are as described above only evaluated on $MGO_{0.1}$ and LNG. A brief explanation of the calculation of the engine efficiency based on the fuel consumption is given in Annex B.

Table 5-2: Clustered engine technology overview by fuel type

Oil-based fuels		Gas-based fuel
HFO, $LSFO_{0.5, Blend}$, $LSFO_{0.5, LScrude}$	$MGO_{0.1}$	LNG
2-stroke SS-Diesel		2-stroke SS-Diesel-DF
		2-stroke SS-Otto-DF
4-stroke MS-Diesel-CI/DF		4-stroke MS-Otto-SI
		4-stroke MS-Otto-DF
not applicable	4-stroke HS-Diesel-CI	4-stroke HS-Otto-SI
not applicable	GT	GT
not applicable	CCGT	CCGT

Geographical Coverage

The maritime industry operates on a global scale and the data collected from the engine manufacturers are globally on duty and hence representative.

5.1.4. Multifunctional Processes and Allocation Rules

There is no multifunctional process in the Tank-to-Wake part of the assessment for marine engines as the only output of the system is propulsion energy.

5.1.5. Cut-off Criteria

As summarised in section 5.1.3, the system boundaries are defined based on relevance to the goal of the study.

GHG impacts that potentially occur as a result of a chemical reaction of used Exhaust Gas Cleaning System (EGCS) cleaning water (on open loop EGCS) and sea water are neglected in this study.[26] Emissions that occur due to the removal of waste products coming from the EGCS or from fuel treatment are not included as they are dependent on the actual technology used onboard a ship. Non-methane hydrocarbon emissions from LNG are neglected due to their negligible contribution to the GWP on a Well-to-Wake basis (less than 0.5 %).

[25] For a more detailed explanation of the aggregation process, see section 5.2.

[26] A scrubber cleans the exhaust gases of SO_X emissions by using a solvent that is sprayed into the exhaust gas. The solvent reacts with the sulphur oxide emissions to form sulphuric acid. In open-loop EGCS (scrubber) sea water is used as solvent. The acidic water is discharged to the sea. According to [66] the discharged scrubber acidic water triggers a reaction with bicarbonates creating CO_2 which is released to the atmosphere.
According to [64], the molar ratio of SO_X released during combustion (and eventually discharged as acidic water into sea) to CO_2 released to the atmosphere is assumed to be 1.7 (resulting in 1.17 g CO_2 / g SO_2 [23]) which shows that with the sulphur contents assumed within this study, this effect is minor. This represents a conservative approach with respect to the potential benefits of LNG, as the CO_2 emissions would increase the GHG emissions of oil-based fuels and not LNG fuelled vessels.

5.2. Tank-to-Wake – Inventory Analysis

5.2.1. Data Collection Procedure

For the Tank-to-Wake analysis, primary data were collected from engine manufacturers and ship operators (for EGCS) using customised data collection questionnaires (spreadsheets), which were distributed by email to the data providers in the participating companies. The collected data include consumption and emission data for engines running on LNG, MGO and HFO for 25 %, 50 %, 75 % and 100 % of the maximum continuous rating of the engine (engine load). A webinar was organised introducing the questionnaire to the data providers. Upon receipt by *thinkstep*, each questionnaire was crosschecked for completeness and plausibility. If gaps, outliers, or other inconsistencies were identified, *thinkstep* engaged with the data provider to resolve such issues bilaterally. The following companies provided primary Tank-to-Wake information directly and gave advice based on their individual expertise:

- Carnival Corporation & plc
- Caterpillar MaK
- Caterpillar Solar Turbines
- GE Aviation
- MAN Energy Solutions SE
- MTU Friedrichshafen GmbH
- Winterthur Gas & Diesel Ltd.
- Wärtsilä Oyj Abp

Experts from DNV-GL were included for their expertise in marine energy management and for crosschecking of the consumption mark-ups for auxiliary services as described in the following section.

The data were provided in brake power specific units (kWh) per individual engines and per engine load point and clustered as shown in Table 5-2. The individual data points are averaged for the different engine load points resulting in one average value for each load point and each engine technology. For reciprocating engines, the load points are further weighted according to the IMO E2/E3 cycle as described in Annex B. For gas turbines with simple and combined cycle, the 75 % and 100 % load point are averaged as the IMO E2/E3 cycle does not apply here. All data refer to the LHV listed in Table B-5 and Table B-6 in Annex B and are shown in detail in Table 5-8 to Table 5-12.

The engine manufacturers provided between 1-3 representative datasets each representing consumption and emission data of one individual engine out of their portfolio. Table 5-3 shows an overview of the number of datasets that were collected for the different engine technologies.

Table 5-3: Overview of the collected datasets of the engine manufacturers separated in fuel and engine technology

	Oil-based fuels		Gas-based fuel
	$HFO_{2.5}$	$MGO_{0.1}$	LNG
2-stroke SS-Diesel-DF or Otto-DF	3	6	3 + 3
4-stroke MS-Diesel-CI	2	2	*not applicable*
4-stroke MS-Diesel-DF or Otto-DF	2	2	4
4-stroke MS-Otto-SI	*not applicable*	*not applicable*	2
4-stroke HS-Diesel-CI	*not applicable*	1	*not applicable*
4-stroke HS-Otto-SI	*not applicable*	*not applicable*	1
Gas turbine simple cycle (GT)	*not applicable*	2	2
Gas turbine combined cycle (CCGT)	*not applicable*	2	2

For the 2-stroke slow speed engines, six datasets were provided for the operation on MGO and three for the operation of HFO. Three datasets each were provided for the two LNG technologies (Diesel-DF and Otto-DF). As described in section 3, 4-stroke medium speed CI and DF engines are aggregated as one engine technology when using oil-based fuels. In total eight datasets have been provided equally distributed for HFO and MGO operation. For LNG operation, four datasets for DF engines and two datasets for SI engines have been used. Data for the high-speed engine were provided by one OEM for MGO and LNG operation. The two gas turbine suppliers each provided one representative dataset for MGO and LNG in simple and combined cycle operation. In total, 39 engine specific datasets have been collected and evaluated.

5.2.2. Tank-to-Wake – Inventory Analysis

In the following section, the inventory of the Tank-to-Wake analysis is described in detail explaining the datasets which comprise test-bed data (data from engine laboratories) for marine engines running on LNG, MGO and HFO.

A general description on the different data collected broken down by the specific fuel consumption, CH_4, N_2O, NO_X, PM and SO_X emissions including relevant calculations and assumptions is provided followed by the description of the actual data collected.

General Description of the Data Collected

Fuel consumption (SFOC):

Due to differing test-bed capabilities, not all engine manufacturers were able to provide fuel consumption and emission data on MGO and HFO. In these cases, HFO data is derived from MGO consumption data, the ratio of the LHV (Annex B, Table B-6) of $HFO_{2.5}$ and $MGO_{0.1}$ is used. For the analyses of $LSFO_{0.5,\ Blend}$ as well as $LSFO_{0.5,\ LScrude}$, consumption data is derived from $HFO_{2.5}$ in the same manner (Annex B, Table B-6).

For oil-based marine fuel operation, delivered data are in most cases not separated into pilot and main fuel consumption as the pilot fuel consumption is included in the main fuel consumption.

As described in section 5.1.3, the auxiliary services needed to run the main engine are included in the system evaluated. However, the pump setup differs from engine to engine and is not always included in the test-bed data. Therefore, mark-ups representing the additional energy consumption needed for their operation are derived [48] [49] [50] [51] [52] [53] [54] [55] and applied if not already included in the data provided (Table 5-4). The energy needed for oil and fuel supply is included in the figure “general pumps”. The high-pressure LNG pump is only needed for the operation of the 2-stroke SS Diesel-DF engine (see section 5.1.3) due to the high injection pressure (300 bar).

Table 5-4: Energy consumption for auxiliary services needed to run the main ship engine [48] [49] [50] [51] [52] [53] [54] [55][27]

	Increase in fuel consumption (SFOC)	DSI
General pumps for reciprocating engines	+ 1.0 %	primary
LNG pump for 2-stroke SSD engine[28]	+ 0.5 %	primary
Pumps for GT operation	+ 0.2 %	primary
Pumps for CCGT operation	+ 0.5 %	primary

Methane emission (CH_4):

Methane (CH_4) emissions are not always directly measured on the test-bed and are mostly part of unburned hydrocarbon (UHC) emissions. For LNG operation it is assumed that 90 % of UHC emissions are CH_4-emissions. This value is based on the experience of the engine manufacturers and can vary between 80 and 95 % ([50], [53]) as it is highly dependent on the gas quality and hence the methane content of LNG. The remaining 10 % unburned hydrocarbon are potentially also contributing to the GWP, however, are cut-off as they are estimated to contribute less than 0.5 % to the GHG WtW emissions when using the VOC characterisation factor taken from IPCC AR5 [15].

Nitrous oxide emission (N_2O):

Nitrous oxide (N_2O) emissions result from the combustion of fuels and are related to the fuel used. Typically, these emissions are not measured on the test-bed and hence have been derived using emission factors related to the fuel consumption as shown in Table 5-5:

Table 5-5: N_2O Emissions factor per fuel [56]

Fuel	EF N_2O [g/g fuel]	DSI
HFO, $LSFO_{0.5, Blend}$, $LSFO_{0.5, LScrude}$	0.00016	literature
$MGO_{0.1}$	0.00015	literature
LNG	0.00011	literature

Nitrogen oxide emission (NO_X):

As the exhaust gas after-treatment system is not necessarily manufactured by the engine OEM, some OEMs were not able to provide Tier III data for the engines running on oil-based marine fuels. Hence, assumptions for the after-treatment system have to be used. The SCR system is chosen as the main reference case for engines running on oil-based marine fuel. This included data for urea solution consumption (a 32.5 % urea solution is used to neutralise NO_X emissions), as well as additional fuel consumption ([49], [51]) due to the operation of the SCR system which were derived from existing primary engine manufacturers datasets (see Table 5-6). NO_X-emissions in these cases are assumed to be on the IMO limit (Annex B, Table B-2) for the respective engine technologies. As seen in Table 5-6, the use of SCR is a trade-off between fuel and urea consumption. Increased fuel consumption

[27] For the fuel preparation and heating, no data are collected since the energy demand is rather small and similar between gas and oil-based marine fuel operation [54] [53]. Other studies [66], also neglect the energy needed for fuel preparation. A calculation based on the fuel consumption of the MAN 6G90ME10.5 engine running on HFO [71] assuming a needed temperature increase of 80°C (50°C fuel tank temperature to 130°C injection temperature) results in additional main engine power of 0.8 % in the IMO E2/E3 cycle. As this is expected to be similar for LNG fuelled engines, this is not considered in the study.

[28] As the 2-stroke SSD engine uses a high-pressure injection system, the energy needed to increase the gas pressure is higher in comparison to the other engine technologies. Therefore, an additional 0.5 % is added to the 1.0 % for general pumps.

enables the operation of less urea and vice-versa. For $LSFO_{0.5,\ Blend}$ and $LSFO_{0.5,\ LScrude}$, NO_X emissions are assumed to be the same as with HFO.

Table 5-6: Assumptions for Tier III (ECA) operation with oil-based marine fuels based on data from [50] and [51]

	Unit	IMO E2/E3 Cycle	DSI
2-stroke engines			
Fuel consumption	[% of SFOC]	+ 0.4 %	primary
32.5 % urea solution	[g/kWh]	20.6	primary
4-stroke engines			
Fuel consumption	[% of SFOC]	+ 0.6 %	primary
32.5 % urea solution	[g/kWh]	15.7	primary

For the 2-stroke slow speed Diesel-DF engine running on LNG, MAN provided data for their EcoEGR system [49]. Here, combustion gases are cooled and recirculated back into the combustion chamber. By doing this, part of the oxygen of the intake air is replaced by CO_2 which has a higher heat capacity, thus reducing the peak temperature of the combustion process and hence reducing the formation of NO_X[29] [57]. At 2-stroke slow speed Diesel-DF engine, EcoEGR systems are used instead of a SCR system.

Particulate matter emission (PM):

Particulate matter emissions where supplied by most OEMs as total PM emissions and not classified in different particle sizes due to data availability. Where no data is available, PM is stated as “not available”. As for NO_X emissions, PM emission for $LSFO_{0.5,\ Blend}$ and $LSFO_{0.5,\ LScrude}$ are assumed to be the same as with HFO.

Sulphur oxide emission (SO_X):

SO_X emissions are directly linked to the sulphur content of the fuel. SO_X emissions are therefore derived from the fuel consumption using a stochiometric approach assuming all sulphur reacts to SO_2.

$$S + O_2 \rightarrow SO_2$$

This means one gram of S in the fuel results in two grams of SO_2. For HFO with an assumed sulphur content of 2.5 wt. % (global average), an EGCS is needed to be able to comply with the IMO 2020 global sulphur cap (MARPOL convention Annex VI). On-board measurement data from [58] are used (Table 5-7) and applied on the inventory of the engines running on HFO when evaluating the EGCS operation. This leads to the following changes in fuel consumption and pollutant emissions.

Table 5-7: Resulting fuel consumption and emission altering due to the operation of an open-loop EGCS when running on HFO [58]

	Increase due to EGCS operation	DSI
Fuel consumption	+ 1.0 %	primary
SO_X	- 97.7 %	primary
NO_X	+ 1.5 %	primary
PM	- 45.7 %	primary

[29] For more information regarding the influence of NO_X reduction technologies on WtW GHG emissions, see Annex G.

The measured EGCS is an open-loop scrubber installed on a Wärtsilä 8L46CR 8.4 MW engine running on HFO [58]. Other technologies such as closed-loop, hybrid or dry Exhaust Gas Cleaning System (scrubber) are also available in shipping and analysed in section 6.7. However, open-loop EGCS (scrubbers) are the most widely used technology making up more than 63 % of the EGCS installed or on order [59].

PM and SO_X are both aerosols emissions coming from different sources. SO_X emissions are a result of the reaction of oxygen with the sulphur bound in the fuel. PM emissions contain all sorts of particles leaving the engine due to impurities of the fuel or the intake air. The water used in ECGS systems sticks to these aerosols resulting in a reduction of both PM and SO_X-emissions.

Summarised, Table 5-7 can be seen as a conservative approach from an LNG perspective, since fuel consumption increases at HFO fuelled engines ranges from 1 to 4 %. Higher increases in the fuel consumption at HFO fuelled engines are addressed by scenario analyses in section 6.7.

Inventory of the Engines Investigated

The primary data which were supplied by the engine manufacturers (OEMs) mentioned above are shown below. The data represent the averaged data among the different engine technologies including SCR or EcoEGR is the case of the 2-stroke slow speed diesel DF engine, if applicable. Pilot fuel consumption is added to the main fuel consumption for the operation of oil-based marine fuels. For LNG operation, $MGO_{0.1}$ is used as pilot fuel where needed.

The data shown in Table 5-8 to Table 5-12 are primary data provided by the engine manufacturers if not stated otherwise. They include the assumptions made for fuel, gas, oil and coolant pumps as well as consumption data for SCR operation were applicable (taken from Table 5-4 to Table 5-6). The fuel consumption and emission data resulting from the operation of the EGCS when using $HFO_{>2.5}$ (Table 5-7) are also applied in the GHG model but not explicitly shown here. Hence, the data below represent the fuel consumption (including mark-ups) and direct emissions of the engines. All data is related to compliance with the IMO Tier III NO_X limits.

2-stroke slow speed engines:

The primary data collected for the 2-stroke engines are shown in Table 5-8 broken down by the fuel used and the combustion cycle. HFO fuel consumption data is scaled up from MGO as described above as no data were provided.

For compliance with the IMO Tier III NO_X-limits the operation of a SCR system is applied as described in Table 5-6 for the combustion of oil-based marine fuels. For LNG operation, EcoEGR data [49] is used for the Diesel-DF engine to comply to the IMO Tier III limits. The Otto-DF engine complies to the IMO Tier III limits without after-treatment.

Both LNG powered engines have comparable fuel consumption of around 147 g/kWh (combined main and pilot fuel). Methane slip of the Diesel-DF engine is stated by MAN as 0.1 % of the LNG main fuel consumption. The methane slip of the Otto-DF engine is derived from the collected data as 1.5 % in the IMO E2/E3 cycle.

PM emissions were not provided as PM measurement is not standard for such big engines and hence are marked as not available (n.a.).

Table 5-8: Tier III fuel consumption and emission data (primary) for 2-stroke slow speed engines based on the IMO E2/E3 cycle [53], [49], (est. = estimated)

	Oil-based fuels			Gas-based fuel	
g/kWh	$HFO_{2.5}$	$MGO_{0.1}$	$LSFO_{0.5}$ LScrude or Blend	LNG	LNG
Combustion cycle		Diesel		Diesel-DF	Otto-DF
Main fuel consumption	184.8	174.0	181.2_{est}	141.3	145.1
Pilot fuel consumption	-	-	-	6.4	1.5
Urea solution consump.	20.6	20.6	20.6_{est}	-	-
CH_4 absolute *CH_4 relative*	-	-	-	0.14 *0.1 %*	2.10 1.5 %
N_2O	0.029	0.026	0.028_{est}	0.016	0.016
SO_X	9.15	0.34	1.79_{est}	0.01	0.003
NO_X	3.40_{est}	3.40_{est}	3.40_{est}	3.40_{est}	0.88
PM	n.a.	n.a.	n.a.	n.a.	n.a.

4-stroke medium speed engines:

4-stroke medium speed engines have a higher fuel consumption due to the lower engine efficiency compared with 2-stroke slow speed engines. This is the case for all fuel types.

The data for the oil-based fuels are based on an aggregation of datasets including measured fuel, urea consumption and resulting NO_X emissions and datasets complying to IMO Tier III including the assumptions made in Table 5-4 to Table 5-6.

Both LNG powered engines have similar LNG fuel consumption with the DF engine needing additional pilot fuel. Methane slip for the SI engine is 1.3 % of the LNG consumption. DF engines are sensitive to methane slip as they are designed to also run on oil-based marine fuels alone. The respective CH_4 emissions make up 2.5 % of the LNG fuel consumption.

Table 5-9: Tier III fuel consumption and emission data (primary) for 4-stroke medium speed engines based on the IMO E2/E3 cycle [49], [54], [51] (est. = estimated)

	Oil-based fuels			Gas-based fuel	
g/kWh	$HFO_{2.5}$	$MGO_{0.1}$	$LSFO_{0.5}$ LScrude or Blend	LNG	LNG
Combustion cycle		Diesel		Otto-SI	Otto-DF
Main fuel consumption	197.5	184.7	$193._{est}$	155.8	156.5
Pilot fuel consumption	-	-	-	-	2.8
Urea solution consump.	15.7	15.7	15.7_{est}	-	-
CH_4 absolute *CH_4 relative*	-	-	-	2.00 1.3 %	3.84 *2.5 %*
N_2O	0.031	0.027	0.031_{est}	0.017	0.017
SO_X	9.87	0.37	1.92_{est}	0.00	0.01
NO_X	2.55	2.55	2.55_{est}	1.20	1.96
PM	1.231	0.173	1.231_{est}	0.008	0.016

4-stroke high speed engines:

Table 5-10 shows the consumption and emission data for 4-stroke high speed engines that were delivered. As mentioned above, these engines only run on low-sulphur fuel and hence data were delivered for $MGO_{0.1}$ and LNG operation. Due to data availability, no Tier III data were supplied when running on $MGO_{0.1}$. Therefore, the assumptions described in Table 5-6 are applied on the Tier II data to be able to compare the two engines.

Fuel consumption of LNG is 196.2 g LNG/kWh with a methane slip of 1.7 %. PM data were not provided for 4-stroke high speed engines.

Table 5-10: Tier III fuel consumption and emission data (primary) for 4-stroke high speed engines based on the IMO E2/E3 cycle [50]

	Oil-based fuel	Gas-based fuel
g/kWh	$MGO_{0.1}$	LNG
Combustion cycle	Diesel	Otto-SI
Main fuel consumption	219.6	196.2
Pilot fuel consumption	-	-
Urea solution consumption	15.7	-
CH_4 absolute ***CH_4 relative***	-	3.25 *1.7 %*
N_2O	0.033	0.022
SO_X	0.44	0.00
NO_X	2.01	1.51
PM	n.a.	n.a.

Gas turbines in simple and combined cycle:

The following tables show the fuel consumption and emissions data for gas turbines in simple (GT, Table 5-11) and combined cycle (CCGT). Table 5-12 cycle for $MGO_{0.1}$ and LNG operation. As mentioned above the data are averaged values of the 75 % and 100 % engine load point. Pilot fuel is not used in any of the gas turbine applications.

In gas turbines, methane slip is small with 0.04 % (GT) respectively 0.03 % (CCGT) of the LNG consumption.

Gas turbines running on $MGO_{0.1}$ or LNG are both compliant to IMO Tier III NO_X-limits without further after-treatment systems.

Table 5-11: Tier III fuel consumption and emission data (primary) for simple cycle gas turbines (GT) based on the average of 75 and 100 % engine load [48], [52]

	Oil-based fuel	Gas-based fuel
g/kWh	$MGO_{0.1}$	LNG
Combustion cycle	Brayton simple (GT)	
Main fuel consumption	247.2	215.9
Pilot fuel consumption	-	-
Urea solution consumption	-	-
CH_4 absolute ***CH_4 relative***	-	0.08 *0.04 %*
N_2O	0.037	0.024
SO_X	0.49	0.00
NO_X	1.59	1.11
PM	0.124	0.055

Table 5-12: Tier III fuel consumption and emission data (primary) for combined cycle gas turbines (CCGT) based on the average of 75 and 100 % engine load [48], [52]

	Oil-based fuel	Gas-based fuel
g/kWh	$MGO_{0.1}$	LNG
Combustion cycle	Brayton combined	
Main fuel consumption	174.4	145.3
Pilot fuel consumption	-	-
Urea solution consumption	-	-
CH_4 absolute ***CH_4 relative***	-	0.05 *0.03 %*
N_2O	0.026	0.016
SO_X	0.35	0.00
NO_X	1.17	0.77
PM	0.088	0.038

As of today, the application of the combined cycle gas turbines in ship operation is limited to a few vessels.

5.2.3. Background Data

The GHG impact of the production of the urea solution (mixture of 32.5 % urea and 67.5 % deionised water) that is needed for the operation of the SCR system is taken from *thinkstep's* GaBi LCI databases [14]. A list of the key background datasets is given in Annex E.

5.2.4. The GHG model in the GaBi Software System

Figure 5-2 shows the TtW model that was set up in the GaBi software. It includes the combustion part of the respective engine (shown for the 2-stroke Slow Speed Diesel-DF). In this process, the consumption and emission data described above are implemented. For each engine technology as clustered in Table 5-2 and each fuel used, one model is set-up resulting in 23 engine models.

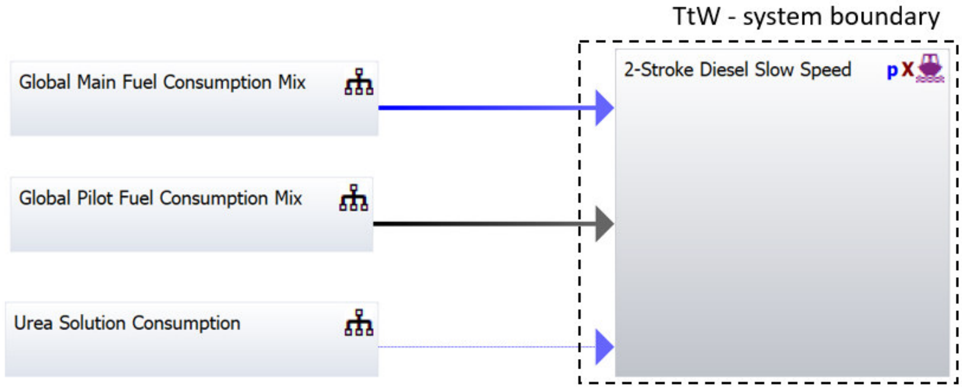

Figure 5-2: GaBi screenshot of the combustion as modelled (Sankey diagram) (Example: 2-stroke slow speed Diesel-DF engine) [26]

5.3. Tank-to-Wake – Local Pollutant Emissions of Marine Fuels

In contrast to greenhouse gases, the location of where local pollutants are emitted matters. This aspect has been addressed by the introduction of emission control areas for SO_X (also addressing PM) and NO_X. For this reason, the evaluation of local pollutants within this study is restricted to use phase of the life cycle, meaning the combustion of the fuel and is therefore addressed in the Tank-to-Wake section.

In the following paragraphs the pollutant emissions covered in this study are investigated by analysing the data described in the inventory analysis in section 5.2.2. SO_x, NO_X and PM emissions are the same values as shown in Table 5-8 to Table 5-12 for $HFO_{2.5}$, $MGO_{0.1}$ and LNG operation. For the case of the operation of $HFO_{>2.5}$ with an ECGS, the emissions are reduced under consideration of Table 5-7. $LSFO_{0.5}$ emissions are estimated to be the same as $HFO_{2.5}$ emissions apart from SO_X which is derived by the sulphur content of the fuel.

5.3.1. Tank-to-Wake – Local Pollutant Emissions 2-stroke Slow Speed Engines

Table 5-13 shows the local pollutant emission weighted according the IMO E2/E3 cycle for 2-stroke slow speed engines running on different fuels.

The SO_X emissions are directly linked to the fuel consumption and the sulphur content of the fuel. Hence high sulphur fuels produce high sulphur oxide emissions. When using an EGCS, SO_X emissions are reduced by around 98 % (see Table 5-7) and are in the same order of magnitude as the emissions in $MGO_{0.1}$ operation. The sulphur oxide emissions of LNG powered engines are rather insignificant as the sulphur content of LNG is assumed to be zero and therefore – if present – are coming from the combustion of the pilot fuel.

Data provision for nitrogen oxide emissions for the operation of oil-based fuels in Tier III mode were limited, hence all data set are based on the worst-case assumption of being on the Tier III threshold of 3.40 g NO_X/kWh for engines below 130 rpm (see Annex B). The Otto-DF engine running on LNG shows the lowest NO_X emissions.

PM data were not provided for any of these engines.

Table 5-13: Tank-to-Wake - Local pollutant emissions of 2-stroke slow speed engines [23], [53], [49] (est. = estimated)

	Oil-based fuels				Gas-based fuel	
g/kWh	$HFO_{2.5}$[30]	$MGO_{0.1}$	$HFO_{>2.5}$ + EGCS	$LSFO_{0.5}$ LScrude or Blend	LNG	LNG
Combustion cycle			Diesel		Diesel-DF	Otto-DF
SO_X	9.15	0.34	0.21	1.79_{est}	0.01	0.003
NO_X	3.40_{est}	3.40_{est}	3.40_{est}	3.40_{est}	3.40_{est}	0.88
PM	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

5.3.2. Tank-to-Wake – Local Pollutant Emissions 4-stroke Medium Speed Engine

The dual fuel 4-stroke medium speed engine running on LNG shows minor sulphur oxide emissions which are caused by the small amount of pilot fuel burned. The spark ignited pure gas engine (SI) shows no sulphur oxide emissions.

NO_X emissions of engines running on oil-based fuels (Diesel combustion cycle) are close to the average IMO Tier III NO_X limit as reduction of NO_x tends to increase fuel consumption of the engine or increases the amount of urea solution needed which engine manufacturers try to avoid. The NO_X emissions of LNG powered engines are below the IMO Tier III limit even though no after-treatment system is applied here. The main reason is the combustion based on the Otto cycle and the resultant lower peak temperatures (see section 5.1.3).

Particulate matter emissions are highest for the heavy fuel oil with 1.231 g PM/kWh. The cleaning process of an EGCS tends to reduce PM emissions as well (see Table 5-7) reducing it to around half of the original engine combustion emissions. PM emissions of $MGO_{0.1}$ are 86 % lower than PM emissions of HFO (0.173 versus 1.231 g PM/kWh). With engines running on LNG, PM emissions are reduced by 90-96 % to below 0.02 g PM/kWh (DF engine) and below 0.01 g PM/kWh (SI engine) respectively.

Table 5-14: Tank-to-Wake - Local pollutant emissions of 4-stroke medium speed engines [23], [49], [54], [51] (est. = estimated)

	Oil-based fuels				Gas-based fuel	
g/kWh	$HFO_{2.5}$[13]	$MGO_{0.1}$	$HFO_{>2.5}$ + EGCS	$LSFO_{0.5}$ LScrude or Blend	LNG	LNG
Combustion cycle			Diesel		Otto-SI	Otto-DF
SO_X	9.87	0.37	0.23	1.92_{est}	0.00	0.01
NO_X	2.55	2.55	2.55	2.55_{est}	1.20	1.96
PM	1.231	0.173	0.684	1.231_{est}	0.008	0.016

5.3.3. Tank-to-Wake – Local Pollutant Emissions 4-stroke High Speed Engine

The SO_X dependence on the fuel consumption and sulphur content of the fuel has been described in section 5.2.2. The same characteristics apply here. NO_x emissions of LNG are with 1.51 g NO_X/kWh

[30] As described in section 3, Table 3-1 HFO with an average sulphur content of 2.5 wt. % sulphur is used.

24 % lower than when operating with oil-based $MGO_{0.1}$. Particulate matter emissions were not provided for these engines and are therefore not shown.

Table 5-15: Tank-to-Wake - Local pollutant emissions of 4-stroke high speed engines [23], [50]

	Oil-based fuel	Gas-based fuel
g/kWh	$MGO_{0.1}$	LNG
Combustion cycle	Diesel	Otto-SI
SO_X	0.44	0.00
NO_X	2.01	1.51
PM	n.a.	n.a.

5.3.4. Tank-to-Wake – Local Pollutant Emissions Gas Turbine

Gas turbines in simple cycle operation produce the same absolute amount of emissions as in combined cycle operation. However, due to the higher power output in combined cycle operation the brake power specific emissions are lower for combined cycle operation.

Sulphur oxide emissions of gas turbines in simple and combined cycle operation are zero for LNG operation as no pilot fuel is used.

Gas turbines do not need any kind of NO_X after treatment-system to comply with the IMO Tier III NO_X-limits for both $MGO_{0.1}$ and LNG operation. However, NO_X emissions of LNG combustion are 43 % lower than NO_X emissions of $MGO_{0.1}$ operation[31].

The use of LNG reduces gas turbine PM emissions about 55 % compared with the operation with $MGO_{0.1}$.

Table 5-16: Tank-to-Wake - Local pollutant emissions of simple cycle gas turbines based on the average of 75 and 100 % engine load [23], [48], [52]

	Oil-based fuel	Gas-based fuel
g/kWh	$MGO_{0.1}$	LNG
Combustion cycle	Brayton simple	
SO_X	0.49	0.00
NO_X	1.59	1.11
PM	0.124	0.055

Table 5-17: Tank-to-Wake - Local pollutant emissions of combined cycle gas turbines based on the average of 75 and 100 % engine load [23], [48], [52]

	Oil-based fuel	Gas-based fuel
g/kWh	$MGO_{0.1}$	LNG
Combustion cycle	Brayton combined	
SO_X	0.35	0.00
NO_X	1.17	0.77
PM	0.088	0.038

[31] The data presented show compliance to IMO Tier III limits. In discussion with industry experts it was stated that the gas turbines are capable of NO_x levels below 0.5 g/kWh [48].

6. Well-to-Wake Analysis

6.1. Well-to-Wake – Scope of the Study

6.1.1. Product System

The Well-to-Wake analysis combines the Well-to-Tank part (section 4) and the Tank-to-Wake part (section 5) and assesses the overall emissions from the fuel supply and the fuel combustion in the assessed ship engines.

6.1.2. Product Functions and Functional Unit

The function of the whole Well-to-Wake product system (fuel supply and fuel use) is the power to serve the transport of goods and/or people by marine ships. The engine energy output expressed in kWh is the property to be used to describe the functional unit. The functional unit is to provide 1 kWh brake power. The reference flow related to the defined functional unit is 1 kWh brake power specific unit. For instance, GHG emissions are expressed in g CO_2-eq/kWh.

The relation per kWh ensures that the main objective of the study, the evaluation of GHG emissions of LNG as marine fuel compared with conventional oil-based fuels is achieved over the whole life cycle. The evaluation of GHG emissions of the transportation itself (e.g. emissions per cargo and nautical mile) is not within the scope of this study as well as the consideration of different ship applications, e.g. cargo, ferries, cruises.

6.1.3. System Boundary

The system boundary of the product system includes the supply and combustion of the fuel in ship engines. Figure 6-1 shows the Well-to-Wake system boundary for LNG with the WtT and TtW life cycle stages combined (refer to Figure 4-2 and section 5.1).

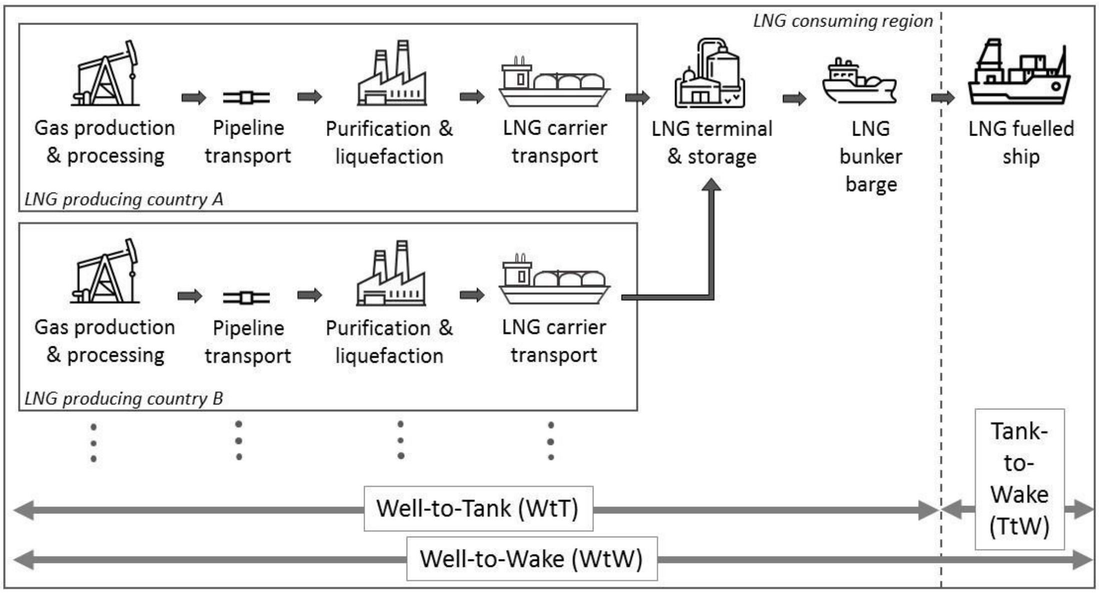

Figure 6-1: Well-to-Wake analysis – LNG supply and combustion [9]

The WtW analysis of oil-based fuels consists of the WtT part as described in Figure 4-2 the combustion of the fuel is described in section 5.1.

6.2. Well-to-Wake – Inventory Analysis

All data for the Well-to-Tank analysis and the Tank-to-Wake analysis are documented in sections 4.2 and 5.2. Figure 6-2 shows the WtW model that was set up in the GaBi software. It includes the combustion element of the respective engine and the supply of the fuels and respective auxiliaries (e.g. urea solution).

Figure 6-2: GaBi screenshot of the WtW process as modelled (Sankey diagram) (Example: combustion and supply for the 2-stroke slow speed Diesel-DF engine) [26]

6.3. Well-to-Wake – GHG Emissions of Current Marine Fuels

This section provides the Well-to-Wake GHG emissions for the product system assessed, i.e., LNG and oil-based marine fuels used in the different engine technologies and applications. The results are displayed per functional unit and compared with defined alternatives. As described above, the results are based on the weighting of steady-state engine load points according to the IMO E2/E3 cycle (75 and 100 % average for the gas turbine applications) in Tier III operation as described in Annex B. The results for Tier II operation are displayed in Annex G. All data refer to the LHV and CO_2 emission factors for complete combustion listed in Table B-5 and Table B-6 in Annex B.

Note, the methane emissions (slip) are subtracted from the specific fuel consumption for the calculation of the combustion CO_2 emissions to avoid double-counting of CO_2 combustion emissions and CO_2-eq emissions resulting from methane slip.

The difference on a TtW basis (combustion only) can be calculated by relating the combustion emissions of LNG to the combustion emissions of HFO. For the 2-stroke SS-Diesel-DF engine (see next section), the TtW reduction would be 28 % [(417-583)/583 g CO_2-eq/kWh = 28 %].

6.3.1. Well-to-Wake – GHG Emissions - 2-stroke Slow Speed Engine

Figure 6-3 shows the overall brake power specific Well-to-Wake GHG emissions of 2-stroke slow speed engines (g CO_2-eq/kWh) broken down by fuel supply and fuel combustion (WtT and TtW). The share of emissions resulting from the supply of the fuel is higher for LNG powered engines compared with engines powered by oil-based marine fuels although overall GHG emissions are lower. This is the case due to higher GHG emissions per MJ of fuel when using LNG as shown in section 4.3.

The overall GHG emissions of $MGO_{0.1}$ operation is 686 g CO_2-eq/kWh, while running on $HFO_{2.5}$ 697 g CO_2-eq/kWh are emitted.

Both engine technologies for LNG applications investigated (Diesel and Otto cycle LNG engines), achieve a net GHG reduction compared with the oil-based marine fuels. The 2-stroke slow speed Diesel-DF engine (SS-Diesel-DF) running on LNG emits 549 g CO_2-eq/kWh which is 21 % less compared with HFO operation (20 % compared with $MGO_{0.1}$) over the whole life cycle. The 2-stroke slow speed Otto engine (SS-Otto-DF) emits 598 g CO_2-eq/kWh and achieves a GHG reduction of 14 % compared with HFO (13 % compared with $MGO_{0.1}$).

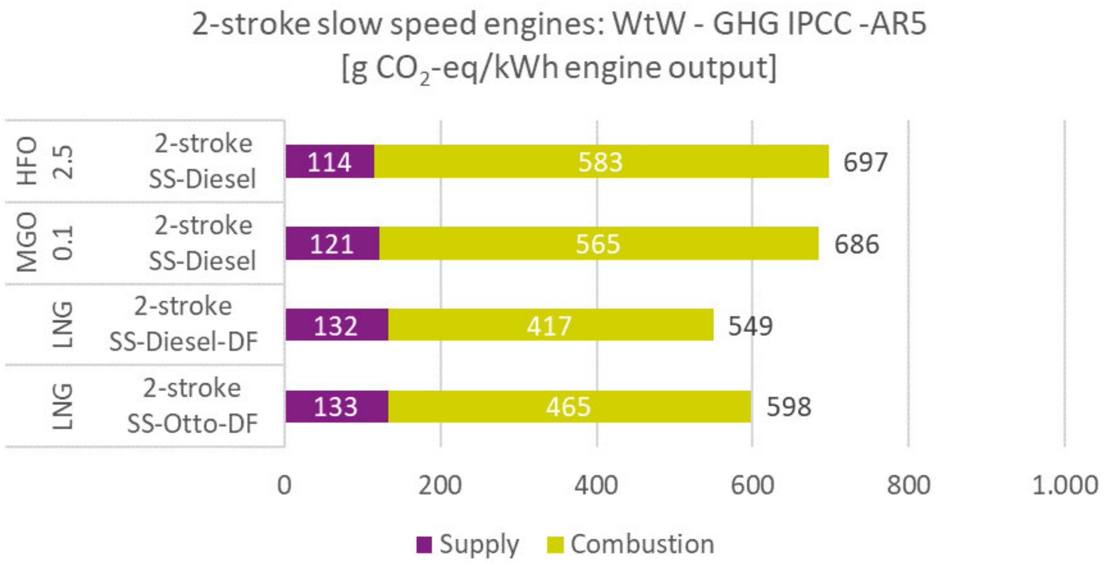

Figure 6-3: Well-to-Wake - GHG emissions of 2-stroke slow speed engines - breakdown by fuel supply and combustion [23]

Figure 6-4 shows the same absolute values but broken down into the main individual emissions CO_2, CH_4, and N_2O. The CO_2 emissions that result from supply and combustion of the fuel make up the highest share of the overall GHG emissions of all engine technologies and fuels analysed. For oil-based marine fuels, methane emissions are mainly released during the production and processing of crude oil. For LNG, the WtW GHG emissions resulting from unburned methane (CH_4) are 37 g CO_2-eq/kWh when using the 2-stroke SS-Diesel-DF engine and 96 g CO_2-eq/kWh using the 2-stroke SS-Otto-DF engine. Nitrous oxide emissions (N_2O) occur during the combustion of the fuel (see section 5.2.2) and are shown in the graphs but not quantified due to their minor share of the overall emissions (around 1 %).

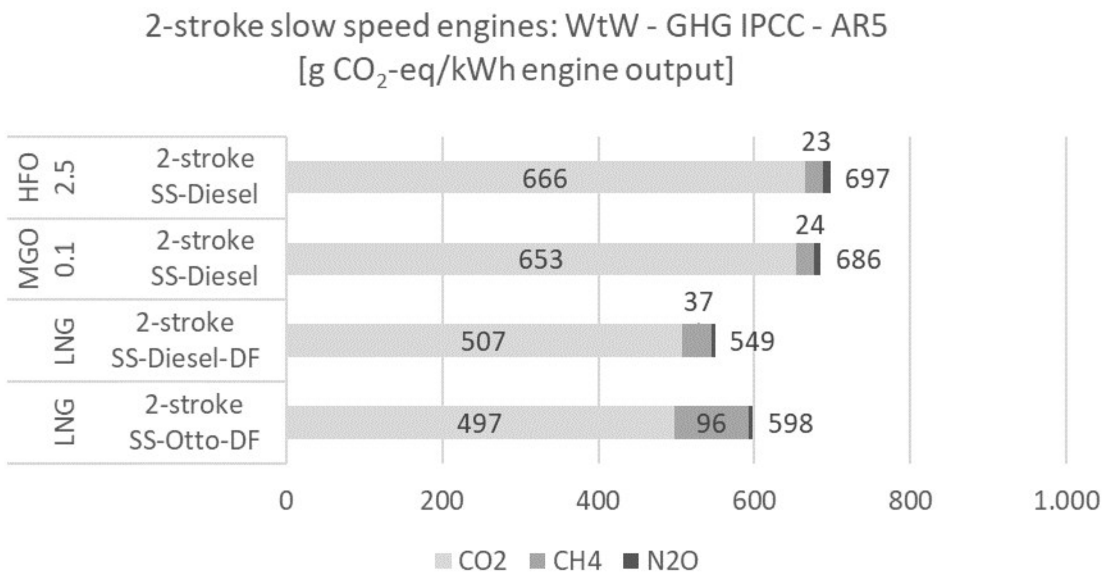

Figure 6-4: Well-to-Wake - GHG emissions of 2-stroke slow speed engines - breakdown by main individual emissions [23]

Table 6-1 shows the WtW GHG emissions resulting from methane based on the characterisation factor for methane of 30 (IPCC, AR5) [15]. The methane slip indicated by the primary data described in Table 5-8 is reflected in the GHG emissions resulting from unburned methane in the combustion process. The SS-Diesel-DF engine shows methane emissions of 0.14 g/kWh resulting in 4 g CO_2-eq/kWh which is less than 1 % of the total WtW GHG emissions of the engine. Due to the low-pressure injection system and the combustion in the Otto cycle, the SS-Otto-DF engines shows methane emission of 2.1 g/kWh resulting in 63 g CO_2-eq/kWh (11 % of total WtW GHG emissions) (Table 5-8). GHG emissions from methane emissions in the supply chain are comparable as the fuel consumption of the two engines is comparable.

Table 6-1: Contribution of methane emissions to WtW GHG emissions of 2-stroke slow speed engines [23]

g CO_2-eq/kWh	Oil-based fuels		Gas-based fuel	
	$HFO_{2.5}$	$MGO_{0.1}$	LNG	LNG
2-stroke slow speed	Diesel		Diesel-DF	Otto-DF
Total WtW GHG emissions	697	686	549	598
- of which methane	23	24	37	96
- supply	*23*	*24*	*33*	*33*
- combustion	-	-	*4*	*63*

6.3.2. Well-to-Wake – GHG Emissions - 4-stroke Medium Speed Engine

Figure 6-5 shows that the 4-stroke medium speed engines running on HFO emit 741 g CO_2-eq/kWh. Both LNG engines investigated (DF and pure gas, SI engines) show a reduction of GHG emissions compared with the operation with oil-based fuels. Medium speed dual fuel (DF) engines in gas mode emit 692 g CO_2-eq/kWh resulting in a GHG reduction compared with HFO operation of 7 % (4 % compared with $MGO_{0.1}$). Medium speed SI engines emitting 629 g CO_2-eq/kWh can achieve a GHG reduction of 15 % compared with the HFO operation (13 % compared with $MGO_{0.1}$).

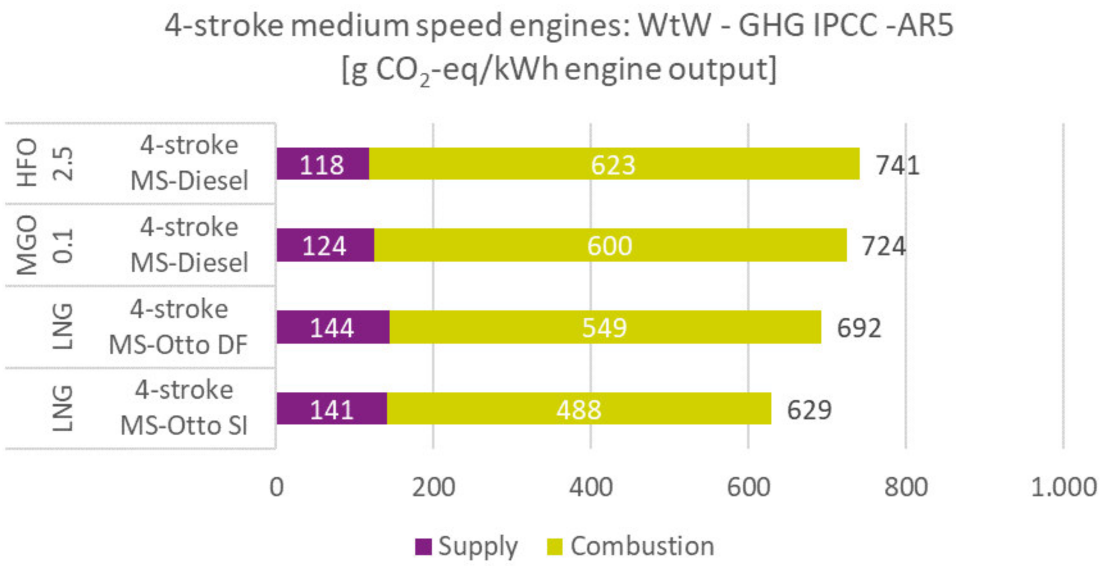

Figure 6-5: Well-to-Wake - GHG emissions of 4-stroke medium speed engines - breakdown by fuel supply and combustion [23]

Figure 6-6 shows that GHG emissions resulting from CH_4 emissions make up 22 % of the total GHG emissions of LNG dual fuel engines (151 of 692 g CO_2-eq/kWh), the share of CO_2 of the overall GHG emissions are 78 % (e.g. for HFO operation, this share is 96 %).

Table 6-2 gives an overview of the contribution of methane to the total WtW GHG emissions of 4-stroke medium speed engines. With SI engines, 96 g CO_2-eq result from unburned methane in the supply chain and during combustion. The methane slip during combustion results in 60 g CO_2-eq/kWh which is 10 % of the total WtW GHG emissions of the engine. As the emission data in Table 5-9 indicates, the MS-Otto-DF engine is more sensitive to methane slip. 115 g CO_2-eq/kWh are emitted during the combustion (16 % of the total WtW GHG emissions) with additional 36 g CO_2-eq/kWh coming from methane emissions from the supply chain. The emissions from the supply chain are comparable for both engine technologies as the main fuel consumption is comparable.

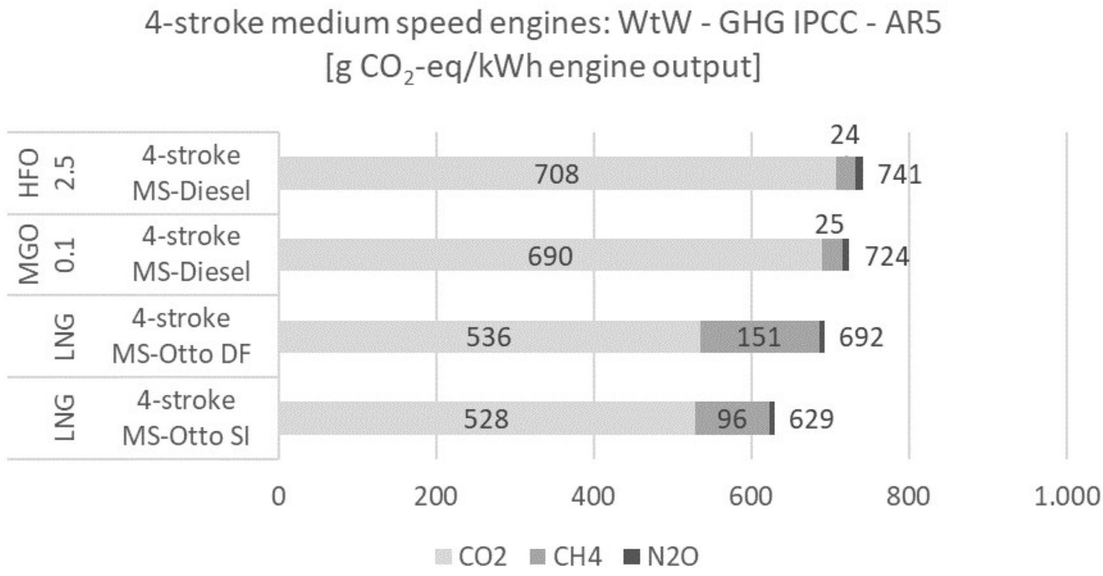

Figure 6-6: Well-to-Wake - GHG emissions of 4-stroke medium speed engines - breakdown by main individual emissions [23]

The contribution of methane emissions is shown in Table 6-2.

Table 6-2: Contribution of methane emissions to WtW GHG emissions of 4-stroke medium speed engines [23]

g CO_2-eq/kWh	Oil-based fuels		Gas-based fuel	
	$HFO_{2.5}$	$MGO_{0.1}$	LNG	LNG
4-stroke medium speed	Diesel		Otto-SI	Otto-DF
Total WtW GHG emissions	741	724	629	692
- of which methane	24	25	96	151
- supply	*24*	*25*	*36*	*36*
- combustion	*-*	*-*	*60*	*115*

6.3.3. Well-to-Wake – GHG Emissions - 4-stroke High Speed Engine

As mentioned above, high speed engines are only capable of running on low sulphur fuel and therefore only the operation with $MGO_{0.1}$ and LNG is considered here. The GHG emissions in $MGO_{0.1}$ operation of the high-speed Diesel engine investigated amount to 859 g CO_2-eq/kWh. The high-speed engine running on LNG in an Otto cycle combustion emits 812 g CO_2-eq/kWh which is equal to a reduction of 5 %. This can be explained by the lower fuel consumption when using LNG.

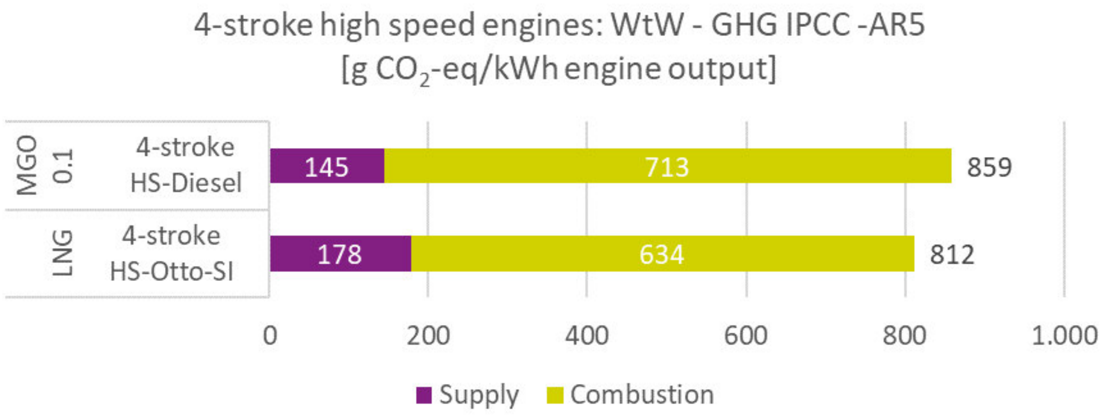

Figure 6-7: Well-to-Wake - GHG emissions of 4-stroke high speed engines - breakdown by fuel supply and combustion [23]

GHG emissions resulting from methane emissions are 142 g CO_2-eq/kWh which is 18 % of the overall GHG emissions of the LNG engine.

Table 6-3 shows the GHG emissions resulting from methane in the context of the total WtW GHG emission. 98 g CO_2-eq/kWh are related to the methane slip in the engine (12 % of the total WtW GHG emissions) with the supply chain accounting for 45 g CO_2-eq/kWh.

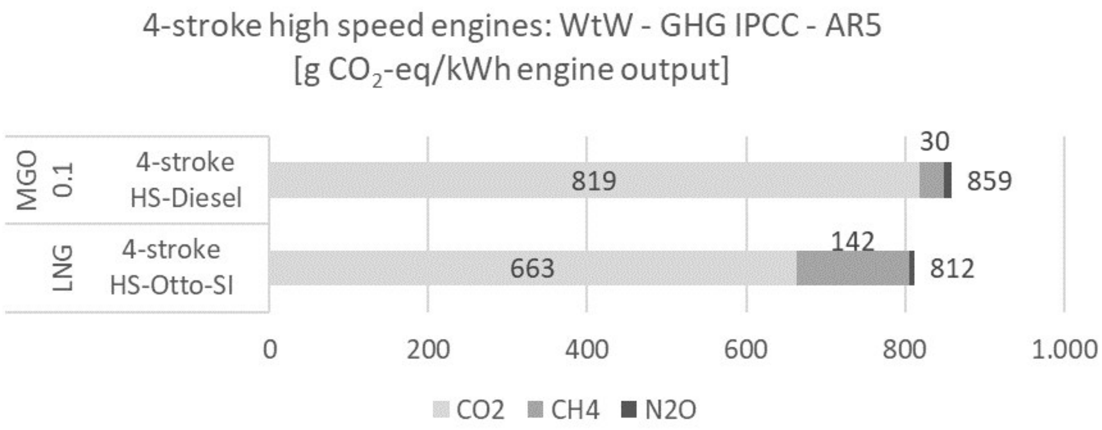

Figure 6-8: Well-to-Wake - GHG emissions of 4-stroke high speed engines - breakdown by main individual emissions [23]

Table 6-3: Contribution of methane emissions to WtW GHG emissions of 4-stroke high speed engines [23]

g CO_2-eq/kWh	Oil-based fuel	Gas-based fuel
	$MGO_{0.1}$	LNG
4-stroke high speed	Diesel	Otto-SI
Total WtW GHG emissions	859	812
- of which methane	30	142
- supply	*30*	*45*
- combustion	-	*98*

6.3.4. Well-to-Wake – GHG Emissions - Gas Turbines

Figure 6-9 and Figure 6-10 display the GHG emissions of gas turbines running on $MGO_{0.1}$ and LNG. The GHG emissions in simple cycle operation using $MGO_{0.1}$ are calculated as 954 g CO_2-eq/kWh. When running on LNG, GHG emissions are reduced to 798 g CO_2-eq/kWh which corresponds to a 16 % reduction. Figure 6-9 bottom shows the GHG emissions of a combined cycle gas and steam turbine. With similar fuel consumption and emissions, the engine output and hence the engine efficiency is increased significantly resulting in lower specific GHG emissions both for LNG (537 g CO_2-eq/kWh) as well as for $MGO_{0.1}$ operation (673 g CO_2-eq/kWh). The potential GHG reduction of LNG fuelled gas turbines in combined cycle is 20 %.

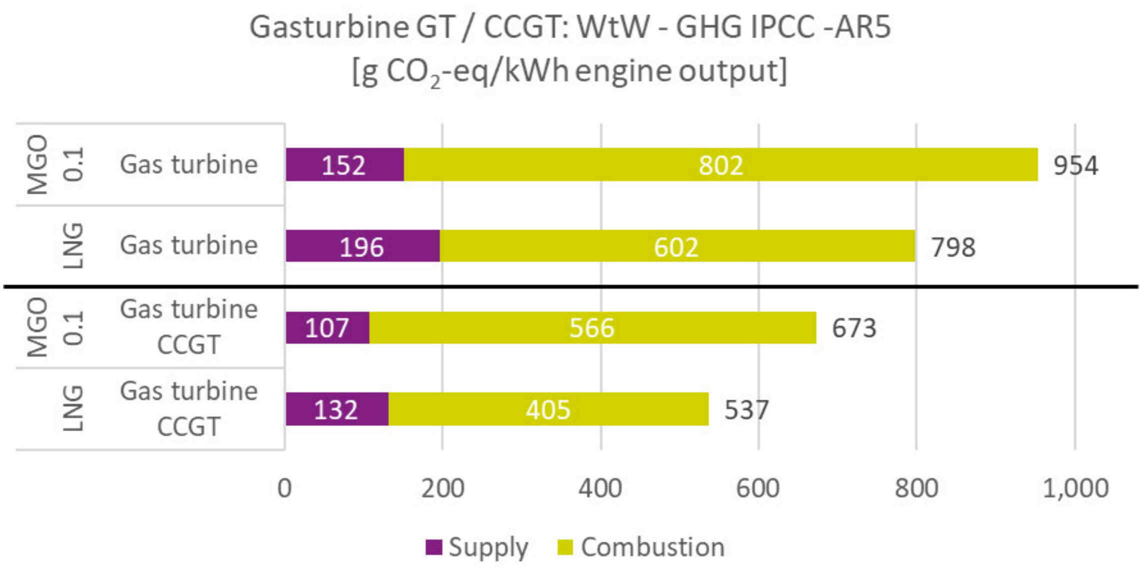

Figure 6-9: Well-to-Wake - GHG emissions of gas turbines in simple cycle (top) and combined cycle (bottom) breakdown by fuel supply and combustion [23]

Figure 6-10 shows that for gas turbines running on LNG, GHG emissions resulting from methane are relatively low compared with reciprocating engines. This is due to the negligible amount of unburned hydrocarbons during the combustion of the fuel. The emissions reported here are mainly coming from the supply of the fuel. This is also reflected by the data in Table 6-4. Methane emissions from the combustion account for less than 0.4 % of the total WtW GHG emissions. The main source of methane emissions and related GHG emissions is the supply chain.

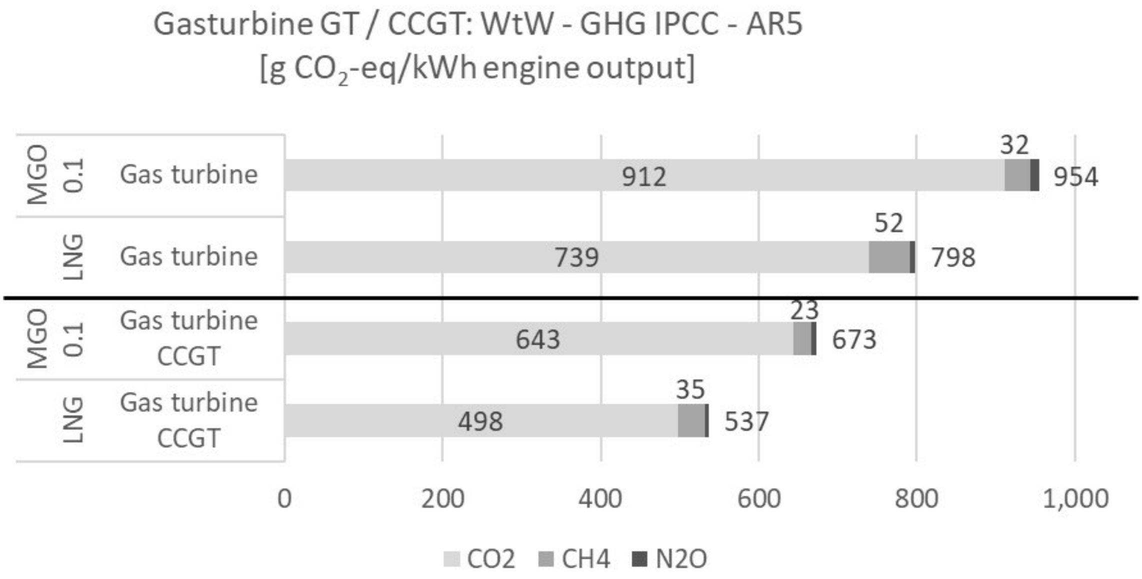

Figure 6-10: Well-to-Wake - GHG emissions of gas turbines in simple cycle (top) and combined cycle (bottom) breakdown by main individual emissions [23]

Table 6-4 outlines the methane emission contribution analysis.

Table 6-4: Contribution of methane emissions to WtW GHG emissions of gas turbines [23]

g CO_2-eq/kWh	**Oil-based fuel**		**Gas-based fuel**	
Gas turbines	$MGO_{0.1}$		LNG	
	GT	CCGT	GT	CCGT
Total WtW GHG emissions	954	673	798	537
- of which methane	32	23	52	35
- supply	*32*	*23*	*49*	*33*
- combustion	-	-	*2*	*2*

6.4. Theoretical Benefits for the Global Ship Fleet by introducing LNG

As seen in the previous section, the level of GHG reduction of LNG compared with current oil-based marine fuels highly depends on the engine technology investigated. In order to comment to a "global GHG reduction when operating on LNG", the engines and fuels currently used are taken as a basis for comparison.

Figure 5-1 in section 5.1.3 shows the status of the global fleet in 2015. It shows which engine technologies burns how much of the total fuel used in shipping. The share is displayed again in Table 6-5. The last column includes the reduction compared with the fuel used (HFO or $MGO_{0.1}$) as calculated in the section above, Figure 6-3 to Figure 6-8. This is based on the assumption that the LNG engines evaluated are equally represented. For example, for 2-stroke engines, the Otto-DF and Diesel-DF engine each have a 50:50 share, and the same applies for the 4-stroke medium speed Otto-DF and Otto-SI medium speed engines. Depending on the reference fuel, the average GHG benefit of LNG burned in 2-stroke engines for example ranges from 13 to 20 % ($MGO_{0.1}$) and 14 to 21 % ($HFO_{2.5}$), see Figure 6-3. The difference in GHG emissions when running on $HFO_{2.5}$ and $MGO_{0.1}$

is coming from the different fuel properties (LHV and carbon content, hence CO_2 emission factor) and the different GHG emissions from the supply of $HFO_{2.5}$ and $MGO_{0.1}$.

Table 6-5: GHG benefit (theoretically) of using LNG at the global ship fleet [17], [23]

Engine	Fuel	Share of global fuel usage	GHG benefit of using LNG
2-stroke slow speed	HFO	68 %	18 %
	$MGO_{0.1}$	4 %	16 %
4-stroke medium speed	HFO	10 %	11 %
	$MGO_{0.1}$	8 %	9 %
4-stroke high speed	$MGO_{0.1}$	5 %	5 %
Others		5 %	-
Total		**100 %**	**~15 %**

Multiplying the share of global fuel used in these engines with the average benefit of LNG (weighted average), this results in a global GHG reduction potential when using LNG compared with fuel use in 2015 of ~15 %[32, 33].

6.5. Well-to-Wake – GHG Emissions of post-2020 Marine Fuels

In this section, the GHG emissions from LNG powered engines are shown in comparison with the post-2020 fuels defined by the project consortium as described in Table 3-1: $HFO_{>2.5}$ with EGCS, $LSFO_{0.5,\ Blend}$ and $LSFO_{0.5,\ LScrude}$. This is done for 2-stroke slow speed as well as for 4-stroke medium speed engines. 4-stroke high speed engines and gas turbines in simple and combined cycle operation are not considered in this section as they only run on $MGO_{0.1}$ and LNG. As $MGO_{0.1}$ and LNG are both 2020 compliant fuels, the way of producing them will not change and hence the GHG results will not change as well.

6.5.1. Well-to-Wake – GHG Emissions - 2-stroke Slow Speed Engine

Figure 6-11 displays the GHG emissions of LNG in comparison with the defined post-2020 marine oil-based fuels for 2-stroke slow speed engines. The GHG emissions of HFO when using an EGCS are 704 g CO_2-eq/kWh. The use of different EGCS technologies (scrubbers) can result in higher fuel consumption. This is addressed by a scenario of increased fuel consumption in section 6.7.

$LSFO_{0.5,\ LScrude}$ is - as defined in section 3 - based on crude oil with a low sulphur content and hence does not need further energy intensive desulphurisation to reach the 2020 global sulphur limit of 0.5 wt.%. The overall WtW GHG emissions of $LSFO_{0.5,\ LScrude}$ are in the same order of magnitude (695 g CO_2-eq/kWh) as $LSFO_{0.5,\ Blend}$ (699 g CO_2-eq/kWh).

Compared with the operation of today's $HFO_{2.5}$, without an EGCS (697 g CO_2-eq/kWh), as displayed in Figure 6-3, the GHG emissions of the defined post-2020 fuels do not vary significantly.

[32] Consistently using the highest GHG reduction value of the engines, the global reduction would be 18 %. Using the lowest reduction value, would results in 11 % global reduction instead of 15 %.
[33] Assuming that the GHG emissions of the fuel supply are being constant, i.e. not considering any consequential changes that may occur in the fuel supply if the demand increases significantly.

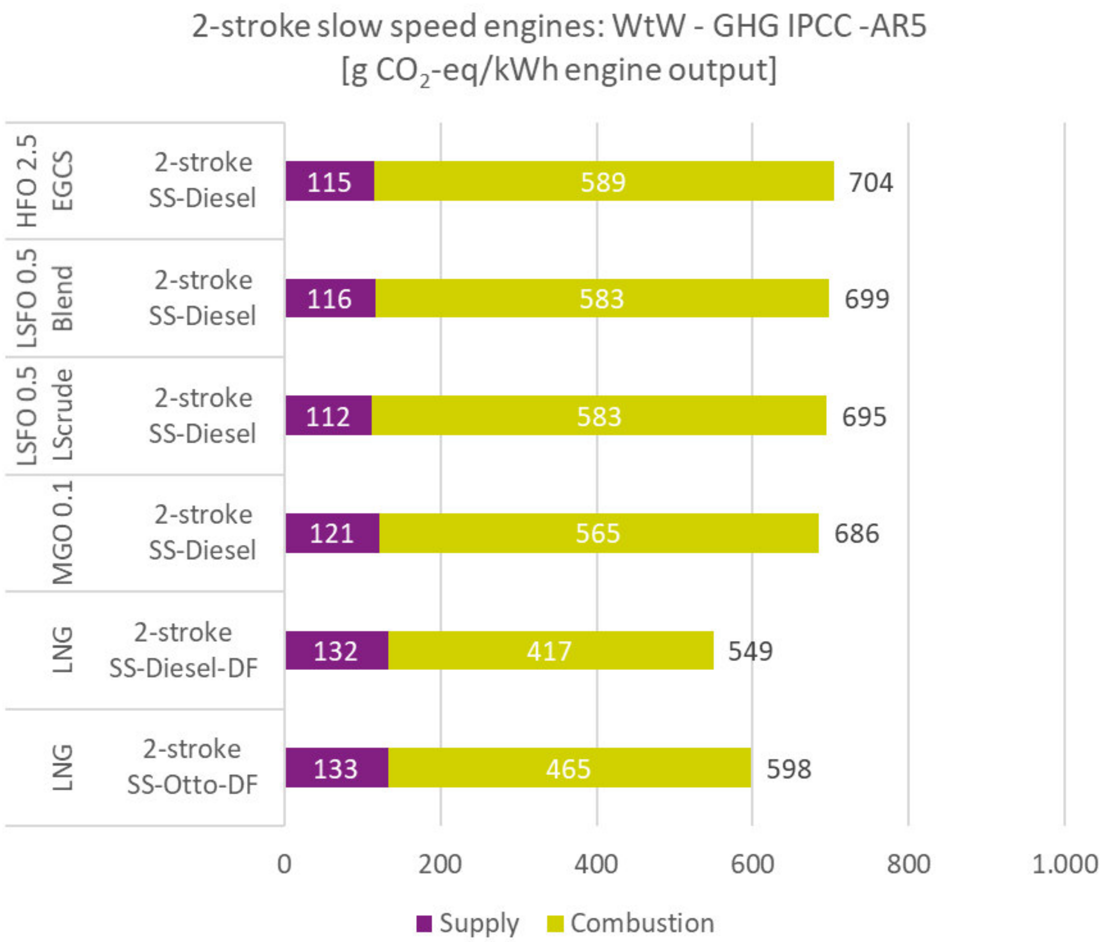

Figure 6-11:WtW GHG emissions of post-2020 fuels used in 2-stroke slow speed engines [23]

Table 6-6 shows the GHG reduction of LNG powered engines compared with engines running on different oil-based marine fuels using the results from Figure 6-3 and Figure 6-11. It outlines that the 2-stroke SS-Diesel-DF engine running on LNG shows a GHG advantage of 20 to 22 % depending on the reference fuel. Comparing LNG only to the defined post-2020 fuels (HFO with EGCS, $LSFO_{0.5, LScrude}$ and $LSFO_{0.5, Blend}$), it shows a benefit of between 21 and 22 %.

Table 6-6: GHG reduction of LNG powered 2-stroke slow speed engines compared with operation with different oil-based fuels [23]

GHG reduction to oil-based fuels	Current oil-based fuels		Post-2020 oil-based fuels		
	$HFO_{2.5}$	$MGO_{0.1}$	$HFO_{>2.5}$ + EGCS	$LSFO_{0.5, Blend}$	$LSFO_{0.5, LScrude}$
2-stroke SS-Diesel-DF	21 %	20 %	22 %	21 %	21 %
2-stroke SS-Otto-DF	14 %	13 %	15 %	14 %	14 %

2-stroke slow speed Otto-DF engines using LNG show an overall GHG benefit of 13 to 15 % when comparing them with Diesel cycle engines burning oil-based fuels.

6.5.2. Well-to-Wake – GHG Emissions - 4-stroke Medium Speed Engine

The same characteristics that apply to 2-stroke slow speed engine running on oil-based marine fuels, also apply to 4-stroke medium speed engines. The GHG difference between HFO operation with EGCS (749 g CO_2-eq/kWh) and operation on $LSFO_{0.5,\ LScrude}$ (739 g CO_2-eq/kWh) is 10 g CO_2-eq/kWh. $LSFO_{0.5,\ Blend}$ operation results in GHG emissions of 742 g CO_2-eq/kWh.

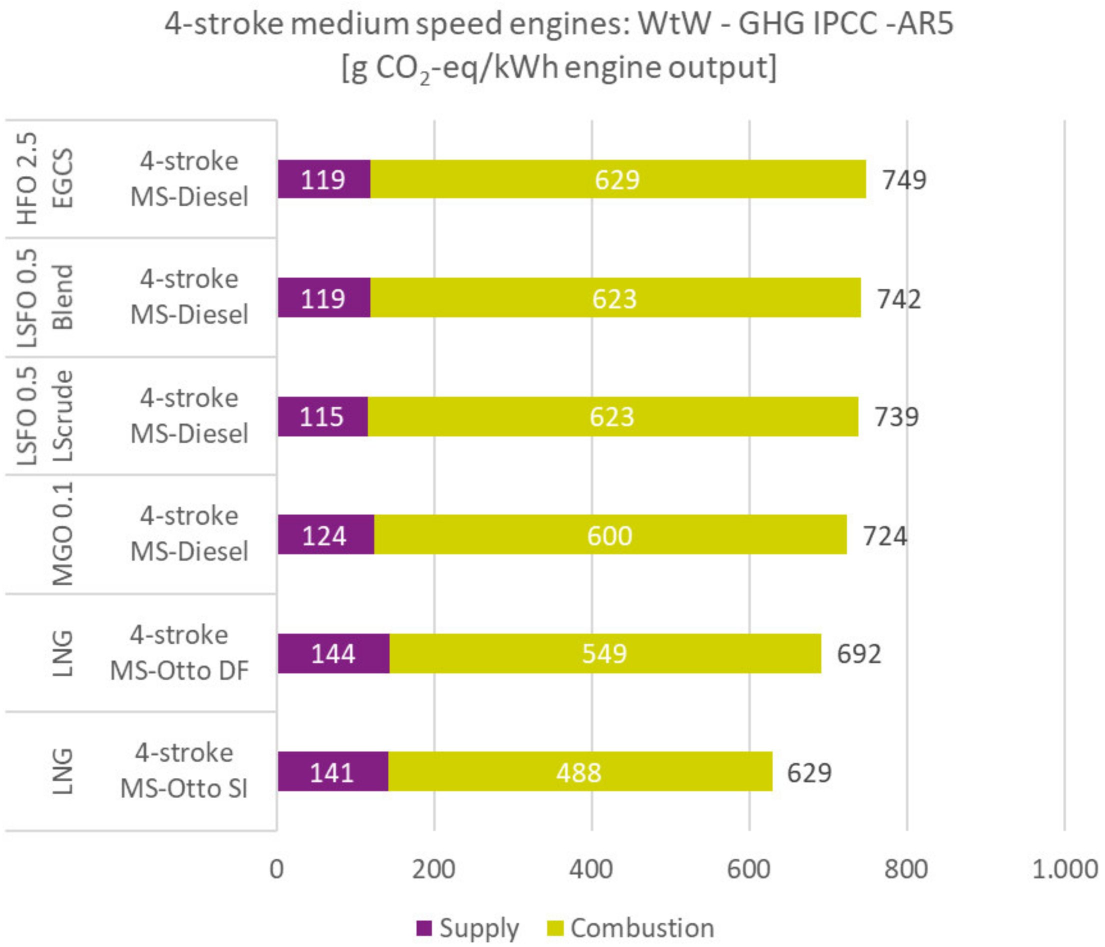

Figure 6-12:WtW GHG emissions of post-2020 fuels used in 4-stroke medium speed engines [23]

Table 6-7 shows the relative GHG reduction of the two 4-stroke medium speed engines investigated within this study. The dual fuel engine running on LNG gives a GHG benefit of 4 to 8 % compared with oil-based fuels. The spark ignited engine shows reduced GHG emissions of 13 to 16 %.

Table 6-7: GHG reduction of LNG powered 4-stroke medium speed engines compared with operation with different oil-based fuels [23]

GHG reduction to oil-based fuels	Current oil-based fuels		Post-2020 oil-based fuels		
	$HFO_{2.5}$	$MGO_{0.1}$	$HFO_{>2.5}$ + EGCS	$LSFO_{0.5,\ Blend}$	$LSFO_{0.5,\ LScrude}$
4-stroke MS-Otto-DF	7 %	4 %	8 %	7 %	6 %
4-stroke MS-Otto-SI	15 %	13 %	16 %	15 %	15 %

6.6. Well-to-Wake – GHG Emissions in Comparison with Other Studies

As seen in section 6.3 and 6.5, the GHG emissions are highly dependent on the application and hence engine technology. General statements on the GHG of LNG as marine fuel can therefore be rather misleading and special care has to be taken when comparing the results.

SINTEF [60] recently analysed the GHG emissions of different LNG powered engines in operation on a ship and compared them with test-bed data received from manufacturers (only combustion phase, TtW). The average methane slip emissions provided by engines manufacturers to SINTEF for SI engines is 2.8 g CH_4/kWh for the IMO E2/E3 cycle. This is comparable to the average data received in this study (2.0 g CH_4/kWh for medium speed engines, Table 5-9). For 4-stroke medium speed SI engines, the Tank-to-Wake (combustion) GHG emissions are reported as 528 g CO_2-eq/kWh (444 g CO_2-eq due to complete fuel combustion and 84 g CO_2-eq due to methane slip) which is in the same order of magnitude as the value calculated within this study (488 g CO_2-eq/kWh, see Figure 6-5).

For the 4-stroke medium speed Otto-DF engines, the average methane emissions are stated in [60] as 7.6 g CH_4/kWh which is higher than the average data collected within this study by a factor of two. Care must be taken when interpreting these data as this engine is the only engine technologies where SINTEF measured lower CH_4 emissions (5.3 g CH_4/kWh) than what were provided by the manufacturers. In general, comparison of test-bed data and real operation data is difficult due to the stationary vs. transient operating conditions. Due to the higher methane emissions, TtW GHG emissions are 669 g CO_2-eq/kWh which is significantly higher than what is calculated in this study (549 g CO_2-eq/kWh, Figure 6-5). The fuel consumption mentioned by SINTEF is comparable to that provided by the engine OEMs within this study[34].

The 2-stroke Otto-DF engine is also mentioned in the study [60] with total hydrocarbon emissions ranging between 2.8 to 3.8 g CH_4/kWh depending on the engine load point. Assuming a methane share of 90 % (see section 5.2.2), this is in the same order of magnitude as was provided within this study (see Table 5-8). However, GHG emissions for this engine are not calculated by SINTEF.

TNO [61] investigated the use of LNG as shipping fuel in the Netherlands. They received CH_4 data from a gas engine supplier which states 2.0 % methane slip at high loads and between 2.5 and 8.5 % at very low loads for SI and DF engines. The raw data collected within this study show similar characteristics (higher methane slip at low loads) but lower absolute numbers (1.3 % for SI and 2.5 % for DF engines for the IMO E2/E3 cycle, see Table 5-9). For the calculation of the GHG emissions, a methane slip of 2.6 % was used resulting in a calculated range of CO_2 emissions per MJ of fuel of 78.4-92.6 g CO_2-eq/MJ depending on different fuel supply chains including the combustion of LNG. Assuming a fuel consumption of 156.5 g LNG / kWh (4-stroke medium speed DF engine. Table 5-9, neglecting pilot fuel) this leads to CO_2-eq emissions per kWh of 603-713 g CO_2-eq/kWh. The value calculated within this study using a global LNG supply is 692 g CO_2-eq/kWh (see Figure 6-5) which is within the range indicated by TNO.

A study recently published by Transport & Environment [62] calculated the potential GHG reduction when switching from HFO or MGO to LNG using data of a study done by Ricardo [63]. They compared three different LNG supply chains ranging from 18.8-24.6 g CO_2-eq/MJ with the first value being in the same order of magnitude as that calculated within this study (18.5 g CO_2-eq/MJ, see Figure 4-5). Using the three different supply chains, two scenarios with 1.8 and 3.5 % methane slip have been calculated. The scenario with 1.8 % methane slip and 18.8 g CO_2-eq/MJ results in a maximum GHG reduction of LNG compared with HFO with EGCS of 9.6 % and 3.7 % compared with MGO. The equivalent within this study is the 2-stroke slow speed Otto-DF engine as the methane slip for this

[34] Original data provided by SINTEF refer to the CO_2 emissions from the combustion of LNG. By using emission factor for LNG (Table B-5) the actual fuel consumption in g/kWh was calculated resulting in 162 g LNG/kWh for the SI engine which is comparable to the 155.8 g LNG/kWh used in this study (Table 5-9).

engine is comparable (1.5 %, Table 5-8). Nonetheless, the GHG reduction calculated here is 14 % (Table 6-6) compared with HFO operation with EGCS and 13 % when compared with MGO. This can be explained by the combination of slightly lower LNG WtT (18.5 versus 18.8 g CO_2-eq/MJ) and slightly higher HFO WtT emissions (13.5 versus 13.0 g CO_2-eq/MJ) with slightly lower methane slip during the combustion (1.5 % versus 1.8 %) compared with the study of Transport & Environment [63] [64].

El-Houjeiri [41] compared the use of LNG as marine fuel with HFO produced in different regions. Produced from crude oil from Saudi Arabia, the GHG emissions are ~ 5 g CO_2-eq/MJ which is relatively low in global comparison. The HFO fuels investigated in [41] show GHG emissions for the supply chain between 10 – 14 g CO_2/MJ (depending on the region) which is in line with the findings in this study (Figure F-4).

Data from 4-stroke medium speed dual fuel engines were used that show 0.7 % methane slip at high engine load and 2.3 – 3.6 % at low engine load (taken from a field measurement study conducted by [65]). The data collected within the study at hand range from 2.3 % for high engine load to 3.5 % for low engine load resulting in an overall 2.5 % when weighted according to the IMO E2/E3 cycle (Table 5-9) which is higher than the data collected in [41]. Weighted fuel consumption for the 4-stroke DF engine is 161 g LNG/kWh compared with 156.5 g LNG/kWh (Table 5-9) collected within this study.

HFO fuel consumption reaches 193 g HFO/kWh (compared with 197.5 g HFO/kWh, Table 5-9) with MGO consumption at 199 g MGO/kWh (184.7 g MGO/kWh, Table 5-9). The unusual pattern of higher MGO than HFO consumption was discussed in [65] which resulted in the belief that the engine investigated is designed mainly for HFO operation leading to an overcompensation when using MGO.

Considering HFO from non-Saudi crude combined with the fuel consumption stated (193 g HFO/kWh), the HFO results are comparable. The LNG life cycle GHG emissions are evaluated within three different regions (US Gulf Coast, Europe and Japan) indicating different LNG supply chain emissions. The LNG supply chain emissions (WtT) used by El Houjeiri for the US LNG production are ~ 15 g CO_2-eq/MJ compared with 18.9 g CO2-eq/MJ used in the study at hand for the US and 18.5 g CO2-eq/MJ globally. Due to the differences in the inventory (LNG supply, methane slip) and characterisation factors used[35], the comparison of the LNG results is limited.

6.7. Well-to-Wake – Scenario Analysis

Influence of EGCS (Scrubber) Technologies when Operating on HFO

As mentioned in section 5.2, open-loop EGCS (scrubbers) and their influence on the emissions and fuel consumption of 2- and 4-stroke engines running on HFO were investigated within this study as a default. To take into account different EGCS technologies, a scenario was developed assuming a higher increase in SFOC due to different EGCS technologies. Increasing the fuel consumption by up to 5 % would lead to an increase of the WtW GHG emissions of 3.9 % compared with the base scenario (1 % SFOC increase, see Table 5-7). This is in the same order of magnitude with a study conducted by Shell [66] that takes into account three different scrubber technologies (open-/closed-loop and dry EGCS) resulting in GHG increase between 2.5-5.5 %[36] depending on the technology.

[35] El-Houjeiri uses 36 as characterisation factor for methane compared with 30 in this study.

[36] GHG emissions of the production of the necessary EGCS consumables when using closed-loop or dry EGCS (scrubbers) (NaOH and $Ca(OH)_2$) are included.

Scenario Analysis on Different Maritime LNG Bunkering Pathways

There are three general possible pathways for maritime LNG bunkering operations:

- ship-to-ship
- shore-to-ship
- truck-to-ship.

This study focuses on ship-to-ship since it is seen as the most common upcoming pathway for maritime deep-sea LNG bunkering. Compared with ship-to-ship, shore-to-ship maritime bunkering would lead to a insignificant reduction of 2 % WtT GHG emissions for the global LNG supply. The truck-to-ship maritime bunkering shows a higher impact through an increase in the WtT GHG emissions by 5 %. Under Well-to-Wake perspective the impact is less than 1 %, and hence also insignificant.

Scenario Analysis on the GHG Emissions for the Supply of $LSFO_{0.5,\ Blend}$

As stated in section 4.1.4 the $LSFO_{0.5,\ Blend}$ is a 50:50 blend of residual and distillate marine fuels with an average sulphur content of 0.5 wt. %. Different blends are possible. The fuels are produced from a crude oil with an average sulphur content which requires a modified, more energy intensive refinery structure and more desulphurisation within the whole refinery which increases the GHG emissions. These additional GHG emissions are assumed to be in the range of 2 to 10 %, depending on the blending ratio of residual and distillate marine fuels [11]. After intensive discussions with a representative of CONCAWE [12], 4 % additional GHG emissions for the production are assumed in this study. A scenario analysis has been carried out to investigate the effect of the variation of the additional CO_2 emissions on the WtT results. Assuming 2 % additional CO_2 emissions for the production of $LSFO_{0.5,\ Blend}$ would lead to a reduction in the WtW GHG result of 0.1 %, and an assumption of 10 % additional CO_2 emissions increases the WtW GHG result by 0.2 %. This shows that the effect of the variation of the additional CO_2 emissions on the WtW GHG results in the defined ranges of 2 to 10 % is negligible.

Influence of reduced Methane Slip when Operating on LNG

The theoretical GHG benefit LNG has due to its lower carbon content is partly reduced by methane emissions that escape the combustion chamber of the engine and are directly released to the atmosphere. This is known as methane slip.

Methane slip is mostly an issue for engines that run in the Otto cycle and result from incomplete combustion[37]. This has especially been the case for old engines in low loads as slow combustion is assumed to enable part of the gas to avoid the combustion process [67]. However, according to industry experts, significantly higher methane emissions on low load are not expected for new engines as they are optimised also for low load operation [54]. Dual fuel Otto cycle engines are especially sensitive to methane slip as they are designed to run on both oil-based fuel as well as on LNG[38].

Even though improvements have been made to reduce methane slip during the combustion of LNG, further reduction is necessary to reduce overall WtW GHG emissions. In discussions with industry experts, it was confirmed that substantial efforts are taken to further reduce methane slip by means

[37] 2-stroke slow speed Diesel-DF engines as well as the gas turbine applications have a very small methane slip (<0,3 %) due to the underlying combustion cycle and are hence not analysed here.

[38] There is a trade-off between the maximum temperature of the first piston ring (that basically seals the combustion chamber to the crankcase) and the minimum distance to the combustion chamber. As combustion of HFO leads to higher temperatures, a certain distance from the combustion chamber to the first piston ring is needed to avoid high temperatures at the piston ring. On LNG operation, this distance leads to a dead volume where the flame dies out resulting in incomplete combustion [51].

of engine-internal measures such as combustion optimisation. [49] [53] New engine generations are expected to achieve methane emissions, which are in the 50 % range lower than today's levels.

Another possible solution to tackle methane emissions is the use of methane oxidation catalysts such as the Methane Abatement Catalyst (MAC) currently under development by Shell [36]. Oxidation catalysts are expected to reach methane slip reduction rates between 60-80 % [53].

Two scenarios are calculated taking into account the potential saving's indicated above. This would lead to the following reductions in WtW GHG emissions compared with the base scenario:

Table 6-8: Potential WtW GHG reduction by the optimisation and reduction of methane slip compared with the LNG base case (Figure 6-4 and Figure 6-6) [23]

	2-stroke SS-Otto-DF	4-stroke MS-Otto-SI	4-stroke MS-Otto-DF	4-stroke HS-Otto-SI
40 % CH_4 reduction (with in-engine measures)	4 %	5 %	6 %	4 %
80 % CH_4 reduction (incl. catalyst)	8%	9 %	12 %	7 %

Note: 2-stroke slow speed Diesel-DF engines and gas turbine applications have small resp. negligible methane slip and are hence not shown in the table.

Depending on the engine technology and hence the amount of methane emission in the base scenario, the reduction of methane slip by 40 % leads to a reduction of WtW GHG emissions of 4 to 6 %. By using a catalyst, the potential is even higher resulting in up to 12 % WtW GHG reduction for the 4-stroke medium speed DF engine. Both reductions are significant considering the WtW life cycle.

6.8. Well-to-Wake – Sensitivity Analysis

6.8.1. Well-to-Wake – Sensitivity Analysis on Impact Categories for LNG

As described in section 3.3, all GHG results presented so far refer to the IPCC characterisation factors taken from the 5th Assessment Report (AR5) for a 100-year timeframe (GWP_{100}) [15], as this is currently the most commonly used metric. In order to analyse the sensitivity on the chosen metrics, a sensitivity analysis on the environmental impact category used has been performed. The GHG results based on AR5 GHG results for a 100-year timeframe (GWP_{100}) are compared with the AR4 GHG results for the same timeframe [18], the AR5 GHG results for a 20-year timeframe (GWP_{20}) and the AR5 global temperature potential for a 100-year timeframe (GTP_{100}) [15]. Please remember, the emission factors of the different characterisation schemes are displayed in Table B-1 within Annex B.

As the main differentiator between the characterisation schemes is the characterisation factor for methane emissions, the comparison shown here is related to the engine with the highest absolute methane emissions to make sure that the biggest possible range is illustrated.

Figure 6-13 shows the GHG emissions broken down by emission type for the 4-stroke medium speed engines running on LNG (for the other engines, see Annex G). The different characterisation schemes are all related to the base case which is represented by the results described in section 6.3 (IPCC AR5, 100-year timeframe) and hence amounts to 100 %. The vertical marks represents the comparison with the corresponding oil-based fuels.

The difference from the evaluation using the characterisation factor of AR4 is minor with 2 % difference for the SI engine and 4 % for the DF engine. When evaluating the inventories of the two engines using the IPCC AR5 on a 20-year timeframe (which describes the short-term climate effects) [15], the difference in overall GHG emissions is significant. The GHG emissions of the dual fuel engine increase to 140 % compared with the 100-year timeframe and exceeds the GHG emissions of the respective $HFO_{2.5}$ fuelled engine. Due to the lower methane emissions, the increase in GHG emissions of the SI engine is slightly lower reaching 128 %. This is due to the higher characterisation factor of methane emissions when using the 20-year timeframe (see Figure 6-13) [15].

Using characterisation factors used for the GTP_{100} evaluation [15], the decrease in overall GHG emissions for both engine technologies decrease due to lower characterisation factors, mainly for CH_4 but also for N_2O, which result in a relative decrease to 82 % for the dual fuel (DF) engine and 88 % for the spark ignited (SI) engine.

Although CO_2 emissions from combustion and fuel supply make up the greatest share of the overall GHG emissions, they do not differ between the different characterisation schemes. The main differentiator is, as mentioned above, the amount of methane which is released to the atmosphere. The higher these emissions, the bigger the difference compared with the base case (AR 5, GWP_{100})[39].

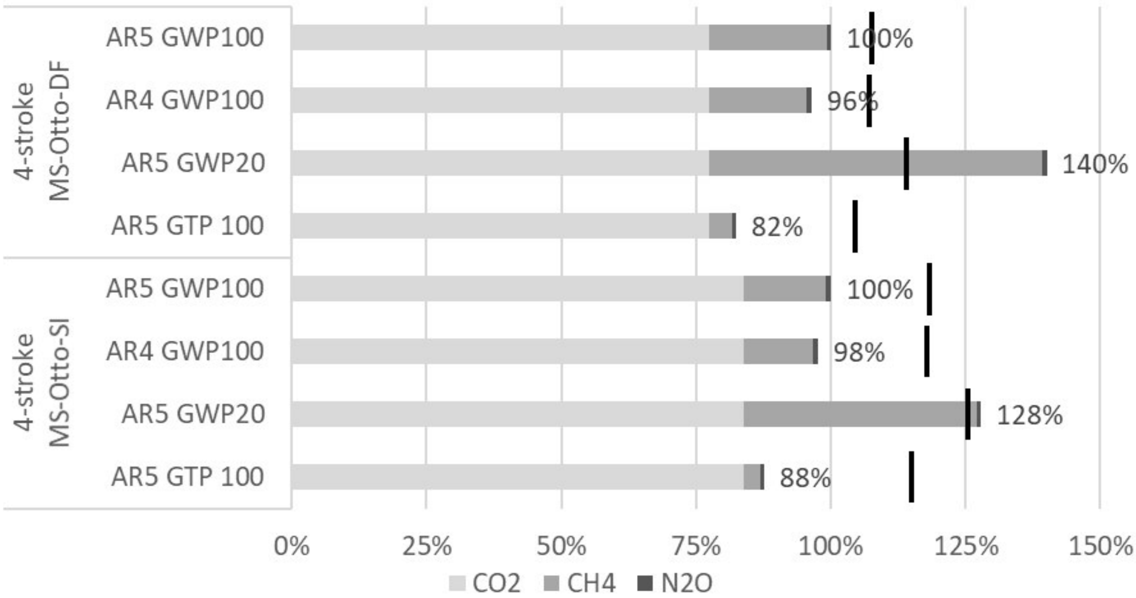

Figure 6-13: Impact of different characterisation factors (relative) on the WtW GHG emissions of 4-stroke medium speed engines when using LNG as fuel compared with IPCC, AR5, GWP_{100} (= 100 %) and oil-based fuel operation ($HFO_{2.5}$) shown as vertical marks [23]

In general, the findings as seen in Figure 6-13 can be transferred to the 2-stroke slow speed engines as well as the 4-stroke high speed engines, although the deviation from the base case differ due to different methane emissions. For gas turbines, because methane emissions during the combustion are generally low, the deviation between AR5 GWP_{100} and the other characterisation schemes is lower.

6.8.2. Well-to-Wake – Sensitivity Analysis on Technical Parameters for LNG

The sensitivity analysis considers the influence on the GHG results of the variation of single parameters in certain ranges. Thus, a sensitivity analysis provides a purposeful evaluation of the

[39] Using a characterisation factor of 36 g CO_2-eq/g CH_4 (which is currently under discussion), the WtW GHG emissions would be 104 % for the 4-stroke MS-Otto-DF engine (AR 5, GWP100=100 %) and 103 % for the 4-stroke MS-Otto-SI engine.

underlying parameters applied in the GHG model, and aims to provide an understanding of the importance and scale of the parameters defined and choices made in the GHG model. The WtW sensitivity analysis on selected parameters has been conducted for:

- LNG 2-stroke slow speed Diesel-DF
- LNG 2-stroke slow speed Otto-DF
- LNG 4-stroke medium speed Otto-DF
- LNG 4-stroke medium speed Otto-SI

Starting from the base case settings, the values of the following parameters are varied by ±50 %:

- GHG emissions of the fuel supply
- Fuel consumption during combustion
- Methane slip during combustion.

This study does not include a detailed analysis of the technical parameters of the LNG supply, such as energy consumption or methane losses along the supply chain. These are discussed and analysed in detail in the NGVA study prepared by *thinkstep* [13] and included in the parameter variation of the total GHG emissions of the fuel supply (sum value, summarising several technical parameters).

Please note: The definition of the +/- 50% variation is based on a theoretical bandwidth. The aim of the sensitivity analysis is to identify the influence of certain parameters on the results rather than showing possible minimum and maximum values of the GHG results. Meaningful variances for these parameters based on minimum and maximum values of the primary and literature data obtained are given in section 6.9.

By recording the effects of the parameter variations on the WtW GHG results, sensitivity diagrams are created. It is important to be aware that:

- each line is based on just three data points (base case, -50 % value and +50 % value) which are connected to each other,
- steep lines stand for parameters with high effect and lines with a low slope for parameters with little effect,
- lines with a positive slope stand for a positive correlation, which means that an increase in the value of the parameter also increases the GHG result, and lines with a negative slope mean that an increase in the parameter value decreases the GHG result.

Since the sensitivity analysis showed quite similar results for the different product systems considered, the results for the 4-stroke medium speed Otto-SI are presented in Figure 6-14 of this section. The results of the other engines can be found in Annex H.

Varying the parameter by ±50 % leads to:

- deviations of 42 to 47 % from the base case WtW GHG results for the fuel consumption during combustion for all investigated LNG engines,
- deviations of 10 to 12 % from the base case WtW GHG results for the GHG emissions of the fuel supply for all investigated LNG engines,
- deviations of 4 to 8 % from the base case WtW GHG results for the methane slip of almost all investigated engines. One exception is the LNG 2-stroke slow speed Diesel-DF. The base case setting for the methane slip of this engine is very low leading to effects of <0.5 % for the ±50 % parameter variation.

For all investigated LNG engines, the fuel consumption during combustion shows a very high impact on the WtW GHG results and dominates the sensitivity analysis.

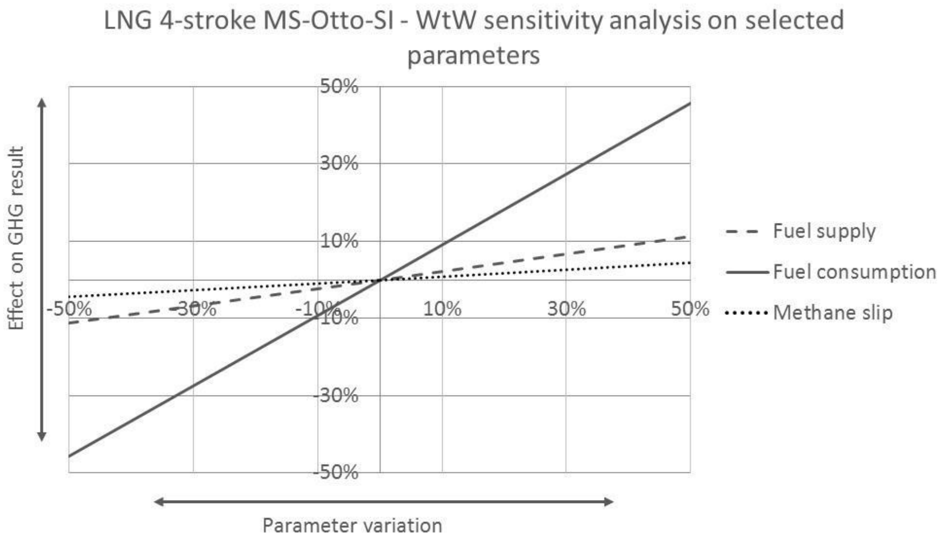

Figure 6-14: Sensitivity analysis on selected parameters from the WtW GHG model of LNG 4-stroke medium speed Otto-SI [23]

6.8.3. Well-to-Wake – Sensitivity Analysis on Technical Parameters for $HFO_{2.5}$

The WtW sensitivity analysis on selected parameters has been conducted for HFO representing the oil-based fuels for the following engines:

- $HFO_{2.5}$ 2-stroke slow speed Diesel
- $HFO_{2.5}$ 4-stroke medium speed Diesel

Starting from the base case settings, the values of the following parameters are varied by ±50 %:

- GHG emissions of the fuel supply
- Fuel consumption during combustion.

Please remember: The definition of the +/- 50% variation is based on a theoretical bandwidth. The aim of the sensitivity analysis is to identify the influence of certain parameters on the results rather than showing possible minimum and maximum values of the GHG results. Meaningful variances for these parameters based on minimum and maximum values of the primary and literature data obtained are given in section 6.9.

The results for the 4-stroke medium speed Diesel are presented in Figure 6-15. The results of the 2-stroke slow speed Diesel engine are provided in Annex H.

Varying the parameter by ±50 % leads to:

- deviations of 49 % from the base case WtW GHG results for the fuel consumption during combustion for both investigated $HFO_{2.5}$ engines,
- deviations of 7 % from the base case WtW GHG results for the GHG emissions of the fuel supply for both investigated $HFO_{2.5}$ engines.

Similar to the investigated LNG engines, the fuel consumption during combustion shows a very high impact on the WtW GHG results of $HFO_{2.5}$.

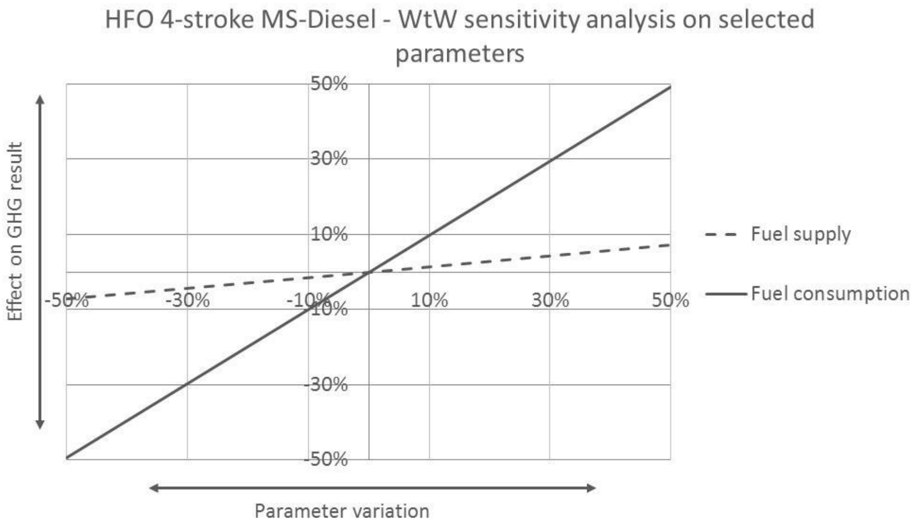

Figure 6-15: **Sensitivity analysis on selected parameters from the WtW GHG model of $HFO_{2.5}$ 4-stroke medium speed Diesel [23]**

6.9. Well-to-Wake – Uncertainty Analysis

Uncertainty analyses test the combined effect of parameter uncertainties on the final results as some of the effects seen in sensitivity analyses may cancel each other out or reinforce each other. The uncertainty analysis is performed using Monte-Carlo simulation which draws random values from defined uncertainty intervals to calculate a multitude of possible results. The less these results vary, the lower is the overall parameter uncertainty of the GHG model. Gaussian distribution functions are used.

Well-to-Wake – Uncertainty Analysis for LNG

In Table 6-9 uncertainty intervals are defined for relevant parameters of the LNG 4-stroke medium speed Otto-SI engine which are independent from each other, called variance 1 and variance 2. Meaningful variances are used as intervals based on minimum and maximum values of the primary and literature data obtained. In total, 10,000 simulations were run with every simulation is generating a GHG result for the product system based on a random combination of parameter values. The Monte-Carlo analysis was calculated using the GaBi software.

Table 6-9: **Uncertainty Analysis - Monte-Carlo simulation for LNG 4-stroke medium speed Otto-SI engine - defined variances [23]**

Process step	Parameter	Variance 1	Variance 2
Supply	GHG emissions of fuel supply	-15 %	+15 %
Combustion	Fuel consumption	-5 %	+5 %
	Methane slip	-20 %	+20 %

The results of the Monte-Carlo simulation for the WtW GHG emissions of the LNG 4-stroke medium speed Otto-SI engine are presented in Table 6-10 and Figure 6-16. The simulations showed that the results based on the GHG model with the parameter settings for the LNG 4-stroke medium speed Otto-SI engine are very stable and robust. The standard deviation of 3.2 % is very low. This low standard deviation is visible in Figure 6-16 as the results create a high Gaussian bell curve. The higher the bell curve, the more stable the results. The median is 0.03 % lower than the base case result and the base case result is within the distribution of the 10,000 simulation runs.

Table 6-10: Uncertainty Analysis - Monte-Carlo simulation for LNG 4-stroke medium speed Otto-SI engine - results [23]

Parameter	Value	Unit
Base case, GHG result	629	g CO_2-eq/kWh
Monte-Carlo simulation		
Median GHG result	629	g CO_2-eq/kWh
Standard deviation	3.2	%
10 % percentile	602	g CO_2-eq/kWh
25 % percentile	615	g CO_2-eq/kWh
75 % percentile	644	g CO_2-eq/kWh
90 % percentile	656	g CO_2-eq/kWh

The percentile values show the distribution of the simulation results. For example, 90 % of all simulation GHG results are below 656 g CO_2-eq/kWh and 10 % of all simulation results are below 602 g CO_2-eq/kWh.

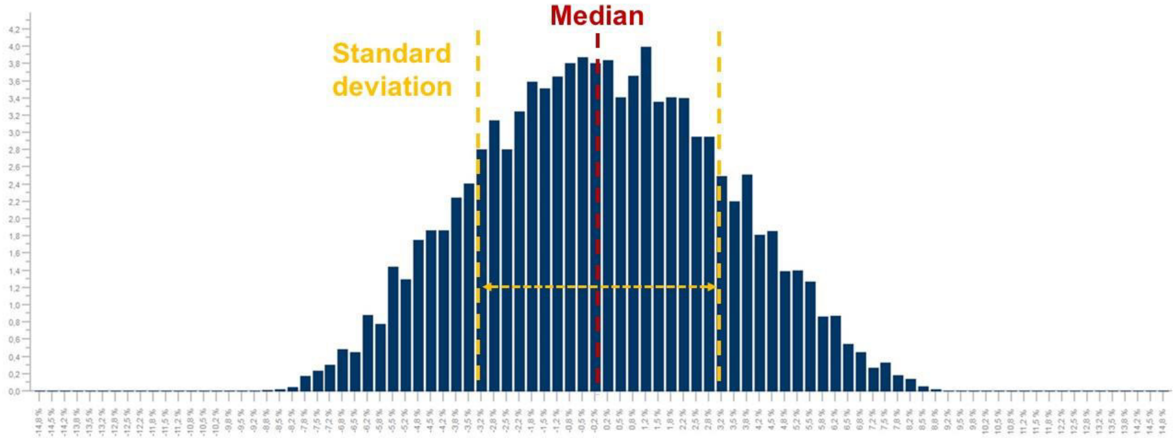

Figure 6-16: Uncertainty Analysis - Monte-Carlo simulation for the LNG 4-stroke medium speed Otto-SI engine - distribution of results, calculated with the GaBi software system [23]

The uncertainty analysis demonstrates the robustness of the calculated WtW GHG results for LNG. The conclusion is there can be high confidence in base case results. The results are judged to be robust and sufficient within the range and distribution functions assumed in this study.

Well-to-Wake – Uncertainty Analysis for $HFO_{2.5}$

Table 6-11 shows the defined uncertainty intervals for relevant parameters of the $HFO_{2.5}$ 4-stroke Diesel medium speed engine. Meaningful variances are used as intervals based on minimum and maximum values of the primary and literature data obtained. In total, 10,000 simulations were run.

Table 6-11: Uncertainty Analysis - Monte-Carlo simulation for $HFO_{2.5}$ 4-stroke medium speed Diesel engine - defined variances [23]

Process step	Parameter	Variance 1	Variance 2
Supply	GHG emissions of fuel supply	-15 %	+15 %
Combustion	Fuel consumption	-5 %	+5 %

Table 6-12 and Figure 6-17 show the results of the Monte-Carlo simulation for the WtW GHG emissions of the $HFO_{2.5}$ 4-stroke medium speed Diesel engine. The simulations showed that the results based on the GHG model with the parameter settings for the $HFO_{2.5}$ 4-stroke medium speed Diesel engine are very stable and robust. The standard deviation of 2.9 % is very low. The median is 0.02 % lower than the base case result. The base case result is within the distribution of the 10,000 simulation runs.

Table 6-12: Uncertainty Analysis - Monte-Carlo simulation for $HFO_{2.5}$ 4-stroke medium speed Diesel engine - results [23]

Parameter	Value	Unit
Base case, GHG result	741	g CO_2-eq/kWh
Monte-Carlo simulation		
Median GHG result	741	g CO_2-eq/kWh
Standard deviation	2.9	%
10 % percentile	713	g CO_2-eq/kWh
25 % percentile	725	g CO_2-eq/kWh
75 % percentile	758	g CO_2-eq/kWh
90 % percentile	771	g CO_2-eq/kWh

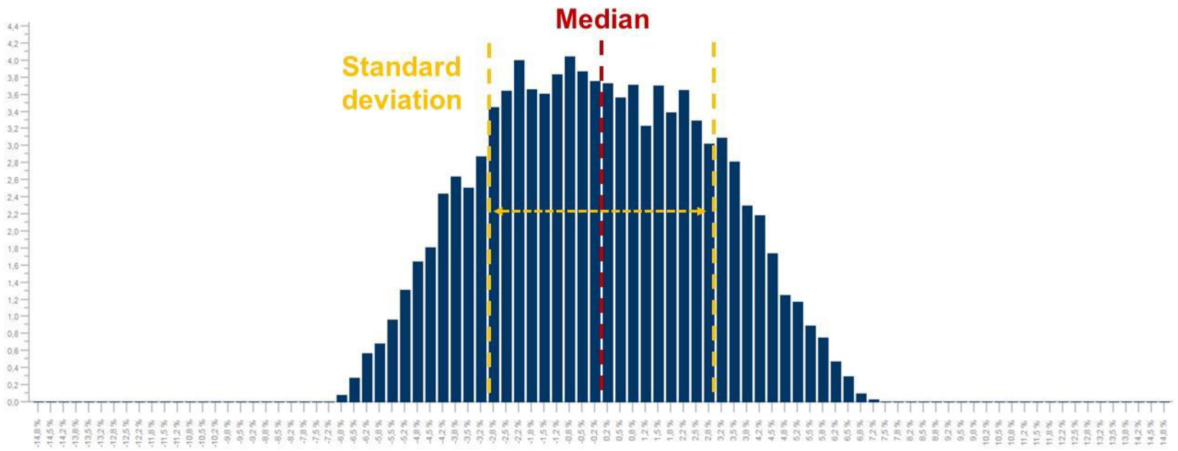

Figure 6-17: Uncertainty Analysis - Monte-Carlo simulation for the $HFO_{2.5}$ 4-stroke medium speed Diesel engine - distribution of results, calculated with the GaBi software system [23]

The results are judged to be robust and sufficient within the range and distribution functions assumed in this study.

7. Outlook - Renewable LNG Supply Sources

This section provides an indicative and informative outlook on the use of bioLNG and synthetic LNG as marine fuel. The analysis was performed as part of the NGVA study [13] in the European context. This overview is not represented as complete nor most up-to-date. For example, the results do not include GHG emissions and removals associated with land use change and land use, in accordance with [16]. However, it gives some understanding on what GHG reduction potential might be possible by using renewable LNG.

Biomethane from renewable resources can be obtained from various pathways and feedstocks:

- Biogas, a mixture of methane and carbon dioxide, from anaerobic digestion, landfill or sewage sludge treatment can be upgraded to Natural Gas quality. Within the last couple of years, the installation of upgrading units has grown. In Europe, additional biogas is mainly produced via anaerobic digestion from organic waste, manure and other suitable residues.
- In addition to anaerobic digestion, synthetic Natural Gas (SNG) can be produced via gasification of lignocellulosic biomass and subsequent methanation or via electrolysis and methanation. The production of methane from electrolysis powered by electricity is considered as a possibility to use surplus electricity from intermittent renewable electricity generation, such as wind power and photovoltaics (PV). Methane produced via electrolysis and methanation has different names, such as Power-to-Gas (PtG), Synthetic Natural Gas (SNG), e-gas, or windgas etc.

bioLNG and synthetic LNG are also being produced via micro or small-scale liquefaction plants. The LNG is distributed typically by LNG truck to the LNG terminal to be used as fuel for ships and for other purposes.

For the analysis, data from the Renewable Energy Directive (RED) [68], mainly the Fuel Quality Directive (FQD) [69], and its related Council Directive (EU) 2015/652 [70] have been used for the supply of biomethane from residues and manure and SNG. Data for the micro scale liquefaction are based on literature[40]. Data for the distribution of bioLNG and synthetic LNG are taken from the NGVA study [13][41]. For the LNG terminal operations and bunkering the same data as for fossil LNG are used. The TtW emissions are calculated based on the consumption values and GHG emissions of the defined engines in section 5.

The clear advantage of bioLNG and synthetic LNG is that the carbon dioxide emitted is effectively carbon neutral, i.e., no additional CO_2 is released and therefore not accounted in the WtW analysis. Only the CH_4 and N_2O emissions of the combustion are considered in the TtW GHG emissions. Apart of the carbon neutrality of bioLNG and synthetic LNG themselves, CO_2 emissions from fuel supply for pumping LNG, etc., such as CO_2 emissions from the electricity grid are accounted.

The analysis of renewable supply sources is assessed for:

- LNG 2-stroke slow speed Diesel-DF
- LNG 2-stroke slow speed Otto-DF

[40] For a micro scale liquefaction plant in the range of 2,000-30,000 tonnes per annum using mixed refrigerant, Wärtsilä indicates an electricity consumption of 0.7 kWh/kg [81]. For the liquefaction of biomethane the average European grid mix is used as electricity supply. For SNG the assumption has been made that the liquefaction uses the same electricity supply as the electrolysis, i.e., electricity from wind.

[41] Potential gas losses during LNG distribution are cut-off.

- LNG 4-stroke medium speed Otto-DF
- LNG 4-stroke medium speed Otto-SI
- LNG 4-stroke high speed Otto-SI

The assumption is made that no technical changes in engines are needed for the use of bioLNG and synthetic LNG.

The GHG emissions for using 100% fossil LNG, 100% synthetic LNG or 100% bioLNG as well as possible blends for the 2-stroke slow speed engines are shown in Figure 7-1. Compared with fossil LNG, the use of blends can reduce the WtW GHG emissions by 13 % to 18 % and the use of 100% bioLNG or synthetic LNG show a WTW GHG reduction potential of 64 % or as much as 92 %.

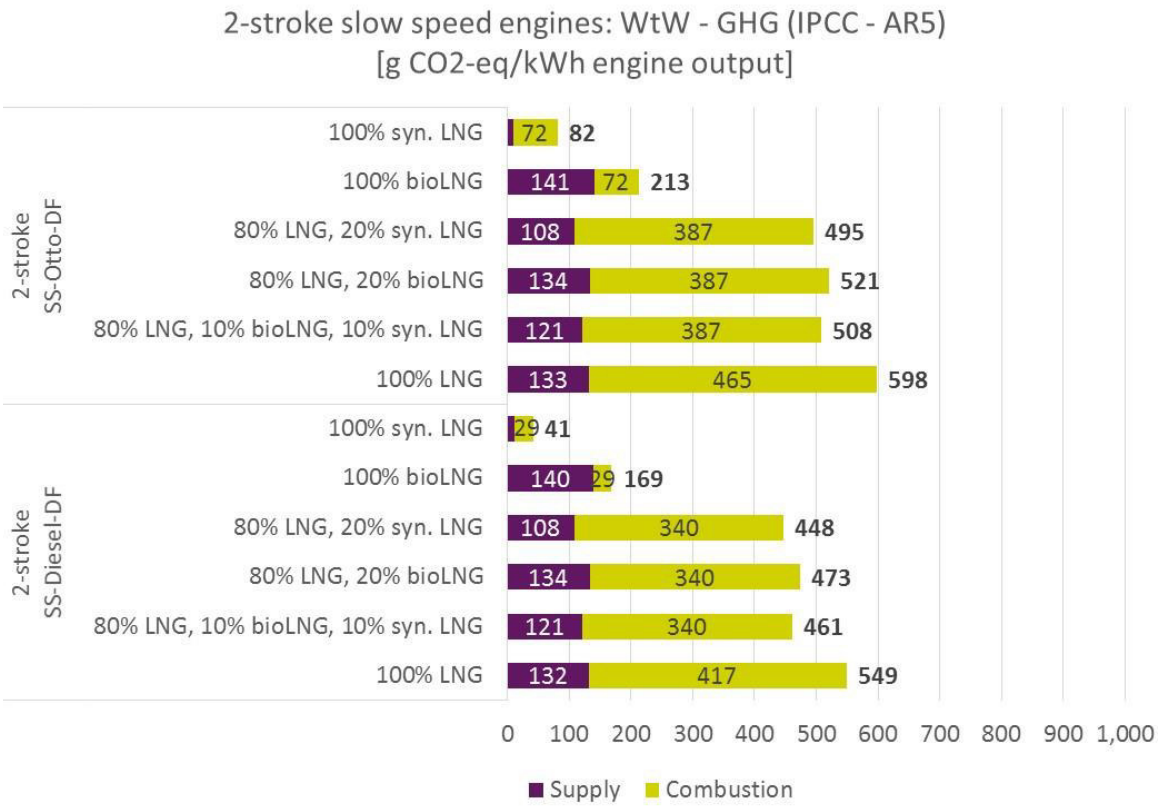

Figure 7-1: WtW GHG emissions of current and future LNG sources used in 2-stroke slow speed engines [23]

Figure 7-2 illustrates the possible reduction potentials for 4-stroke medium speed engines. Compared with fossil LNG, blends can result in a reduction by 12 % to 18 % and the use of 100% bioLNG or synthetic LNG in a reduction by 59 to 88 %.

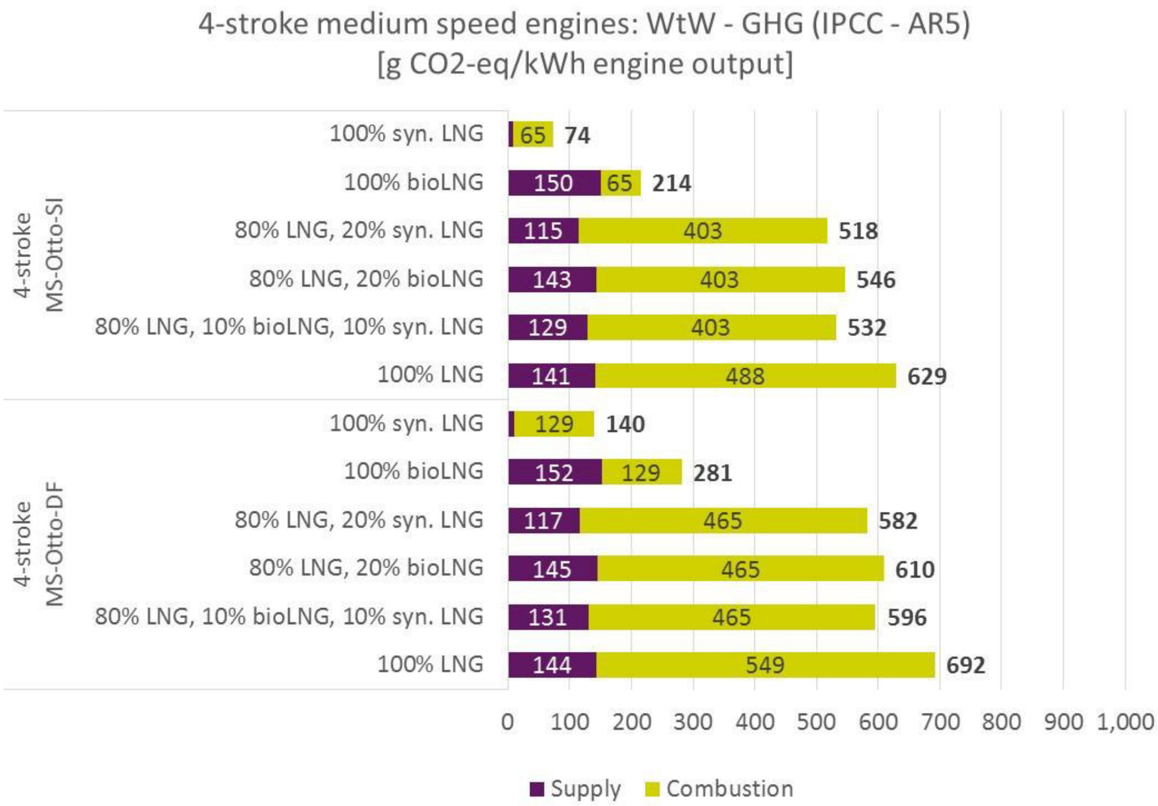

Figure 7-2: **WtW GHG emissions of current and future LNG sources used in 4-stroke medium speed engines [23]**

The GHG emissions for fossil LNG and possible blends for a 4-stroke high speed engine in Figure 7-3 show that the use of blends can reduce the GHG emissions by 13 % to 17 %. 100% bioLNG or synthetic LNG shows reduction potentials between 64 to 86 %.

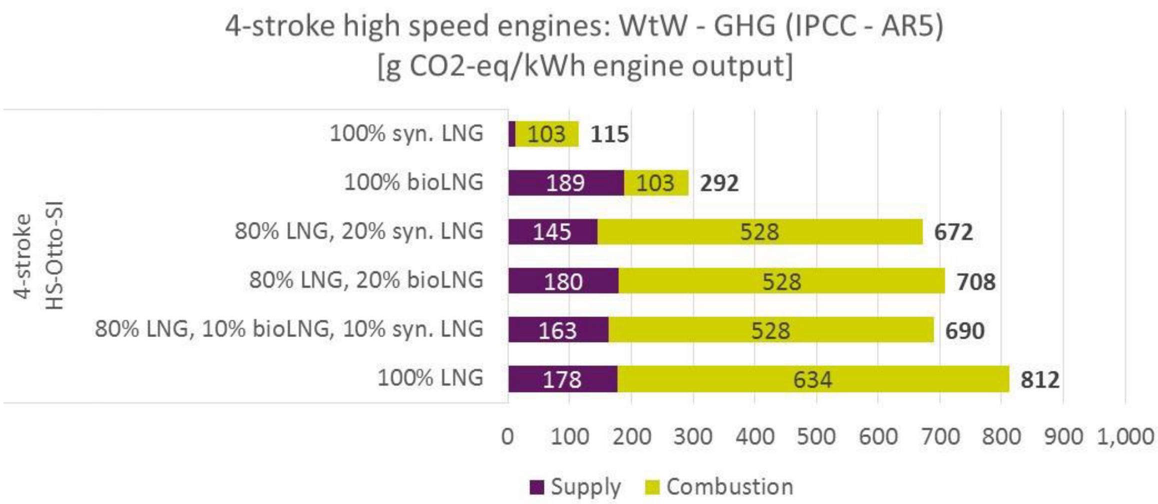

Figure 7-3: **WtW GHG emissions of current and future LNG sources used in 4-stroke high speed engines [23]**

8. Interpretation

8.1. Identification of Relevant Findings

The relevant findings are broken down by its life cycle part.

Well-to-Tank Analysis of LNG

The key findings of the Well-to-Tank analysis of the LNG supply chain are:

- The carbon footprint of the global LNG supply, in tank is 18.5 g CO_2-eq/MJ (LHV).
- Main contributors in terms of life cycle phases ("GHG hot spots") of the average LNG supply chain are:
    - Gas liquefaction (including purification) (50 % contribution, caused by energy consumption)
    - Gas production, processing and pipeline transport to the liquefaction plant (33 % contribution, caused by energy consumption and methane emissions)
    - LNG carrier transport (13 % contribution, defined by the distance travelled and the utilisation (in terms of time) of the LNG carrier)
    - LNG terminal operations and bunkering (4 % contribution, caused by energy consumption and methane emissions).
- Carbon dioxide is the main contributor to the GHG emissions (contribution of 74 %), followed by methane (contribution of 25 %). Nitrous oxide (N_2O) is emitted only in small quantities (contribution of <0.5 %)[42]. Other GHG emissions, like halogenated organic emissions, are included in the background data (e.g. electricity supply) and thus taken into account but can be neglected. The CO_2 emissions mainly come from fuel combustion and small CO_2 amounts vented during processing and purification of Natural Gas if no carbon capture and storage is applied (CO_2-removal). The main sources for the CH_4 emissions are fugitive emissions.
- The GHG emissions for the LNG supply chain differ from region to region due to different natural reservoir characteristics, and hence production technologies applied, ambient temperatures at liquefaction, transport distances, etc. Technology consideration as well as a country-by-country analysis to get to a global average are key for the assessment of the supply chains.
- The comparison with other studies reveals that the results are in the same order of magnitude. Differences can be explained by differences in the scope of the studies or data used.

Well-to-Tank Analysis of Current and Post-2020 Oil-based Marine Fuels

The calculated global results of the current oil-based fuel supply chains and the post-2020 scenarios on oil-based marine fuel supply chains are in the same order of magnitude (±4,5 %), ranging from 13.2 to 14.4 g CO_2-eq/MJ (LHV) fuel. Especially, the calculation of the post-2020 fuels is associated with uncertainties. Different crude oil properties and refinery settings, different levels of desulphurisation and blending ratios, and assumptions made as well as methodological differences like different allocation methods can lead to different results. This means that interpretation and

[42] N_2O emissions occur during combustion processes within the LNG supply chain and they are included in the background data used.

comparison of results needs to be undertaken with care. See also section 9.2 “Recommendations”, update of the study 2020/2021, once more information which fuel will penetrate the market are known. Even if the uncertainties for post-2020 fuels are quite high, differences to current marine fuels higher than ±10 % seems unlikely.

Air Quality and Local Pollutants

The relevant findings of the Tank-to-Wake component of the life cycle are limited to the local pollutant emissions investigated in this study (SO_X, NO_x and PM). Aspects regarding the GHG emissions are discussed in the section “Well-to-Wake” below. The results of pollutant emissions are directly linked to the inventory analysis and hence to the data that were collected from the engine OEMs.

The relevant findings of the Tank-to-Wake analysis are:

- SO_X and PM emissions are mainly dependent on the fuel used.
- SO_X emissions directly relate to the amount of sulphur in the fuel hence are highest for the high sulphur fuels such as HFO and lowest for LNG (assumed as zero within this study). This shows that most of the fuel that is used today (HFO with a global average sulphur content of 2.5 wt. % [10]) is not compliant to the IMO 2020 sulphur regulations.
- NO_X emissions are mainly dependent on the underlying combustion cycle and not directly linked to the fuel. Gas turbines running on a simple or combined Brayton cycle show low NO_X emission (1.17 – 1.59 g NO_X/kWh) for $MGO_{0.1}$ operation with LNG giving reduction of around 30 %. For reciprocating Diesel cycle engines, the NO_X emissions are mostly just below the respective Tier III limit. This is also the case for the 2-stroke slow speed Diesel-DF engine when running on LNG. The Otto cycle engines using LNG show a good margin to the respective Tier III limit. The 2-stroke slow speed Otto-DF engine reduces NO_X by nearly 80 % compared with oil-based fuel operation; the 4-stroke medium speed SI engine reduces NO_x by half with the DF engine resulting in 20 % NO_X-reduction which is comparable to the NO_X savings of the 4-stroke high speed engine.
- PM emissions of the 4-stroke medium speed engines are highest for the operation with HFO (1.23 g PM/kWh) and lowest for LNG (0.012 g PM/kWh on average). This means that LNG is able to deliver PM reduction of up to 99 % compared with HFO operation. When operating a EGCS, HFO PM levels can be reduced by 45.7 % resulting in a PM benefit of LNG of 98 %.

In summary, the combustion of LNG shows the lowest emissions of sulphur oxides and particulate matter of the fuels investigated. NO_X emissions are also reduced significantly compared with Diesel cycle operation.

Well-to-Wake Analysis: Greenhouse Gas Emissions

As described above, engine technologies used in shipping have quite different characteristics[43] and are used in different applications and hence not directly comparable. The study therefore intended to compare the use of LNG with the use of current and post-2020 oil-based marine fuels within a certain engine technology.

The main findings of the Well-to-Wake analysis investigating greenhouse gas emissions are:

- The GHG emissions resulting from the supply of the fuel make up 16 – 18 % of the overall WtW emissions of oil-based marine fuels and 21 – 25 % of the emissions of the LNG life cycle. This is also reflected by the higher CO_2-eq emissions per MJ of fuel of LNG compared with oil-based fuels.
- Carbon dioxide is the main contributor (~ 99 % for oil-based fuels and 77 – 98 % for LNG), followed by methane (mainly LNG) and nitrous oxide (N_2O). The latter is only contributing by

[43] e.g. combustion cycle, engine efficiency, single-/dual fuel capability, methane slip, etc.

around 1 %. Although methane emissions contribute up to a maximum 22 % of the total WtW GHG emissions of LNG, they are especially important due to the high characterisation factor (30 g CO_2-eq/g CH_4, IPCC AR5 GWP_{100}). Every gram gas combusted rather than directly released to the atmosphere reduces the TtW GHG emissions by 27.3 g CO_2-eq[44].

- The difference in overall WtW emissions for current $HFO_{2.5}$ and its investigated alternatives as of 2020 ($HFO_{>2.5}$ + EGCS, $LSFO_{0.5,\ Blend}$, $LSFO_{0.5,\ LScrude}$ and $MGO_{0.1}$) are minor. Looking at the 2-stroke slow speed Diesel engines, the respective WtW GHG emissions range from 686 – 704 g CO_2-eq/kWh indicating an overall deviation of 3 % (see Figure 6-3 and Figure 6-11).
- The WtW GHG emissions of 2-stroke slow speed engines running on HFO are 697 g CO_2-eq/kWh and 686 g CO_2-eq/kWh when using $MGO_{0.1}$. As the combustion principle of the two 2-stroke slow speed engines using LNG is different, GHG emissions also differ despite comparable fuel consumption. The 2-stroke slow speed Otto-DF engine reaches a GHG reduction with respect to HFO of 14 % and the 2-stroke slow speed Diesel-DF engine of 21 % with respect to HFO (see Figure 6-3), when running on LNG.
- The 4-stroke medium speed engines running with HFO emit 741 g CO_2-eq/kWh and 724 g CO_2-eq/kWh when running on $MGO_{0.1}$. For the 4-stroke dual fuel engine running on LNG, 692 g CO_2-eq/kWh are calculated of which 151 g CO_2-eq/kWh are related to unburned methane both from the supply as well as from the combustion phase. The GHG benefit compared with HFO is 7 %. CO_2-eq emissions of the SI engine resulting from methane emissions account for 96 g CO_2-eq/kWh leading to total WtW GHG emissions of 629 g CO_2-eq/kWh which equals a GHG reduction of 15 % with respect to HFO.
- 4-stroke high speed engines do not use high sulphur fuel and are hence evaluated based on the operation with $MGO_{0.1}$. In LNG operation, the 4-stroke high speed engine emit 812 g CO_2-eq/kWh of which 142 g CO_2-eq/kWh result from methane that is released to the atmosphere. This equals a reduction of 5 % compared with $MGO_{0.1}$ operation (859 g CO_2-eq/kWh, see Figure 6-7).
- Gas turbines running on $MGO_{0.1}$ show total WtW GHG emissions of 954 g CO_2-eq/kWh due to the lower efficiency of the Brayton cycle. The overall WtW GHG emissions in LNG operation are calculated to 798 g CO_2-eq/kWh indicating a reduction of 16 %. The same order of magnitude can be seen for combined cycle operation.

Considering the marine engines currently in operation and the amount of fuel burned in these engines, a complete switch from oil-based marine fuels to LNG could immediately reduce GHG emissions by ~15 % based on the assumptions made in this study (see section 6.3).

Scenario, Sensitivity and Uncertainty Analysis

A scenario on the influence of different EGCS (scrubber) technologies when operating on HFO shows that by increasing the fuel consumption by another 4 percentage points, the WtW GHG emissions increase by another 3.9 % compared with a 1 % increase in fuel consumption in the base case.

The scenario analysis on different maritime LNG bunkering pathways indicates a possible change in the WtT GHG results of LNG by -2 % when using shore-to-ship, or +5 % truck-to-ship instead of ship-to-ship. Under Well-to-Wake perspective the impact is less than 1 %, and hence insignificant.

The scenario analysis on the GHG Emissions for the supply of $LSFO_{0.5,\ Blend}$ shows that the effect of the variation of the additional CO_2 emissions by 2 to 10 % is negligible on the total WtW GHG results.

As the methane emissions resulting from incomplete combustion are one of the main reasons why the theoretical GHG reduction due to the lower carbon content of LNG are not currently being

[44] One gram LNG combusted results in 2.750 g CO_2-eq (see Annex B) compared with 30 g CO_2-eq when released directly to the atmosphere.

achieved, a lot of effort is being put into the development of engines with lower methane slip. This is addressed by two scenarios with different methane slip reduction ratios. As indicated by industry experts, a reduction of the methane slip of around 40 % by engine optimisation is attainable, which would reduce the WtW GHG emissions of LNG engines between 4-6 % with respect to current levels depending on the engine technology. Methane oxidation catalysts are a promising technology to further reduce WtW GHG emissions; this technology, however, has yet to mature and become commercially available for large bore internal combustion engines.

In addition, new conversion technologies, such as fuel cells, may also penetrate the market in the upcoming years and may further help to reduce GHG intensity of LNG fuelled vessels.

The sensitivity calculated using different impact categories (IPCC AR5 GWP_{100}, GWP_{20}, GTP_{100} and IPCC AR4 GWP_{100}) shows that the characterisation factor of methane has a significant influence on the final WtW results. E.g. for the 4-stroke medium speed Otto-DF engine, the calculated WtW results range from 82 % to 140 % compared with the base case GWP_{100} (AR5).

The sensitivity analyses on the technical parameters reveals a strong dependency of the WtW GHG intensity on the fuel consumption during combustion. The variations of the methane slip associated with LNG fuelled engines and the GHG emissions of the fuel supply for LNG and $HFO_{2.5}$ also show effects on the results.

An uncertainty analysis was performed to test the robustness of the WtW GHG results towards the combined parameter variations based on the LNG 4-stroke medium speed Otto-SI and the $HFO_{2.5}$ 4-stroke slow speed Diesel engine. The overall WtW GHG results are deemed to be robust based on the simulation results.

Outlook

This study indicates that a significant reduction of the WtW GHG emissions of LNG as a marine fuel can be achieved in future. The actual reduction will of course depend on the energy and actions of the relevant organisations involved.

In addition to the developments and improvements at the ship engines (see descriptions in the section above), developments and technical improvements in the LNG supply chain will reduce the WtT GHG emissions. Compared with fossil LNG, the use of blends, such as 80 % fossil LNG and 20 % renewable LNG supply (bioLNG and/or synthetic LNG) shows large reduction potentials and can reduce the WtW GHG emissions of LNG as a marine fuel by 12 to 18 %. The reduction potential for the use of 100% bioLNG or synthetic LNG is even higher (59 to 92 %).

8.2. Assumptions and Limitations

This assessment considers global warming as an environmental impact category only. However, the study assesses the supply and use of LNG as a marine fuel according to ISO 14040/44 [1] [2] and compares the GHG results with values for other marine fuels. This study is a Well-To-Wake analysis, however the data collection focuses more on the TtW analysis than the WtT analysis because the majority of the WtT primary data were already collected within the NGVA study [13]. These data are supplemented by *thinkstep*'s LCI databases [14] and literature. TtW primary data have been collected intensively for the combustion of the fuels in ship engines from engine OEMs.

The analysis of local pollutants (air quality) was limited to the use phase of the fuels and was carried out solely for the TtW part.

It must be noted that all conclusions are drawn from the considered global warming potential and local pollutants. The analysis of other environmental impact categories, indicators and pollutants might lead to other conclusions.

The assumptions made, and limitations identified within the assessment of the use and supply of LNG are the following:

- The global LNG supply is based on the analysis of five LNG supply regions (Europe, North America, Asia Pacific, China, and Middle East) which are based on the LNG supply chains of nine countries. Obviously not all regions are analysed, however, the main producing and consuming countries are investigated.
- Based on the distance and vessel capacities, the LNG carrier transport is considered for each region individually. Short distance transport (<125,000 m^3), long distance transport (125,000 m^3 to 180,000 m^3) and long-distance transport (>180,000 m^3) categories have been used. In addition, in all categories, the LNG carrier fleet mix by propulsion type has been modelled.
- For the LNG supply chain, mainly primary data from the NGVA study prepared by *thinkstep* [13] and data from *thinkstep's* GaBi LCI databases [14] were used. The data used were circulated among data providers in the participating companies (i.e. Shell [30], Total [31] and Exxon Mobil for the US LNG supply chain [27]) for validation . Primary data were used for maritime LNG bunkering, provided by Shell [30].
- The calculation of the WtT GHG results of refinery products is associated with uncertainties. Different crude oil properties and refinery settings, different levels of desulphurisation and blending ratios, and assumptions made, as well as methodological differences such as different allocation methods can lead to different results. However, the impact on a Well-to-Wake perspective is of minor relevance as a sensitivity analysis demonstrated.
- Emissions related to the manufacturing / building / installation of the infrastructure are not considered in this study because they are negligible.
- The calculations done within this study are based on the defined heating values and CO_2 emission factors for the respective fuels. Since a lot of different fuels with different qualities (and hence heating value, carbon content, impurities, etc.) are often defined as HFO and MGO, emissions of a certain fuel with deviating characteristics will most likely differ from the emissions calculated here.
- The data provided by engine manufacturers represent steady state test-bed conditions on four different engine loads. To represent reality as closely as possible, the IMO E2/E3 cycle was used as the main point of comparison. In consultation with the owner/operators within the wider SEA\LNG and SGMF membership it was agreed that this was a reasonable methodology to approximate the operating profile of the current fleet. However, different ship applications, itineraries, weather conditions and load profiles will have a big influence on the operation of the engines and result in different load profiles from those considered by the IMO E2/E3 cycle. In actual ship applications, high shares of transient engine operation are likely showing load shifts that are not reflected within this study. Port operations was also not in focus in this study. These have an influence on both the fuel consumption as well as the emissions (GHG and local pollutants). As the engines are mainly optimised on certain load points, transient engine operation will most likely increase GHG emissions.
- Dual fuel engines are capable of running on both oil-based fuels as well as on LNG. They typically start and stop on oil-based marine fuels. As the data collected is based on steady-state conditions, fuel switches from oil-based to LNG (and vice versa) and their related GHG emissions are not included.
- Unburnt hydrocarbon emissions other than methane or cut off from the evaluation due to the neglectable contribution (>0.5 %) to the total WtW GHG emissions.

- The calculation to quantify the theoretical benefit for the global ship fleet by introducing LNG (see section 6.4), is based on the assumption that the LNG engines evaluated are equally represented. For example, for 2-stroke engines, the Otto-DF and Diesel-DF engine each have a 50:50 share, and the same applies for the 4-stroke medium speed Otto-DF and Otto-SI medium speed engines.
- The energy consumption for the auxiliary services needed to run the main engine (see Table 5-4, mark-ups) are mostly expert judgement from industry experts and do not represent actual test-bed data.
- For certain engines, no primary data were provided for PM measurements. This is mostly the case for the large 2-stroke slow speed engines. The influence of black carbon is not investigated within this study.
- For the WtW GHG analysis of the renewable LNG supply chains, the assumption is made that no technical changes in engines are needed.
- The assumptions for the prospective outlook are only indicative and do not necessarily reflect the most probable future trends. Instead, they are intended to demonstrate the theoretical effect of potential developments.

In general, a conservative approach from a LNG perspective, i.e. not favouring LNG compared with oil-based fuelled engines, have been applied because a) for oil-based engines black carbon emissions are not considered (though potentially contributing to the global warming potential), b) for oil-based engines low mark-up values for EGCS operation are used, c) GHG impacts occurring as a result of a chemical reaction of used EGCS cleaning water (at open loop EGCS) and sea water are neglected and d) it is assumed that up to 90 % of the measured total hydrocarbon tailpipe emissions of the LNG engines are pure methane (recent studies show lower numbers).

8.3. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data, either collected within this study or taken from the NGVA study [13] in combination with consistent LCA information from literature and *thinkstep's* GaBi LCI databases [14] are used. The LCI datasets from the databases are widely distributed and used with the GaBi 8 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are crosschecked with the GHG results of datasets from other databases and with key parameters and GHG results from industry and literature regarding the respective goal and scope (time, technology and geographical coverage).

8.3.1. Precision and Completeness

- ✓ **Precision:** Measured primary data are considered to be of the highest precision, followed by calculated data, literature data and estimated data. As the majority of the relevant foreground data are measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be high for the TtW element. Most engine manufacturers provided test-bed data. Data of the MAN 2-stroke engines were provided by MAN via the CEAS Engine Calculation tool [71] and considered as representative by MAN[45]

[45] Via the CEAS tool, only consumption data can be accessed. Assumptions for the emissions were made in accordance with MAN where needed (see section 5.2) [49].

[49]. Variations across different manufacturers were balanced out by using averages. For the WtT part, mainly primary data from the NGVA study prepared by *thinkstep* [13] and data from *thinkstep's* GaBi LCI databases [14] were used. The data used were circulated among respective data providers in the participating companies (i.e. Shell [30], Total [31] and Exxon Mobil for the US LNG supply chain [27]) for validation and adapted, if necessary. Primary data were used for maritime LNG bunkering, provided by Shell [30]. All background data are sourced from *thinkstep's* GaBi LCI databases [14] with the documented precision. A list of the key background datasets is given Annex E. In summary, the precision can be seen as appropriate according to the goal and scope of the study.

- ✓ **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data is considered to be high. All background data are sourced from *thinkstep's* GaBi LCI databases [14] with the documented completeness.

8.3.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while all background data were sourced from the *thinkstep's* GaBi LCI databases [14] or literature.
- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modelling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modelling approaches.

8.3.3. Representativeness

- ✓ **Temporal:** Nearly all primary data were collected for the time period 2016-2018. All secondary data come from *thinkstep's* GaBi LCI databases [14] and are representative of the years 2015-2018. As the study intended to be up-to-date to the best extend possible, temporal representativeness is considered to be high.
- ✓ **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. Where country-specific or region-specific data were unavailable in exceptional cases, proxy data were used. An overview on the proxy data used is given in Annex E. Geographical representativeness is considered to be high with regards to the goal and scope of this study.
- ✓ **Technological:** All primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable in exceptional cases, proxy data were used. An overview on the proxy data used is given in Annex E. Technological representativeness is considered to be high.

In order to fill data gaps and to avoid inconsistencies, bilateral communication with the data providers helped to improve the quality of the data basis. As internal stakeholder process, the members of the project consortium were invited to provide feedback and comments to the draft version of the study report hence improving the quality of the assessment.

This study is ISO 14040/44 conforming [1], [2] and a review in accordance with ISO/TS 14071 [21] was performed.

thinkstep considers the data quality assessment to be sound. Areas where the data quality may be low, are discussed in detail in this report. Main data quality issues are addressed in the reports, such as the lack of primary data for e.g. LNG supply data for Australia, Indonesia, Malaysia and Trinidad

& Tobago, or the uncertainty in the calculation of WtT GHG results of oil-based marine fuels due to different crude oil properties and refinery settings, different levels of desulphurisation and blending ratios, assumptions made and methodological differences like different allocation methods.

8.4. Model Completeness and Consistency

8.4.1. Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regards to the goal and scope of this study.

8.4.2. Consistency

System boundaries, allocation rules, and the impact assessment method have been applied consistently throughout the study. All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimised by using *thinkstep's* GaBi LCI databases [14]. A list of the key background datasets is given in Annex E. This approach ensures that the different product systems are equivalent and that differences in the results reflect actual differences between the product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.

9. Conclusions, and Recommendations

9.1. Conclusions

This study is based on high quality, reliable, and up-to-date industry-based life cycle data for the use of LNG as a marine fuel and has been conducted in accordance with ISO 14040/14044 with respect to data quality, and the completeness and consistency of the model. The study has been validated by the consortium industry partners and critically reviewed in accordance with ISO/TS 14071 by an independent expert review panel.

The study demonstrates the benefit from reduced WtW GHG emissions that comes from the use of LNG as a marine fuel compared with current and post-2020 oil-based fuels like $HFO_{2.5}$, $HFO_{>2.5\ with\ EGCS}$, $MGO_{0.1}$, $LSFO_{0.5,\ Blend}$ and $LSFO_{0.5,\ LScrude}$. The lower carbon content and higher energy content of LNG compared with the other oil-based marine fuels lead to a better overall GHG performance even though the fuel supply of LNG shows a higher GHG profile.

The amount of unburned methane that escapes the combustion process, known as methane slip, and is released to the atmosphere and hence increases the GHG emissions of LNG is critical and is closely related to engine technology.

The study also shows that general statements of the benefit of LNG with respect to GHG emissions is difficult as the marine engine market consists of different engines technologies, developed for different applications and resulting in different engine characteristics (2-/4-stroke, single/dual fuel, combustion cycle, efficiency, methane slip, exhaust gas cleaning system, etc.), and hence different GHG intensities.

However, it is possible to make an indicative statement of an advantage of LNG versus oil-based marine fuels in the range of 4 to 22 %, depending on the engine technology. Nonetheless, considering that black carbon, which would increase the GHG intensity of the oil-based engines, was not included, this can be seen as a likely conservative calculated benefit from the use of LNG.

Looking at the global shipping fleet broken down by engine technology and corresponding fuel, the total GHG emissions could be reduced immediately by ~15 % when switching from oil-based marine fuels to LNG, not taking into account the requested investment needed to do this immediate change.

Technical developments and improvements in the LNG supply chain and LNG engines - especially regarding the reduction of methane emissions - play a fundamental role in further improving the benefits from the use of LNG as a marine fuel. The study shows that biofuels like bioLNG and synthetic LNG have a potential to further reduce the GHG intensity. Improvements in the combustion process in the engine focussing on the reduction of methane emissions and the use of specific after-treatment system can further decrease the overall WtW GHG emissions of LNG. New conversion technologies, such as fuel cells, may also penetrate the market in the upcoming years and may further help to reduce GHG intensity of LNG fuelled vessels.

Other alternative fuels such as Liquified Petroleum Gas (LPG) and methanol derived from Natural Gas, were assed briefly, see Annex G “Well-to-Wake – GHG Emissions of Methanol and LPG”. Initial results show GHG benefits for LPG compared with $HFO_{2.5}$, while methanol has slightly higher emissions than $HFO_{2.5}$. However, further analysis is needed to derive reliable conclusions on LPG and methanol.

As the study is based on primary, steady-state test-bed data for the combustion of the fuels and on the most recent available technology in the market, the results are seen as robust. Transient, on-board measurement data from ship operation can further increase the quality of the study.

Independent of the engine technology, the study shows, that LNG provides a major advantage in terms of improving air quality which is specifically relevant in ports and coastal areas. Beyond the benefits associated with reducing air pollutants (sulphur oxides, nitrogen oxides and particulate matters), LNG represent part of solution to reduce GHG emissions of international shipping by at least 50 % by 2050 (compared with 2008) and contribute to the International Maritime Organization (IMO) GHG reduction targets [5]. Methane emission from the supply chain and engine methane slip need to be reduced further to maximise the positive impact on both air quality and GHG emissions. The use of bioLNG or synthetic LNG is also key to reduce GHG impact.

9.2. Recommendations

Please note that the recommendations given in section 9.2 are out of the scope of the critical review since the section contains recommendations which are more general and not directly derived from the results of this study.

Improving Technology and Reducing Emissions

Technology progress and continuous improvement measures have increased energy efficiencies of ships and supply chains in the last years. There are a range of opportunities to improve efficiencies and reduce emissions across the supply chains further. This held true for the LNG as well as oil-based fuel systems. Examples are, application of best practices in crude oil and Natural Gas production, minimising global supply distances (trades), increasing efficiencies in liquefaction and refining and reducing methane emissions (methane slip) at ship engines (applicable for some engine technologies). Analyses in this study has shown that engine optimisation and the use of catalysts, can reduce Well-to-Wake GHG emissions by up to 10-15 %, depending on engine technology. This should be energetically pursued and implemented at the earliest opportunity by the relevant industry parties, in order to support the IMO 50 % GHG reduction target by 2050 [5].

As a consideration, regulations on methane slip may help by giving planning certainty to stakeholders, including ship owners, operators, manufacturers, and, importantly, investors. Since policy and regulatory certainty is often key to industry developments, a regulation may be seen as an appropriate strategy to support the GHG emission reduction target. Regulation may provide the essential ingredient of certainty needed by industry to provide direction for future actions, and, most importantly, investment. However, no industry sector has such requirements nowadays, including the current oil-based ship fleet, and hence competitive disadvantage should be avoided.

Recommendation: Gas supplying companies should continue working on minimising methane emissions along the LNG supply chain.

Recommendation: Gas supplying companies should invest and develop/communicate action plans for bio and synthetic gas production.

Recommendation: The ship engine manufacturers (OEMs) should increase investment and effort on engine optimisation, particularly in the areas of energy efficiency and minimisation of methane slip. They should also increase research on the use of catalysts.

Recommendation: The ship and engine manufacturers (OEMs) should develop and publish action plans to reduce methane slip. This plan will demonstrate to policy makers and the community the focus and commitment of the industry. The plan should give milestones for action and should be regularly reviewed and the progress used as part of industry communication programmes.

Recommendation: The ship and engine manufacturers (OEMs) as well as the gas suppling companies should consult with Government and other appropriate groups, including customers and other stakeholders, on possible policies and regulations that could provide certainty for future developments.

The Importance of Accurate and Comprehensive Information

This study has used best available data as its basis. Limitations of data, including the necessity of using literature sources where no other was available, and out-of-date data, have been clearly identified in order to provide a transparent data basis. These estimations and assumptions represent a limitation to the results.

Developing appropriate policies and making sound decisions requires accurate, up-to-date data. All relevant ship engine technologies including its special characteristics, such as methane emissions, have been considered and analysed in a differentiated manner in this study. Global fuel supply chains have been analysed on a regional level, and LNG fuelled engines have been compared with current and post-2020 oil-based fuelled vessels.

Furthermore, the scope of this study should be broadened to cover various environmental impacts and resource depletion. In particular the effect of black carbon is currently being discussed widely, which would imply further research to be integrated in a subsequent GHG intensity study.

Recommendation: Develop technologies to enable making on-board measurements looking at transient (real life) operation. This would help to better understand real time fuel consumption and the amount and significance of methane slip.

Recommendation: The extension of the scope to other environmental aspects and impacts, such as black carbon, heavy metals, and resource efficiency would provide a more complete evaluation. It would add a broader quantitative picture to the potential benefits of LNG and complete the GHG impact assessment.

Recommendation: Due to the uncertainty about the post-2020 oil-based fuels, and the lack of information which marine fuel will penetrate the market, as well as ongoing developments in engine technologies, and potential new technologies entering the market, e.g. fuel cells, the study should be updated in 2021/2022.

Economic Aspects

Decisions are often made based on the economic performance of a product system. An economic analysis of the total cost of ownership (TCO) would add a further dimension to this study and would help future ship owners to make more holistic decisions on the product system of choice. This is not only of interest for the fuel selection between LNG and oil-based fuels, but also to quantify the different costs which may accompany the different options for post-2020 fuels.

Recommendation: Perform a total cost of ownership (TCO) analysis, including environmental and human health impacts, for the different engine technologies and corresponding supply chains to analyse the economic impact of LNG fuelled vessels compared with its oil-based.

Dissemination

The results of this study should be used for dialogue with external stakeholders involved in the determination of fuel emission impacts, and development of regulations. These include the International Maritime Organization (IMO), national Environmental Protection Agencies (EPA), and institutions such as the European Commission.

Recommendation: The key results of this study should be disseminated to and discussed with relevant policy and decision makers in government with the objective informing about harmonised usage of LNG related data.

Recommendation: The key results of this study should be disseminated to and discussed with representatives of the International Maritime Organization (IMO) to facilitate the input of high quality, up-to-date information into upcoming work.

The overarching recommendation from this study, asks for further investigations to validate if additional energy efficiency measures and improved logistics and speed adaptations, may close the gap between the calculated GHG reduction provided by LNG and the 50 % GHG emission reduction target to 2050 of the IMO. Beyond question, LNG has a great potential to contribute, apart from the significant benefits in terms of air quality, to the GHG reduction target, however methane emissions need to be reduced to a lowest value possible.

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Annex A: Natural Gas and LNG

Natural Gas

Natural gas is a gaseous hydrocarbon fuel obtained from underground sources. Natural gas remains in the gaseous state under ambient temperature and atmospheric pressure. Conventional natural gas is commonly found in underground sandstone and limestone formation whereas unconventional gas refers to coal bed methane, shale gas, tight gas and gas hydrates.

Composition:

A mixture of primarily methane (CH_4) and smaller amounts of ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}) and other higher hydrocarbons. It generally also includes some inert gases, such as nitrogen (N_2) and carbon dioxide (CO_2), plus trace amounts of impurities (ppb, parts per billion), such as sulphur (e.g., H_2S), and mercury (Hg).

Characteristics:

- Colourless, odourless, tasteless, shapeless and lighter than air. At atmospheric pressure, it is gaseous at any temperature over -162 ºC
- High ignition temperature and narrow flammability range, making it an inherently safe fossil fuel compared with other fuel sources
- Condenses to Liquefied Natural Gas (LNG) when cooled to a temperature of approximately -162°C at atmospheric pressure
- Commercialised natural gas is practically sulphur free and produces - if combusted - virtually no sulphur dioxide (SO_2). It emits lower levels of nitrogen oxides (NO_X) and CO_2 than other fossil fuels

Liquefied Natural Gas (LNG)

Purified natural gas is liquefied for storage and transportation purpose. At atmospheric pressure, LNG stays liquid below temperatures below approx. -162°C.

Composition:

LNG is a mixture of primarily methane (CH_4) and smaller amounts of ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}) and other higher hydrocarbons. It generally also includes some inert gases, such as nitrogen (N_2), plus trace amounts of impurities, such as sulphur (e.g., H_2S), carbon dioxide (CO_2) and mercury (Hg). Since natural gas is further purified before it is liquefied to LNG, LNG contains typically less higher hydrocarbons and impurities compared with gaseous natural gas.

Characteristics

- Colourless, odourless, tasteless and lighter than air
- Volume is typically ~600 times smaller in a liquid state based on composition, pressure and temperature
- With its clean burning properties, it produces less air pollutants and can be more efficient compared with traditional fuels e.g., oil, diesel, wood, coal and other organic matters
- LNG is an option when pipeline gas is not possible or economically viable due to distance, environmental context (deep sea, natural reserve, mountains) or political reasons.

Annex B: Default Values and Conversion Factors

Unit Conversion Factor

Data in g CO_2-eq/MJ (LHV) have to be multiplied by conversion factor 3.6 to receive the data in g CO_2-eq/kWh (LHV).

Characterisation Factors

Table B-1 shows the characterisation factors used for the evaluation of the GWP and GTP based on the IPCC AR4 and AR5 [15], [18].

Table B-1: Emission factors of different IPCC characterisation schemes [15], [18]

	CO_2	CH_4	N_2O
IPCC AR5 GWP_{100}	1	30	265
IPCC AR4 GWP_{100}	1	25	298
IPCC AR5 GWP_{20}	1	85	264
IPCC AR5 GTP_{100}	1	6	234

IMO Regulation on NO_X Emissions

The IMO limit for NO_X emissions are defined in the International Convention for the Prevention of Pollution from Ships (MARPOL) regulation 13 for all marine engines with a maximum continuous rating greater than 130 kW. Different levels of control (Tier) apply based on the construction date of the ship and the respective NO_X limit derived based on the engine's rated speed. Tier III limits only apply everywhere to ships that are operating in Emission Control Areas (ECA) established to limit NO_X emissions. Outside these areas, Tier II limits apply. [72]

Table B-2: IMO NO_X limits as defined in MARPOL Annex VI regulation 13 [72]

Tier	Ship construction date on or after	Total weighted cycle emission limit n = engine's rated speed (rpm) n < 130 [g/kWh]	n = 130 – 1999 [g/kWh]	n ≥ 2000 [g/kWh]
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016	3.4	$9 \cdot n^{(-0.2)}$ e.g., 720 rpm – 2.4	2.0

IMO Regulation on Sulphur and PM Emissions

The IMO regulation 14 of MARPOL defines certain limits on the sulphur content of the fuel bunkered and hence used on the ship. By doing this, the particulate matter and sulphur oxide emissions from the engine are directly influenced and can be kept under a certain limit. By using exhaust gas cleaning systems (EGCS) designed to decrease the sulphur oxide emissions of the combustion gases such as a scrubber, fuels with a higher sulphur content than defined in regulation 14 can be used. As for the NO_X emissions, the IMO differentiates between operation in an ECA zone established to limit emissions of SO_X and PM and the operation outside of such regions. [73]

Table B-3: IMO limits on the sulphur content of marine fuels as defined in MARPOL Annex VI regulation 14 [73]

Outside an ECA established to limit SO_X and particulate matter emissions	Inside an ECA established to limit SO_X and particulate matter emissions
4.5% wt. % prior to 1 January 2012	1.5 wt. % prior to 1 July 2010
3.5% wt. % on and after 1 January 2012	1.0 wt. % on and after 1 July 2010
0.5% wt. % on and after 1 January 2020	0.1 wt. % on and after 1 January 2015

IMO E2/E3 Emission Cycle

The data evaluated within this study is based on the IMO E2/E3 cycle for main propulsion engines. The cycle is used for the engine certification regarding the emissions of NO_x with respect to the Tier limits mentioned above and described in the IMO NO_x technical code [74].

The IMO E2/E3 weighting factors are used to calculate the weighted specific fuel consumption as well as the weighted specific emissions for CH_4, PM, N_2O, NO_x and SO_x. The weighting factors used in the IMO NO_X technical code [74] are applicable to the mass flow rates of the gas. As the data collected within the study are given in g / kWh at the engine load points (25, 50, 75 and 100 % load), the weighting factors have to be reformulated taking into account the measured power (see also section 5.12.6 in the NO_X Technical Code [74]). The resulting weighting factors are shown in Table B-4. The 75 % engine load point makes up 55 % of the overall value and hence contributes the most.

Table B-4: Weighting factors for the IMO E2/E3 cycle for constant speed main propulsion engines [74]

Engine Load Point	25 %	50 %	75 %	100 %
Speed	100 %	100 %	100 %	100 %
E2/E3 weighting factor (mass flow rates)	0.15	0.15	0.5	0.2
E2/E3 weighting factor for specific consumption / emissions	**0.05**	**0.11**	**0.55**	**0.29**

Note, the consumption values and emissions used in the study are calculated as the sum of each weighting factors per engine load point multiplied by the measured specific consumption / emissions per engine load point. For gas turbines the IMO E2/E3 cycle does not apply. Here, an average of the 75 % and 100 % engine load is calculated (representing 87.5 % load).

Engine Efficiency

The fuel consumption vales collected represents the mass of fuel needed to delivery 1 kWh of mechanical energy (g/kWh). The engine efficiency is defined as the ratio of mechanical energy to energy content of the fuel. If the fuel consumption is known, the engine efficiency can be calculated as follows:

$$\eta_{engine} = \frac{P_{out}}{P_{in}} = \frac{3600}{m_{fuel} * LHV_{fuel}}$$

With m_{fuel} being the fuel consumption (g/kWh), and LHV (MJ/kg) as defined in Table B-5 and Table B-6. E.g. the 4-stroke medium speed Otto-SI engine has an engine efficiency of 47 % (gas consumption of 155.8 g/kWh). The diesel counterpart, the 4-stroke medium speed CI engine, has an efficiency of 46 % (MGO consumption of 184.7 g/kWh).

Number Format

For the number format in this report, a decimal dot is applied. Example: 1,234.56. If not otherwise specified, all values are related to the corresponding output.

Natural Gas and Liquefied Natural Gas (LNG)

The values were taken from [75], [3] and *thinkstep's* GaBi LCI databases [14]. Please note that all energy related numbers in this report refer to the lower heating value (LHV). Table B-5 summarises the main properties for Natural Gas and LNG.

Table B-5: Natural Gas and Liquefied Natural Gas (LNG) properties and default values [75] [3], [14].

Properties	Unit	Natural Gas	LNG
Density	[kg/m³]	0.763	450
HHV	[MJ/kg]	52.5	54.1
LHV	[MJ/kg]	47.5	49.2
HHV/LHV	[-]	1.10	1.10
CO_2-emission Factor	[g CO_2/$MJ_{combusted}$]	55.6	55.9
CO_2-emission Factor	[g CO_2/g fuel $_{combusted}$]	2.641	2.750

Heavy Fuel Oil (HFO, Marine Gas Oil (MGO), Methanol and LPG

In Table B-6 properties and default values for other fuels are illustrated. These figures were taken from [75], [3] and *thinkstep's* GaBi LCI databases [14]. LSFO is assumed to have the same emission factor on an energy basis as $HFO_{2.5}$ and $HFO_{>2.5}$.

Table B-6: Other fuel properties and default values [75] [3], [14].

	Unit	$HFO_{2.5}$ / $HFO_{>2.5}$	$LSFO_{0.5, LS\ crude}$ / $LSFO_{0.5, Blend}$	$MGO_{0.1}$	Methanol	LPG
Lower heating value (LHV)	[MJ/kg]	40.2	41.0	42.7	19.9	46.0
Sulphur content	[wt.% S]	2.5 / >2.5	0.5	0.1	-	-
CO_2-emission factor[46]	[g CO_2/ $MJ_{combusted}$]	77.5	77.5	75.1	69.1	65.7
CO_2-emissions factor	[g CO_2/ g $fuel_{combusted}$]	3.114	3.176	3.206	1.375	3.020

Table B-7 states the sulphur content of the region-specific crude oil going into the refinery. These data are sourced from *thinkstep's* GaBi LCI databases [14] and personal communication with an expert from the oil industry [39].

Table B-7: Sulphur content and API gravity of region-specific crude oil [14], [39]

Region	Europe	North America	Asia Pacific	China	Middle East
Sulphur content of crude oil [wt.% S]	1.08	1.43	1.05	1.05	1.30
API gravity [°]	34.4	30.7	35.4	30.9	32.9

[46] CO_2-emission factor, at complete combustion.

Annex C: Well-to-Tank - Scope of the Study

Calculation of LNG Consumption Mixes

The LNG consumption mix of a region considers the indigenous LNG production of the member countries (if applicable) of a region as well as the LNG imports from LNG producing countries to the region and LNG exports of the member countries of the region. The LNG consumption mixes of the five main bunker regions (Europe, North America, Asia Pacific, China and Middle East) are analysed in this study as well as a global LNG consumption mix which is calculated based on these five regions. The mixes are based on two public studies [32] and [76] as not all the required information is available in one study. The approach for the calculation of the consumption mixes is explained below.

First, the member countries of the five regions are defined:

- Europe: all member countries of the European Union (EU-28)
- North America: Canada, Mexico and the USA
- Asia Pacific: Indonesia, Japan, Malaysia, Singapore, South Korea, Taiwan and Thailand
- China: China
- Middle East: Egypt, Israel, Jordan, Kuwait, Oman, Qatar and the United Arab Emirates.

The LNG consumption mix of a region is calculated based on the indigenous LNG production of the member countries (using the capacity and utilisation of the liquefaction plants), the LNG imports from LNG producing countries and the LNG exports of the member countries:

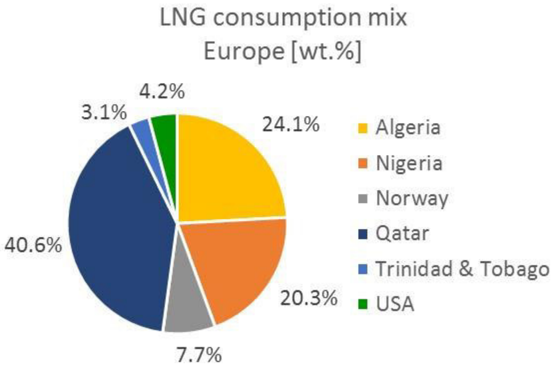
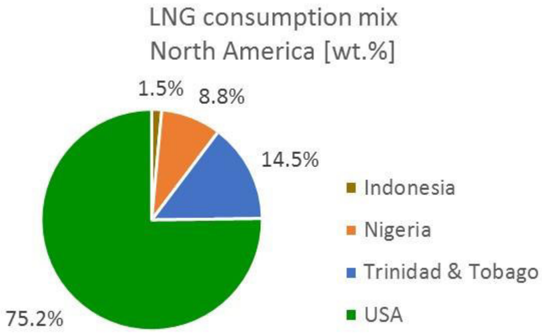
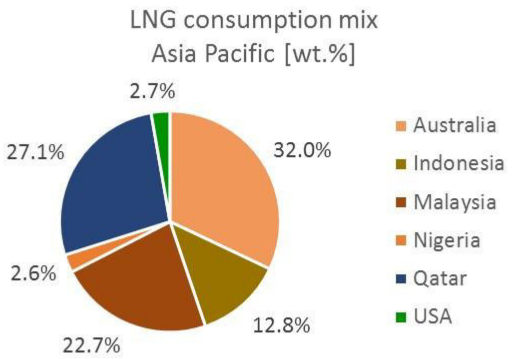
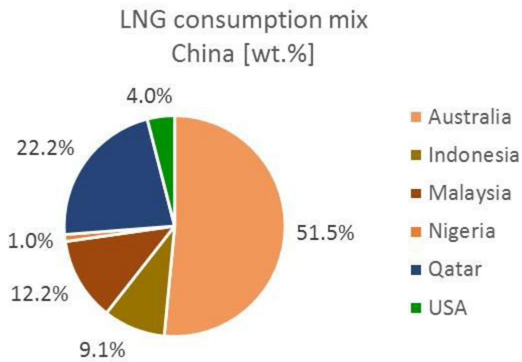
LNG consumption mix = indigenous LNG production + LNG imports - LNG exports.

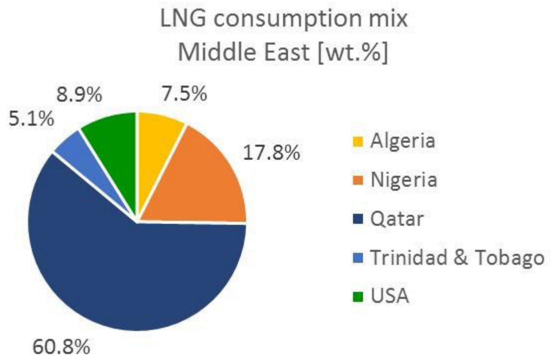
The LNG production of the following countries were defined based on the identification of the most important and the emerging supply chains for LNG bunker fuel and investigated (in alphabetical order):

- Algeria
- Australia
- Indonesia
- Malaysia
- Nigeria
- Norway
- Qatar
- Trinidad & Tobago
- USA.

These nine LNG producing countries were analysed with the aim of reaching the defined threshold of 70 % of the region-specific consumption mixes which was achieved for all regions under consideration. For the GHG modelling of the LNG supply chains of the regions, the LNG consumption mixes are scaled to 100 % (e.g. for China from 90 % to 100 %) as presented in Table C-1.

Table C-1: Liquefied Natural Gas (LNG) consumption mixes 2017 per region as used in this study [32] [76] [23]

<table>
<tr><th>Region</th><th>Modelled LNG consumption mix</th><th>Coverage</th></tr>
<tr><td>Europe</td><td>
</td><td>The countries included in the LNG consumption mix modelled cover >92 % of the actual LNG consumption mix of Europe.</td></tr>
<tr><td>North America</td><td>
</td><td>The countries included in the LNG consumption mix modelled cover >92 % of the actual LNG consumption mix of the region of North America.</td></tr>
<tr><td>Asia Pacific</td><td>
</td><td>The countries included in the LNG consumption mix modelled cover >74 % of the actual LNG consumption mix of the region of the Asia Pacific.</td></tr>
<tr><td>China</td><td>
</td><td>The countries included in the LNG consumption mix modelled cover >90 % of the actual LNG consumption mix of China.</td></tr>
</table>

Region	Modelled LNG consumption mix	Coverage
Middle East		The countries included in the LNG consumption mix modelled cover >72 % of the actual LNG consumption mix of the Middle East.

In addition to these regions, the global LNG consumption mix is calculated based on the absolute LNG consumption data of the five LNG consumption regions as shown in Figure C-1.

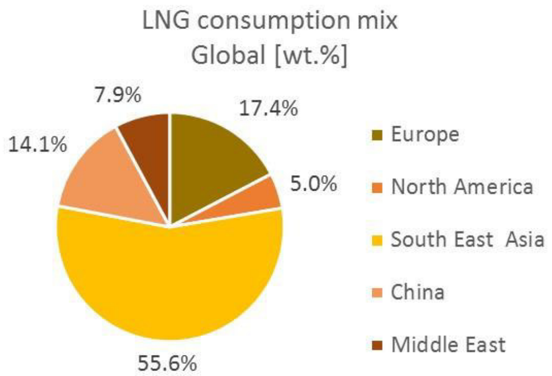


Figure C-1: Global Liquefied Natural Gas (LNG) consumption mix 2017 as used in this study [32] [76] [23]

Calculation of Oil-based Marine Fuel Consumption Mixes

Following the same approach as for LNG, five consumption regions are considered for the oil-based marine fuel supply chains. The procedure is explained below for HFO but is the same for all oil-based marine fuels considered in this study.

The HFO consumption mixes of the five regions (Europe, North America, Asia Pacific, China and Middle East) are analysed in this study as well as a global HFO consumption mix which is calculated based on these five regions. The approach for the calculation of the consumption mixes is explained below.

First, the member countries of the five regions are defined:

- Europe: all member countries of the European Union (EU-28)
- North America: Canada, Mexico and the USA
- Asia Pacific: Indonesia, Japan, Malaysia, Myanmar, Philippines, Singapore, South Korea, Taiwan and Thailand
- China: China
- Middle East: Iran, Iraq, Israel, Kuwait, Oman, Qatar, Saudi Arabia, Turkey and the United Arab Emirates.

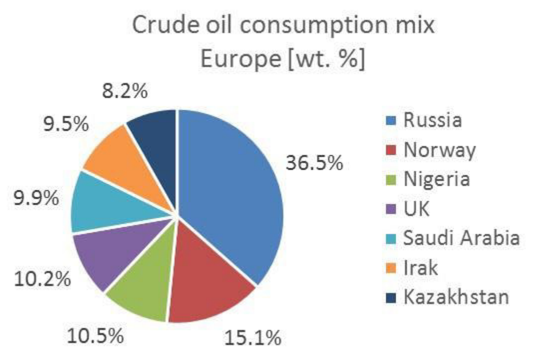
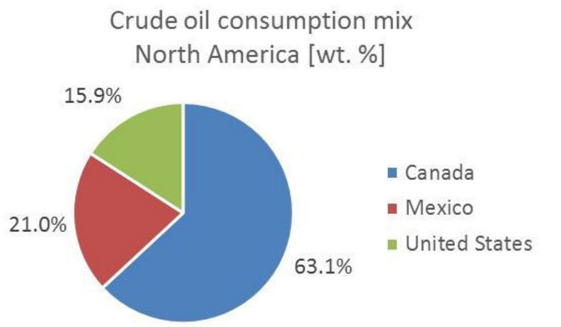
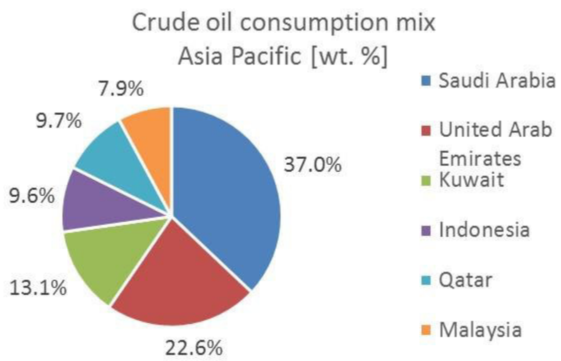
Based on the indigenous crude oil production of the member countries, the imports from crude oil producing countries and the crude oil exports of the member countries, the crude oil consumption mix of a region is calculated:

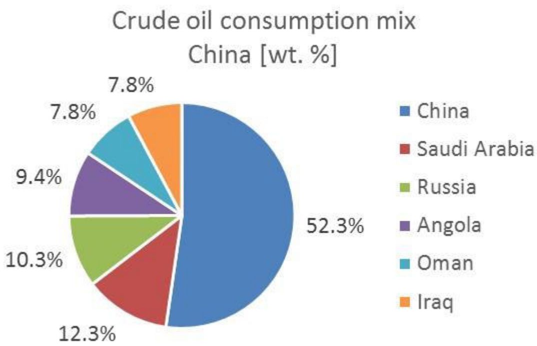
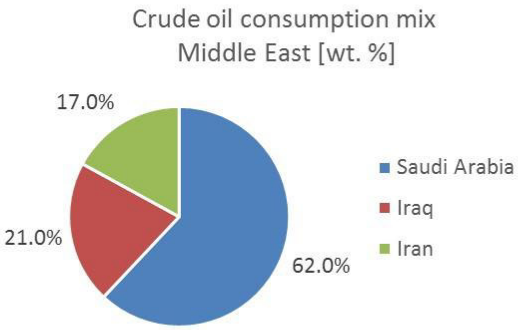
Crude oil consumption mix = indigenous crude oil production + crude oil imports - crude oil exports.

Data on the crude oil consumption are based on the Oil Information 2017 [77] and World Energy Statistics 2017 [78], published by the International Energy Agency (IEA) (reference year: 2015). All shares needed to meet the defined threshold of 70 % of the region-specific consumption mixes are taken into account which led to the analysis of the crude oil supply chains of the following countries (in alphabetical order): Angola, Canada, China, Indonesia, Iran, Iraq, Kazakhstan, Kuwait, Oman, Malaysia, Mexico, Nigeria, Norway, Qatar, Russia, Saudi Arabia, the United Arab Emirates, the United Kingdom, and the United States.

For the modelling of the crude oil supply chains of the regions, the crude oil consumption mixes are scaled to 100 % (e.g. for China from 75 % to 100 %) as presented in Table C-2.

Table C-2: Crude oil consumption mixes per region as used in this study [77] [78] [23]

Region	Modelled crude oil consumption mix	Coverage
Europe		The countries included in the crude oil consumption mix modelled cover 71 % of the actual crude oil consumption mix of the Europe.
North America		The countries included in the crude oil consumption mix modelled cover 80 % of the actual crude oil consumption mix of the region of North America.
Asia Pacific		The countries included in the crude oil consumption mix modelled cover 75 % of the actual crude oil consumption mix of the region of the Asia Pacific.

Region	Modelled crude oil consumption mix	Coverage
China		The countries included in the crude oil consumption mix modelled cover 75 % of the actual crude oil consumption mix of China.
Middle East		The countries included in the crude oil consumption mix modelled cover 75 % of the actual crude oil consumption mix of the Middle East.

The global $HFO_{2.5}$ consumption mix is calculated based on the absolute crude oil consumption data of the five HFO consuming regions, published by the International Energy Agency (IEA) (reference year: 2015) as shown in Figure C-2 [77] [78]. The absolute crude oil consumption data are used as a proxy since the absolute HFO consumption data for the regions are not available.

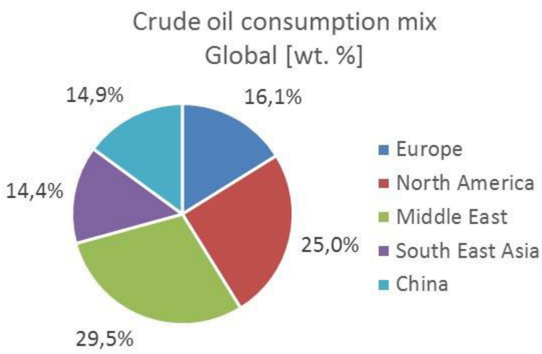


Figure C-2: Global crude oil consumption mix as used in this study [77] [78] [23]

Information on the Well-to-Tank inventory analysis (Annex D) and GHG emissions (Annex E) are shown in the following sections.

Annex D: Well-to-Tank - Inventory Analysis

Production and Processing

Data for the Natural Gas production and processing in Algeria, Nigeria, Norway and Qatar are taken from [13]. The Natural Gas production and processing data for Australia, Indonesia, Malaysia, Trinidad & Tobago and the USA are sourced from *thinkstep's* GaBi LCI databases [14]. Data for US unconventional gas production and processing, including data on the latest analyses of fugitive emissions associated with hydraulic fracturing ("fracking"), are provided by Exxon Mobil [27] and literature [28] [29], and data gaps closed by *thinkstep's* GaBi LCI databases [14]. The following tables specify the key parameters. The quantity of flared gas is included in the quantity of natural gas for energy use. Compared with the other countries considered, Indonesia has by far the highest energy consumption and flaring rates followed by Nigeria.

Table D-1: Energy use (LHV) and gas losses for conventional gas production & processing [13] [14]

Parameter	Unit	Algeria	Australia	Indonesia	Malaysia	Nigeria
Electricity	kJ/t	402,000	1,162	952	1,180	281
Diesel fuel	kJ/t	0	30,211	32,808	31,292	4,782
Crude oil	kJ/t	34,405	0	0	0	0
Natural Gas	kJ/t	1,461,316	539,289	4,392,765	875,643	2,778,789
TOTAL	**kJ/t**	**1,897,721**	**570,662**	**4,426,526**	**908,115**	**2,783,852**
Gas losses	vol.%	2.00	0.10	0.46	0.75	0.11

Table D-2: Energy use (LHV) and gas losses for conventional gas production & processing [13] [14] (continued)

Parameter	Unit	Norway	Qatar	Trinidad & Tobago	USA
Electricity	kJ/t	136,094	0	1,991	20,668
Diesel fuel	kJ/t	92,552	0	25,541	40,320
Crude oil	kJ/t	0	0	0	0
Natural Gas	kJ/t	1,063,493	1,479,673	784,829	1,616,026
TOTAL	**kJ/t**	**1,292,140**	**1,479,673**	**812,361**	**1,677,014**
Gas losses	vol.%	0.01	0.06	0.08	0.10

Table D-3: Energy use (LHV) and gas losses for unconventional gas production and processing [14] [27] [28] [29]

Parameter	Unit	Australia	USA
Electricity	kJ/t	10,228	6,090
Diesel fuel	kJ/t	865,401	367,068
Crude oil	kJ/t	0	0
Natural Gas	kJ/t	399,626	1,040,308
TOTAL	**kJ/t**	**1,275,254**	**1,413,465**
Gas losses	vol.%	0.22	0.62

Natural Gas Pipeline Transport

Data for the Natural gas pipeline transport from the gas production and processing fields to liquefaction plants are sourced from *thinkstep's* GaBi LCI databases [14]. The following tables specify the key parameters. For offshore pipeline transport, the gas losses are set to zero, since the pipeline is a closed system and there is no re-compression taking place. Potential methane emissions of the initial compression unit are included in the processing data.

Table D-4: Distance, kind of pipeline, energy use (LHV) and gas losses for gas transport from the gas production and processing fields to liquefaction plants [14]

Parameter	Unit	Algeria	Australia	Indonesia	Malaysia	Nigeria
Distance	km	542	475	60	500	200
Onshore/offshore	-	onshore	offshore	offshore	onshore	offshore
Electricity	J/(J*km)	0	0	0	0	0
Diesel fuel	J/(J*km)	0	0	0	0	0
Natural Gas	J/(J*km)	3.00E-05	3.00E-05	3.00E-05	3.00E-05	3.00E-05
TOTAL	**J/(J*km)**	**3.00E-05**	**3.00E-05**	**3.00E-05**	**3.00E-05**	**3.00E-05**
Gas losses	Vol.%	8.67E-03	-	-	5.62E-02	-

Table D-5: Distance, kind of pipeline, energy use (LHV) and gas losses for gas transport from the gas production and processing fields to liquefaction plants [14] (continued)

Parameter	Unit	Norway	Qatar	Trinidad & Tobago	USA
Distance	Km	160	80	80	500
Onshore/offshore	-	offshore	offshore	onshore	onshore
Electricity	J/(J*km)	3.26E-06	0	0	0
Diesel fuel	J/(J*km)	1.17E-09	0	0	0
Natural Gas	J/(J*km)	4.42E-06	3.00E-05	3.00E-05	3.00E-05
TOTAL	**J/(J*km)**	**7.68E-06**	**3.00E-05**	**3.00E-05**	**3.00E-05**
Gas losses	Vol.%	-	-	9.00E-03	2.37E-01

Natural Gas Liquefaction (including Purification)

For Natural gas purification and liquefaction, *thinkstep's* proprietary "GaBi LNG model" was used to calculate the GHG intensity [14]. The different liquefaction technologies (as listed in the following table) mainly differ by the refrigerant used and the technology to cool (liquify) the natural gas.

Table D-6: Technology mix of liquefaction (weighted by installed capacity) based on [32]

Technology	Unit	Algeria	Australia	Indonesia	Malaysia	Nigeria
AP-X (Air Product and Chemicals, Inc.)	%	0	0	0	0	0
AP-C3MR (Air Product and Chemicals, Inc.)	%	81	22	71	88	100
AP-C3MR/SplitMR (Air Product, Inc.),	%	19	24	29	12	-
Optimised Cascade (COPOC) (ConocoPhillips)	%	0	54	0	0	0
MCR Linde MFC	%	0	0	0	0	0

Table D-7: Technology mix of liquefaction (weighted by installed capacity) based on [32] (continued)

Technology	Unit	Norway	Qatar	Trinidad & Tobago	USA
AP-X (Air Product and Chemicals, Inc.)	%	-	61	-	-
AP-C3MR (Air Product and Chemicals, Inc.)	%	-	21	-	-
AP-C3MR/SplitMR (Air Product, Inc.),	%	-	18	-	-
Optimised Cascade (COPOC) (ConocoPhillips)	%	-	-	100	100
MCR Linde MFC	%	100	-	-	-

Table D-8: Average annual ambient temperature, and CCS [14]

Technology	Unit	Algeria	Australia	Indonesia	Malaysia	Nigeria
Average ambient temperature	°C	20	22	26	25	27
Share of separated CO_2 for CCS	wt.%	0	0	0	0	0

Table D-9: Average annual ambient temperature, and CCS [14] (continued)

Technology	Unit	Norway	Qatar	Trinidad & Tobago	USA
Average ambient temperature	°C	1	27	26	15
Share of separated CO_2 for CCS	wt.%	100	0	0	0

Table D-10: Energy use (LHV), boil-off gas rate and recovery for gas purification and liquefaction [14]

Parameter	Unit	Algeria OLD[47]	Algeria	Australia	Indonesia	Malaysia
Electricity	kJ/t	89,700	182,421	143,981	186,754	187,724
Natural Gas	kJ/t	11,217,917	4,365,318	5,113,905	4,996,224	4,997,131
TOTAL	**kJ/t**	**11,307,617**	**4,547,738**	**5,257,886**	**5,182,977**	**5,184,855**
Boil-off gas rate	wt.%	3	3	3	3	3
of which: BOG recovery	wt.%	99	99	99	99	99
of which: CH_4 emissions	wt.%	1	1	1	1	1

Table D-11: Energy use (LHV), boil-off gas rate and recovery for gas purification and liquefaction [14] (continued)

Parameter	Unit	Nigeria	Norway	Qatar	Trinidad & Tobago	USA
Electricity	kJ/t	188,422	66,304	290,520	109,218	109,070
Natural Gas	kJ/t	4,847,127	3,485,146	5,220,150	5,802,591	5,012,708
TOTAL	**kJ/t**	**5,035,549**	**3,551,450**	**5,510,670**	**5,911,809**	**5,121,777**
Boil-off gas rate	wt.%	3	1.8	3	3	3
of which: BOG recovery	wt.%	99	99	99	99	99
of which: CH_4 emissions	wt.%	1	1	1	1	1

LNG Carrier Transport

Based on the distance and the vessel capacities, the GHG model distinguishes between the following three LNG transport types:

- Short distance transport (<125,000 m³): The LNG carrier fleet with vessel capacities <125,000 m³ is applied for LNG transport within a region and between regions with a short distance (e.g. LNG transport from Algeria to Europe). The LNG carrier fleet is illustrated in Table D-12.
- Long distance transport (125,000 m³ to 180,000 m³): The LNG carrier fleet for long distance transport (capacities from 125,000 m³ to 180,000 m³) as shown in Table D-13 is used for the transport of LNG between regions.
- Long distance transport (>180,000 m³): The LNG carrier fleet with capacities >180,000 m³ is used for long distance transport, in particular from Qatar (please see Table D-14).

[47] Based on the NGVA study [9], it is assumed that 56 % of the Algerian LNG is produced from modern new LNG plants. The GHG intensity of old plants is estimated using literature [43].

Table D-12: Global market share of propulsion types of <125,000 m³ LNG carriers (related to vessel capacities) in 2017, own calculations based on IGU [32]

Propulsion type	Value/Unit
Steam turbine	100 %
Tri-fuel diesel electric (TFDE)	0 %
Dual-fuel diesel electric (DFDE)	0 %
Slow speed diesel (SSD)	0 %
ME-GI	0 %
X-DF	0 %
Others	0 %

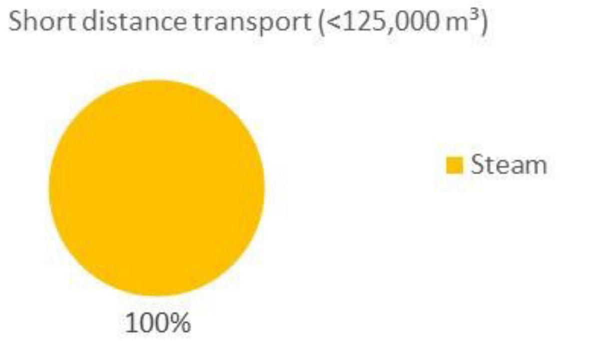


Table D-13: Global market share of propulsion types of 125,000 to 180,000 m³ LNG carriers (related to vessel capacities) in 2017, own calculations based on IGU [32]

Propulsion type	Value/Unit
Steam turbine	53 %
Tri-fuel diesel electric (TFDE)	32%
Dual-fuel diesel electric (DFDE)	6 %
Slow speed diesel (SSD)	1 %
ME-GI	5 %
X-DF	0 %
Others	3 %

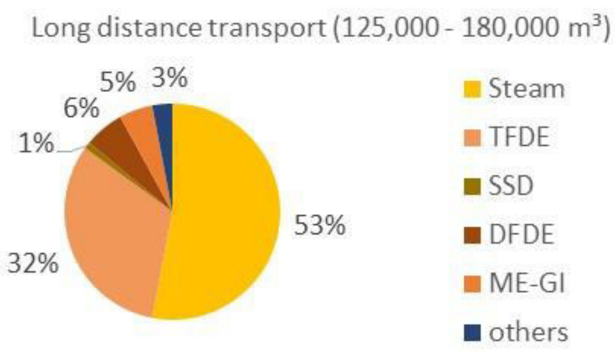


Table D-14: Global market share of propulsion types of >180,000 m³ LNG carriers (related to vessel capacities) in 2017, own calculations based on IGU [32]

Propulsion type	Value/Unit
Steam turbine	0 %
Tri-fuel diesel electric (TFDE)	0 %
Dual-fuel diesel electric (DFDE)	0 %
Slow speed diesel (SSD)	96 %
ME-GI	2 %
X-DF	2 %
Others	0 %

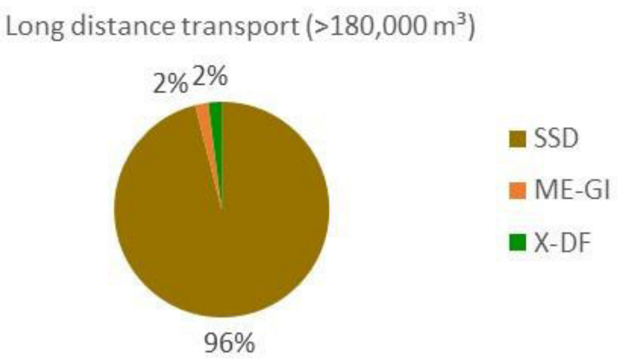


Table D-15 and Table D-16 summarise the fuel consumption and methane emissions of the LNG carrier transport applied to all LNG imports independent of country of origin.

Table D-15: LNG carrier fuel consumption (LHV) and methane emissions of <125,000 m³ LNG carriers, taken from NGVA study [13] and *thinkstep's* GaBi LCI databases [14] and crosschecked with primary data provided by Shell and Total [30] [31]

	Unit / Capacity [m³]	Small DFDE 81,000	Small Steam 65,000
fuelled by HFO	[MJ/MJ*km]	-	4.10E-07
fuelled by MGO	[MJ/MJ*km]	1.57E-07	-
fuelled by BOG	[MJ/MJ*km]	3.29E-06	3.69E-06
TOTAL FUEL[48]	[MJ/MJ*km]	**3.45E-06**	**4.10E-06**
Methane emissions related to BOG from cargo tank to engine	[% of BOG]	0.1	0.1
Methane slip during fuel combustion	[%]	3	0

Table D-16: LNG carrier fuel consumption (LHV) and methane emissions of >125,000 m³ LNG carriers, taken from NGVA study [13] and *thinkstep's* GaBi LCI databases [14] and crosschecked with primary data provided by Shell and Total [30] [31]

	Unit / Capacity [m³]	Steam 140,000	TFDE 160,000	DFDE 174,000	SSD 216,000[49]	ME-GI 174,000[50]	X-DF 174,000[51]
fuelled by HFO	[MJ/MJ*km]	2.99E-07	4.97E-08	-	1.71E-06	-	-
fuelled by MGO	[MJ/MJ*km]	-	6.64E-08	9.24E-08	-	2.00E-09	3.46E-11
fuelled by BOG	[MJ/MJ*km]	2.71E-06	2.44E-06	2.02E-06	-	1.30E-06	1.45E-06
TOTAL FUEL[52]	[MJ/MJ*km]	**3.01E-06**	**2.56E-06**	**2.11E-06**	**1.71E-06**	**1.30E-06**	**1.45E-06**
Methane emissions related to BOG from cargo tank to engine	[% of BOG]	0.1	0.1	0.1	0.1	0.1	0.1
Methane slip during fuel combustion	[%]	0	3	3	0	0.1	1.7

All fuel consumption values are based on round-trip considerations per km, i.e., 0.5 km laden and 0.5 km ballast shipping. The data consider that 98 % of the LNG is unloaded. The remaining 2 % stay in the vessel. The data are taken from the NGVA study [13] and *thinkstep's* GaBi LCI databases [14], crosschecked with [33], [34] and were considered good proxies for LNG carrier transport by representatives of Shell [30] and Total [31]. The fuel consumption values were crosschecked with [32].

The distances for LNG imports are calculated based on [35] and provided in the following tables.

The DSI, data source indicator, describes whether the data are primary, calculated, taken from literature or estimated.

[48] All fuel consumption values refer to regular sailing and do not include port operations.
[49] Corresponds with Q_{Flex} vessel size
[50] Data derived using publicly available data for the MAN ME-GI engine 5G70ME-C9.2-GI assuming the 75 % load point with 36,400 kW installed power.
[51] Data derived using publicly available data for the WinGD X-72 DF engine assuming the 75 % load point with 36,400 kW installed power.
[52] All fuel consumption values refer to regular sailing and do not include port operations.

Table D-17: Sea distances for LNG imports from Algeria [35] and kind of transport

Country of origin	Destination	Distance [km]	Kind of transport	DSI
Algeria (Arzew/Skikda)	Europe (average)	1,466	Short distance transport (<125,000 m³)	literature
Algeria (Arzew/Skikda)	Middle East (Ain Sokhna Höegh)	3,630	Long distance transport (125,000 – 180,000 m³)	literature

Table D-18: Sea distances for LNG imports from Australia [35] and kind of transport

Country of origin	Destination	Distance [km]	Kind of transport	DSI
Australia (Karratha/Curtis)	Asia Pacific (Yokkaichi)	6,560	Long distance transport (125,000 – 180,000 m³)	literature
Australia (Karratha/Curtis)	China (Shanghai)	5,290	Long distance transport (125,000 – 180,000 m³)	literature

Table D-19: Sea distances for LNG imports from Indonesia [35] and kind of transport

Country of origin	Destination	Distance [km]	Kind of transport	DSI
Indonesia (Bontang-Badak)	North America (Cove Point)	20,935	Long distance transport (125,000 – 180,000 m³)	literature
Indonesia (Bontang-Badak)	Asia Pacific (Singapore)	1,950	Long distance transport (125,000 – 180,000 m³)	literature
Indonesia (Bontang-Badak)	China (Guangzhou)	3,210	Long distance transport (125,000 – 180,000 m³)	literature

Table D-20: Sea distances for LNG imports from Malaysia [35] and kind of transport

Country of origin	Destination	Distance [km]	Kind of transport	DSI
Malaysia (Bintulu)	Asia Pacific (Singapore)	240	Short distance transport (<125,000 m³)	literature
Malaysia (Bintulu)	China (Guangzhou)	3,100	Long distance transport (125,000 – 180,000 m³)	literature

Table D-21: Sea distances for LNG imports from Nigeria [35] and kind of transport

Country of origin	Destination	Distance [km]	Kind of transport	DSI
Nigeria (Bonny)	Europe (Rotterdam)	6,950	Long distance transport (125,000 – 180,000 m³)	literature
Nigeria (Bonny)	North America (Cove Point)	9,520	Long distance transport (125,000 – 180,000 m³)	literature
Nigeria (Bonny)	Asia Pacific (Yokkaichi)	19,700	Long distance transport (125,000 – 180,000 m³)	literature
Nigeria (Bonny)	China (Shanghai)	17,390	Long distance transport (125,000 – 180,000 m³)	literature
Nigeria (Bonny)	Middle East (Jordan)	10,390	Long distance transport (125,000 – 180,000 m³)	literature

Table D-22: Sea distances for LNG imports from Norway [35] and kind of transport

Country of origin	Destination	Distance [km]	Kind of transport	DSI
Norway (Hammerfest)	Europe (Rotterdam)	4,260	Long distance transport (125,000 – 180,000 m³)	literature

Table D-23: Sea distances for LNG imports from Qatar [35] and kind of transport

Country of origin	Destination	Distance [km]	Kind of transport	DSI
Qatar (Ras Laffan)	Europe (average)	10,290	Long distance transport (>180,000 m³)	literature
Qatar (Ras Laffan)	Asia Pacific (Yokkaichi)	11,840	Long distance transport (>180,000 m³)	literature
Qatar (Ras Laffan)	China (Shanghai)	10,830	Long distance transport (>180,000 m³)	literature
Qatar (Ras Laffan)	Middle East (Ain Sokhna Höegh)	5,200	Long distance transport (>180,000 m³)	literature

Table D-24: Sea distances for LNG imports from Trinidad and Tobago [35] and kind of transport

Country of origin	Destination	Distance [km]	Kind of transport	DSI
Trinidad & Tobago (Atlantic)	Europe (Rotterdam)	7,505	Long distance transport (125,000 – 180,000 m³)	literature
Trinidad & Tobago (Atlantic)	North America (Cove Point)	3,330	Long distance transport (125,000 – 180,000 m³)	literature
Trinidad & Tobago (Atlantic)	Middle East (Ain Sokhna Höegh)	10,375	Long distance transport (125,000 – 180,000 m³)	literature

Table D-25: Sea distances for LNG imports from the USA [35] and kind of transport

Country of origin	Destination	Distance [km]	Kind of transport	DSI
USA (Sabine Pass)	Europe (Rotterdam)	9,260	Long distance transport (125,000 – 180,000 m³)	literature
USA (Sabine Pass)	North America (Cove Point)	2,960	Short distance transport (<125,000 m³)	literature
USA (Sabine Pass)	Asia Pacific (Yokkaichi)	8,030	Long distance transport (125,000 – 180,000 m³)	literature
USA (Sabine Pass)	China (Shanghai)	18,670	Long distance transport (125,000 – 180,000 m³)	literature
USA (Sabine Pass)	Middle East (Jordan)	12,950	Long distance transport (125,000 – 180,000 m³)	literature

LNG Terminal Operations and Maritime Bunkering

Data for LNG terminal operations are taken from *thinkstep's* GaBi LCI databases [14]. Shell [30] provided data for maritime LNG bunkering (ship-to-ship). The following tables specify the key parameters for LNG terminal operations and maritime bunkering. The DSI, data source indicator, describes whether the data are primary, calculated, taken from literature or estimated.

Table D-26: Energy use (LHV) and methane losses for LNG terminal operations and maritime bunkering (ship-to-ship) [14], [30]

Parameter	Unit	Value	Data provider	DSI
Electricity	kJ/t	4,456	[14]	literature
Methane losses during terminal operations	wt.%	1.5E-03	[14]	literature
Methane losses during bunkering	wt.%	0.0361	[30]	primary

Table D-27: Electricity grid mix datasets used for the modelling of LNG terminal operations and maritime bunkering [14]

Region	Dataset
Europe	EU-28: Electricity grid mix
North America	US: Electricity grid mix (proxy)[53]
Asia Pacific	JP: Electricity grid mix (proxy)[53]
China	CN: Electricity grid mix
Middle East	EG: Electricity grid mix (proxy)[53]

Table D-28: Distance covered, fuel consumption (LHV) and methane emissions of LNG bunker barge, taken from NGVA study [13] and *thinkstep's* GaBi LCI databases [14] and crosschecked with primary data provided by Shell and Total [30] [31]

		LNG bunker DFDE
Unit / Capacity [m³]		10,000
Distance	[km]	10 (roundtrip: 20)
fuelled by HFO	[MJ/MJ*km]	-
fuelled by MGO	[MJ/MJ*km]	3.10E-08
fuelled by BOG	[MJ/MJ*km]	1.70E-06
TOTAL FUEL[54]	[MJ/MJ*km]	**1.74E-06**
Methane emissions related to BOG from cargo tank to engine	[% of BOG]	0.1
Methane slip during fuel combustion	[%]	3

[53] Since a region-specific electricity grid mix is not available

[54] All fuel consumption values refer to regular sailing and do not include port operations.

Annex E: Data Sources and Data Quality

Data Sources and Data Quality of the Foreground System

Table E-1: Overview on data sources and data quality of the foreground system of the LNG WtW analyses

Analysis	Process	Geography	Reference year	DSI[55]	Contribution to GHG results
WtT	Natural gas production and processing	Algeria	2012	NGVA study [13]	21-25 %
		Australia	2015-2017	literature	
		Indonesia	2015-2017	literature	
		Malaysia	2015-2017	literature	
		Nigeria	2015	NGVA study [13]	
		Norway	2015	NGVA study [13]	
		Qatar	2014	NGVA study [13]	
		Trinidad and Tobago	2015-2017	literature	
		USA	2015-2017	primary, literature	
	Natural gas pipeline transport	Algeria	2015	NGVA study [13], literature	
		Australia	2015	literature	
		Indonesia	2015	literature	
		Malaysia	2015	literature	
		Nigeria	2015	NGVA study [13], literature	
		Norway	2015	NGVA study [13], literature	
		Qatar	2015	NGVA study [13], literature	
		Trinidad and Tobago	2015	literature	
		USA	2016	literature	
	Natural gas liquefaction (including purification)	Algeria	2012-2017	NGVA study [13], literature	
		Australia	2015-2017	literature	
		Indonesia	2015-2017	literature	
		Malaysia	2015-2017	literature	
		Nigeria	2015-2017	NGVA study [13], literature	

[55] Data from *thinkstep's* GaBi LCI databases are considered as literature data [14].

		Norway	2015-2017	NGVA study [13], literature	
		Qatar	2015-2017	NGVA study [13], literature	
		Trinidad and Tobago	2015-2017	literature	
		USA	2015-2017	literature	
	LNG carrier transport	global	2017	NGVA study [13], literature	
	LNG terminal operations and maritime bunkering	regions	2018	primary	
	LNG consumption mixes	regions/global	2017	literature	
TtW	LNG engines	global	2018	primary	75-79 %

Table E-2: Overview on data sources and data quality of the foreground system of the oil-based marine fuels WtW analyses

Analysis	Process	Geography	Reference year	DSI[56]	Contribution to GHG results
WtT	Crude oil production and processing	countries	2015	literature	16-18 %
	Crude oil pipeline	global	2015-2017	literature	
	Crude oil tanker	global	2015-2017	literature	
	Crude oil refinery	regions	2004-2017	literature	
	Consumption mixes	regions/global	2015	literature	
TtW	Oil-based marine fuel engines	global	2018	primary	82-84 %

[56] Data from *thinkstep's* GaBi LCI databases are considered as literature data [14].

Background Datasets Used

The key electricity datasets used for the background system are listed in Table E-3, all other key background datasets in Table E-4. All background datasets are sourced from *thinkstep's* GaBi LCI databases 2018 [14]. A detailed description of the datasets can be found in [24].

Table E-3: Key electricity datasets used for background system, obtained from *thinkstep's* GaBi LCI databases 2018 [14]

Process	Geography	Dataset	Data provider	Type[57]	GHG Intensity [gCO_2-eq/kWh]
Electricity	Algeria	Electricity grid mix	thinkstep	agg	848.1
	Australia	Electricity grid mix	thinkstep	agg	885.5
	China	Electricity grid mix	thinkstep	agg	871.5
	Egypt	Electricity grid mix	thinkstep	agg	547.0
	EU-28	Electricity grid mix	thinkstep	agg	418.3
	Indonesia	Electricity grid mix	thinkstep	agg	1,074.5
	Japan	Electricity grid mix	thinkstep	agg	662.9
	Malaysia	Electricity grid mix	thinkstep	agg	843.4
	Nigeria	Electricity grid mix	thinkstep	agg	667.2
	Norway	Electricity grid mix	thinkstep	agg	30.5
	Qatar	Electricity grid mix	thinkstep	agg	619.6
	Trinidad & Tobago	Electricity grid mix	thinkstep	agg	702.8
	USA	Electricity grid mix	thinkstep	agg	616.4

[57] Type of dataset: agg – LCI result; p-agg – partly terminated system; u-so – unit process, single operation

Table E-4: Other key datasets used for background system, obtained from *thinkstep's* GaBi LCI databases 2018 [14]

Process	Geography	Dataset	Data provider	Type
Fuel	Australia	Diesel mix at filling station	thinkstep	u-so
	EU-28	Diesel mix at filling station	thinkstep	u-so
	India	Diesel mix at filling station	thinkstep	u-so
	Malaysia	Diesel mix at filling station	thinkstep	u-so
	USA	Diesel mix at filling station	thinkstep	u-so
	EU-28	Liquefied Petroleum Gas (LPG) (from natural gas)	thinkstep	u-so
	EU-28	Liquefied Petroleum Gas (LPG) (70% propane, 30% butane)	thinkstep	u-so
	EU-28	Methanol mix	thinkstep	u-so
Fuel combustion	global	Diesel CHP	thinkstep	agg
	global	Gas CHP	thinkstep	agg
	global	Gas engine	thinkstep	agg
	global	Gas turbine mechanical	thinkstep	agg
Other materials	US	Urea	thinkstep	agg
	EU-28	Water (deionised)	thinkstep	agg

Proxy data used

Table E-5: Overview on proxy data used

Analysis	Process	Proxy data
WtT of LNG	Natural gas pipeline transport	The LCIs of diesel mixes for some countries are not available in *thinkstep's* GaBi LCI databases, thus • diesel mix of India is used for Algeria, Nigeria, Qatar and Trinidad and Tobago, • diesel mix of Malaysia is used for Indonesia, • diesel mix of EU-28 is used for Norway.
	LNG terminal operations and maritime bunkering	The LCIs of electricity mixes for regions are not available in *thinkstep's* GaBi LCI databases, thus • electricity mix of the USA is used for North America, • electricity mix of Japan is used for Asia-Pacific, • electricity mix of Egypt is used for Middle East.
WtT of oil - based marine fuels	Region-specific and global consumption mix	Absolute oil-based marine fuel consumption data for regions are not available. Absolute crude oil consumption data are used as proxy.
	Refinery	The LCIs of the refinery for some countries and regions are not available in *thinkstep's* GaBi LCI databases, thus • refinery of Japan is used for China and South East Asia, • refinery of India is used for Middle East, • refinery of the USA is used for North America.
	Distribution	In general: crude oil transport pipelines are used as proxy for the transport of the oil-based marine fuels. The LCIs of crude oil transport pipelines for regions are not available in *thinkstep's* GaBi LCI databases, thus • crude oil transport pipeline of Saudi Arabia is used for Middle East, • crude oil transport pipeline of Japan is used for South East Asia, • crude oil transport pipeline of the USA is used for North America.
WtT of LPG and methanol	Distribution	Crude oil transport pipelines are used for the transport of LPG and methanol

Annex F: Well-to-Tank - GHG Emissions

Well-to-Tank - GHG Emissions of LNG

An overview of the GHG results in g CO_2-eq/MJ (LHV) fuel delivered to the tank for the global LNG supply and the five defined LNG consumption regions (Europe, North America, Asia Pacific, China and Middle East) is provided in Figure F-1 and Table F-1. The results are broken down by the main process steps of the LNG supply chain. The GHG emissions for the LNG supply chain differ from region to region.

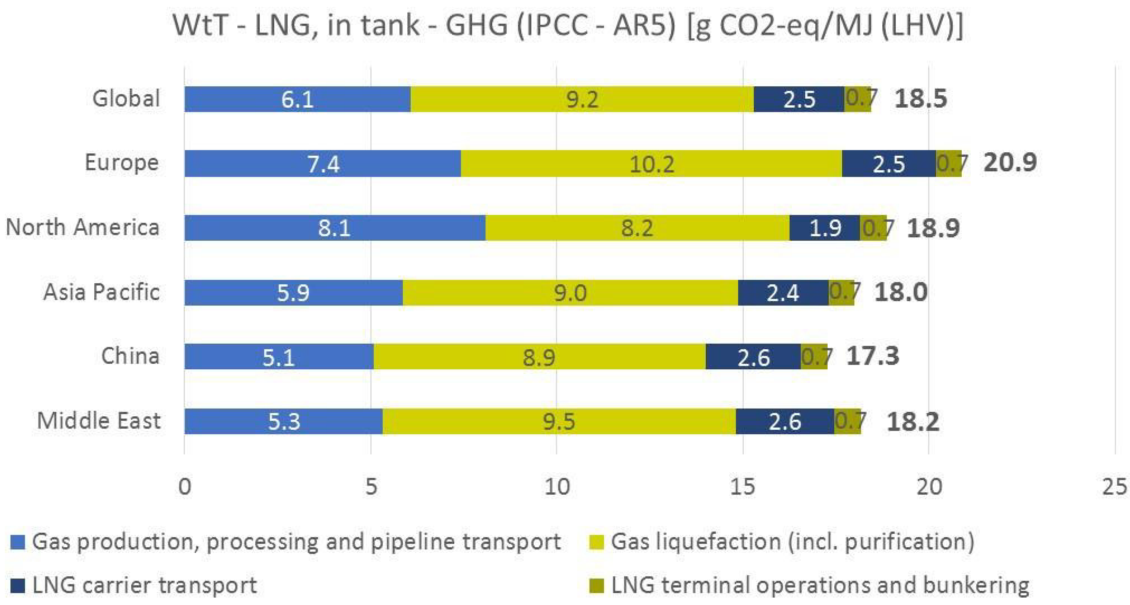


Figure F-1: Well-to-Tank – GHG Emissions: LNG supply (global and regions) – breakdown by main process steps [23]

Table F-1: Well-to-Tank – GHG Emissions: LNG supply (global and regions) – breakdown by main process steps [23]

GHG IPCC - AR5 [g CO_2-eq/MJ (LHV)], in tank	Global	Europe	North America	Asia Pacific	China	Middle East
Gas production, processing and pipeline transport	6.1	7.4	8.1	5.9	5.1	5.3
Gas liquefaction (incl. purification)	9.2	10.2	8.2	9.0	8.9	9.5
LNG carrier transport	2.5	2.5	1.9	2.4	2.6	2.6
LNG terminal operations and maritime bunkering	0.7	0.7	0.7	0.7	0.7	0.7
TOTAL LNG	**18.5**	**20.9**	**18.9**	**18.0**	**17.3**	**18.2**

Figure F-2 and Table F-2 display the same overall results as Figure F-1 and Table F-1, but are broken down into the individual emissions CO_2, CH_4, and N_2O. N_2O contributes to a very small extent, and the contributions of other greenhouse gases also included in the life cycle inventory data are orders of magnitude smaller and therefore excluded from the figure.

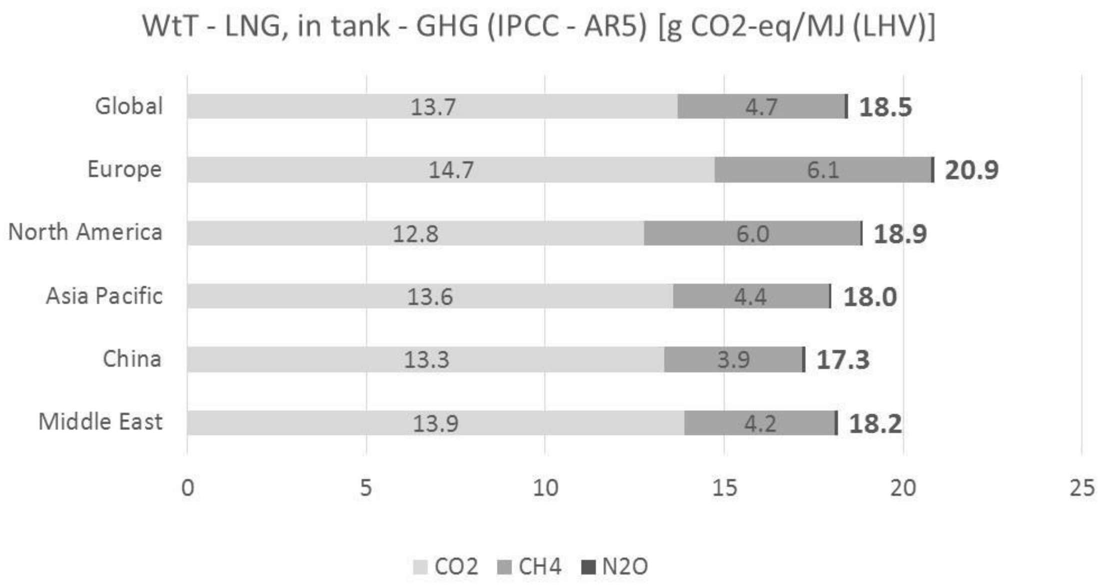


Figure F-2: Well-to-Tank – GHG Emissions: LNG supply (global and regions) – breakdown by main individual emissions [23]

Table F-2: Well-to-Tank – GHG Emissions: LNG supply (global and regions) – breakdown by main individual emissions [23]

GHG IPCC - AR5 [g CO_2-eq/MJ (LHV)], in tank	Global	Europe	North America	Asia Pacific	China	Middle East
CO_2	13.7	14.7	12.8	13.6	13.3	13.9
CH_4	4.7	6.1	6.0	4.4	3.9	4.2
N_2O	0.1	0.1	0.1	0.1	0.1	0.1
TOTAL LNG	**18.5**	**20.9**	**18.9**	**18.0**	**17.3**	**18.2**

Well-to-Tank - GHG Emissions of Oil-based Fuels

The GHG results in g CO_2-eq/MJ (LHV) fuel delivered to the tank of the conventional global oil-based marine fuel supply and the five consumption regions are illustrated in Figure F-3. As the LNG supply, the results differ significantly from region to region. The region-specific refinery structures determine if the GHG emissions of the $HFO_{2.5}$ supply chains are higher or lower than the GHG emissions of the $MGO_{0.1}$ supply chain. Compared with the other regions, the North American refinery shows the highest GHG emissions due to a more energy intensive refinery configuration.

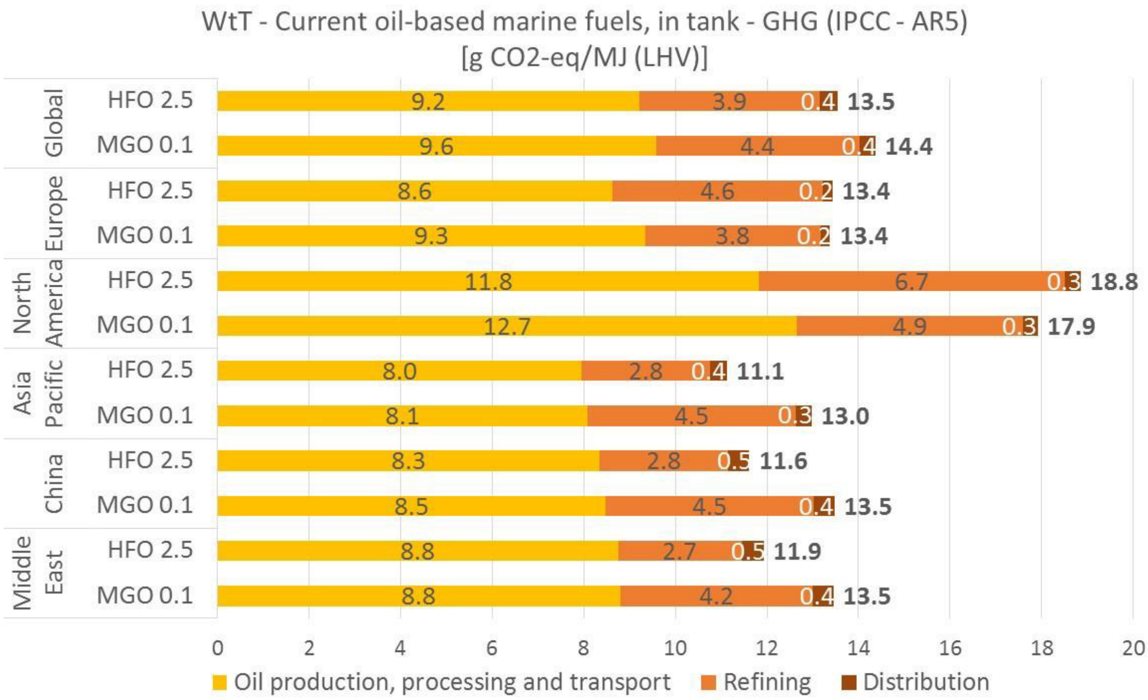


Figure F-3: Well-to-Tank – GHG Emissions: Current oil-based marine fuel supply (global and regions) – breakdown by main process steps [23]

Figure F-4 shows the GHG results in g CO_2-eq/MJ (LHV) fuel for the post-2020 scenarios on the global oil-based marine fuel supply and the five consumption regions.

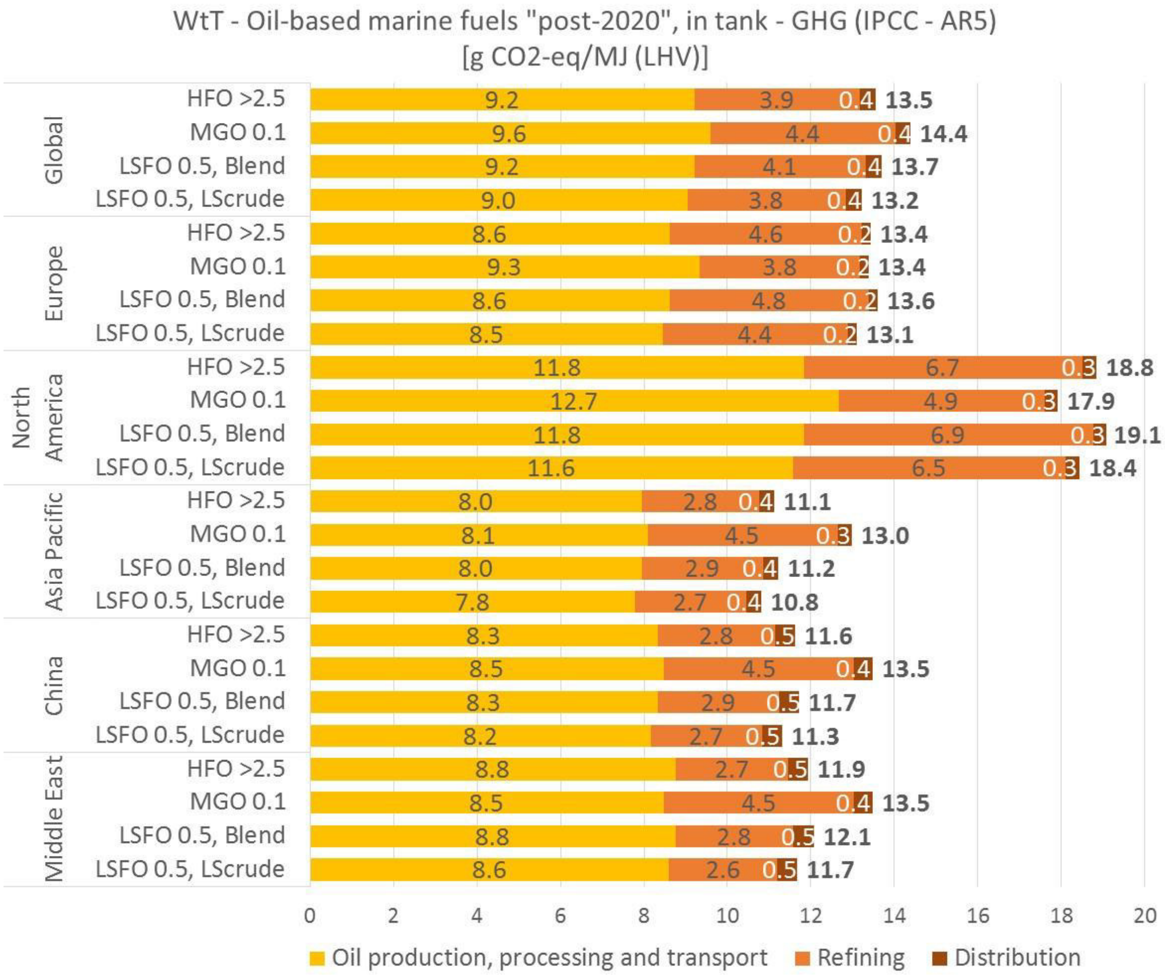


Figure F-4: **Well-to-Tank – GHG Emissions: Oil-based marine fuel supply "post-2020" (global and regions) – breakdown by main process steps [23]**

Annex G: Well-to-Wake GHG Emissions

The following section is supplementary to section 6. It includes the results of the Well-to-Wake GHG emissions for the different engines technologies that are not described in the main body of the study. The first part shows the evaluation of different impact categories on 2-stroke SS and 4-stroke HS engines in Tier III operation. The second part describes the operation of all engines in Tier II areas (outside of ECA) and its presents the WtW GHG emissions. Additionally, the influence of different NO_x-after-treatment system on GHG emissions is discussed briefly.

In the last section of Annex F, the WtW GHG emissions of Methanol and LPG powered engines are briefly discussed.

Well-to-Wake – Impact on GHG Emissions of different Impact Categories

The relative GHG emissions of the different impact categories for the 2-stroke engine are shown in Figure G-1. The calculations are based on the aggregated Tier III inventory data (see Table 5-8). As described in the main body of the study, the direct methane emissions have an influence on the absolute GHG emissions as its characterisation factor is the main differentiator between the impact categories investigated. Depending on the impact category evaluated, GHG emissions vary between 94 and 112 % (2-stroke slow speed Diesel-DF engine) of the base scenario (AR5, GWP_{100}) and between 87 and 130 % (2-stroke slow speed Otto-DF engine)[58].

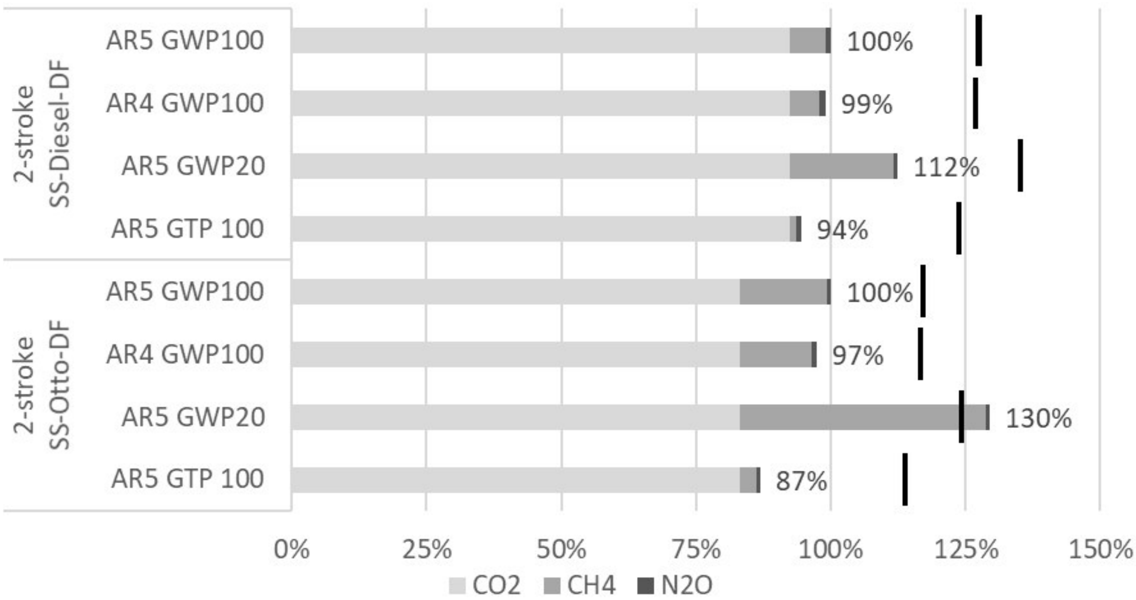


Figure G-1: Impact of different characterisation factors (relative) on the WtW GHG emissions of 2-stroke slow speed engines when using LNG compared with

[58] Using a characterisation factor of 36 g CO_2-eq/g CH_4 (which is currently under discussion), the WtW GHG emissions would reach 101 % for the 2-stroke SS-Diesel-DF engine (AR 5, GWP_{100}=100 %), 103 % for the 2-stroke SS-Otto-DF engine.

IPCC, AR5, GWP_{100} (= 100 %) and oil-based fuel operation ($HFO_{2.5}$) shown as vertical marks [23]

For the 4-stroke high speed engines, results vary between 86 and 132 % of the base scenario[59].

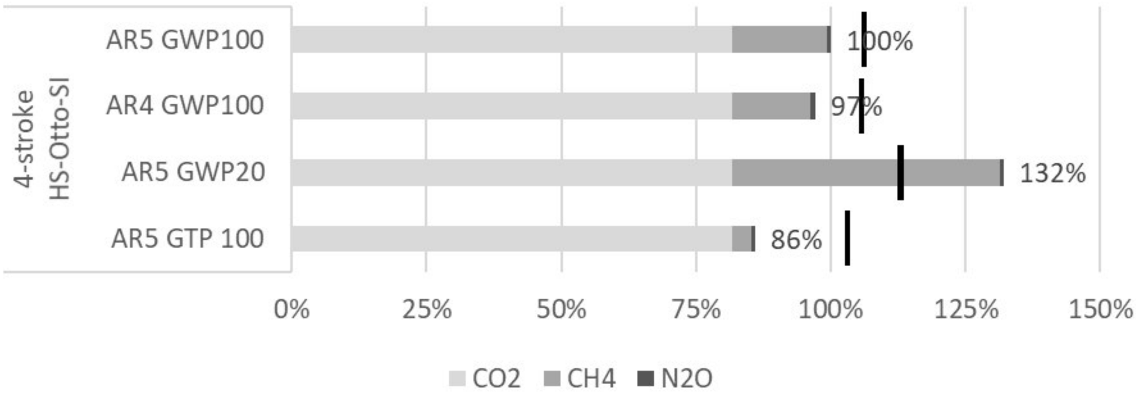


Figure G-2: Impact of different characterisation factors (relative) on the WtW GHG emissions of 4-stroke high speed engines when using LNG compared with IPCC, AR5, GWP_{100} (= 100 %) and oil-based fuel operation ($MGO_{0.1}$) shown as vertical marks [23]

Gas turbine applications are not investigated as the methane slip is negligible.

Well-to-Wake – GHG Emissions in Tier II Operation

Tier III limits are only applicable in ECA zones. The resulting GHG emissions are described in detail in section 6. Outside ECA zones, Tier II limits apply enabling e.g. an operation with oil-based marine fuels without NO_X after-treatment system. WtW GHG emissions of Tier II operation are shown for the 2- and 4-stroke engines based on the Tier II inventory data for the IMO E2/E3 cycle. Gas turbine applications are not described as they comply to the IMO Tier III limit also when running with oil-

[59] Using a characterisation factor of 36 g CO_2-eq/g CH_4 (which is currently under discussion), the WtW GHG emissions would reach 104 % for the 4-stroke HS-Otto-SI engine.

based MGO. Apart from the 2-stroke slow speed Diesel-DF engine, all engines using LNG comply to the Tier III limit hence WtW GHG emissions are the same as described in section 6.3.

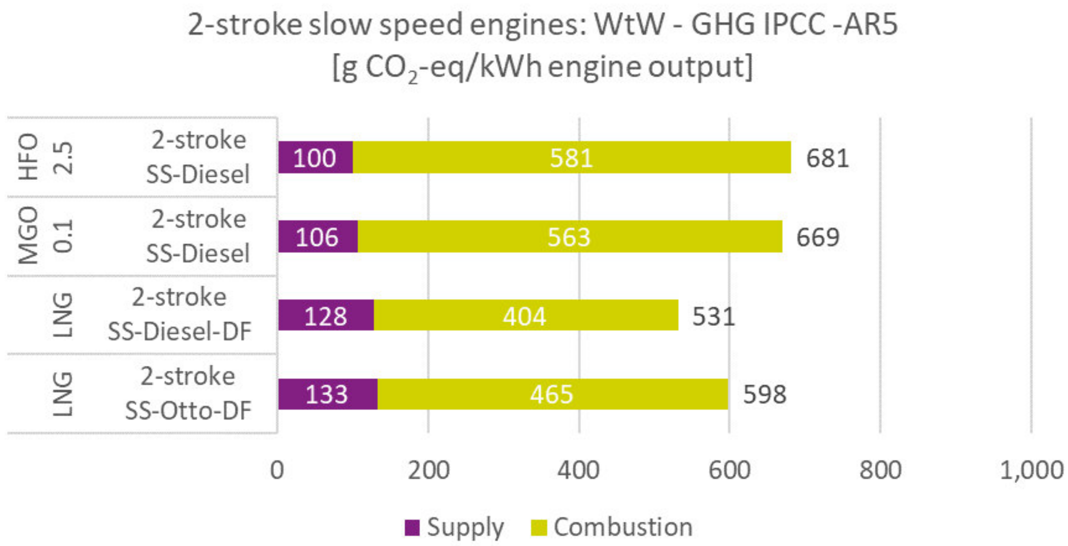


Figure G-3: Well-to-Wake - GHG emissions of 2-stroke slow speed engines (Tier II) [23]

Figure G-3 shows that the GHG emissions of oil-based fuels decrease compared with Tier III operation. This is due to the lower fuel consumption and the absence of urea in Tier II operation. This results in lower WtW GHG emissions of the oil-based marine fuels. The WtW emissions of the 2-stroke slow speed Diesel-DF engine running on LNG decline also to 531 g CO_2-eq/kWh as the switch from Tier III to Tier II operation decreases fuel consumption. The benefit of LNG compared with HFO Tier II operation is 22 %. The GHG benefit of the 2-stroke Otto-DF engine running on LNG compared with HFO Tier II is 12 %.

The same characteristics, i.e. GHG emissions from oil-based operation decreases from Tier III to Tier II, apply to the 4-stroke medium speed engines as less fuel and no urea is needed (see Table 5-6 for reference). Figure G-4 shows the calculated WtW GHG emissions. The benefit of LNG for the 4-stroke MS-Otto DF engine is 4 %. For the 4-stroke MS-Otto-SI engine, the benefit is 13 %.

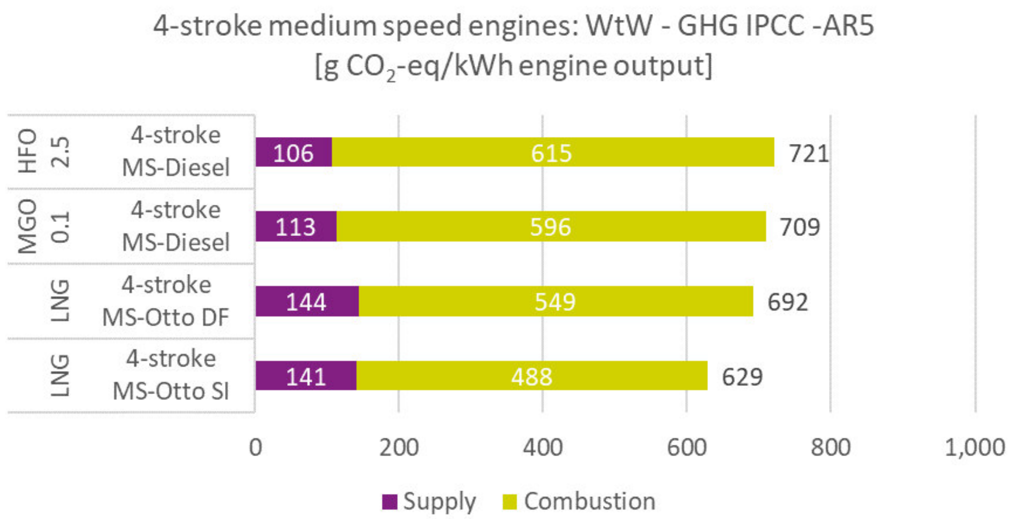


Figure G-4 Well-to-Wake - GHG emissions of 4-stroke medium speed engines (Tier II) [23]

The GHG reduction of LNG used in 4-stroke high speed Otto-SI engines, compared with Tier III operation with $MGO_{0.1}$ of 6 % (Figure 6-7), decreases to 4 % when comparing it to Tier II data as the GHG emissions of $MGO_{0.1}$ operation decline from 859 to 844 g CO_2-eq/kWh.

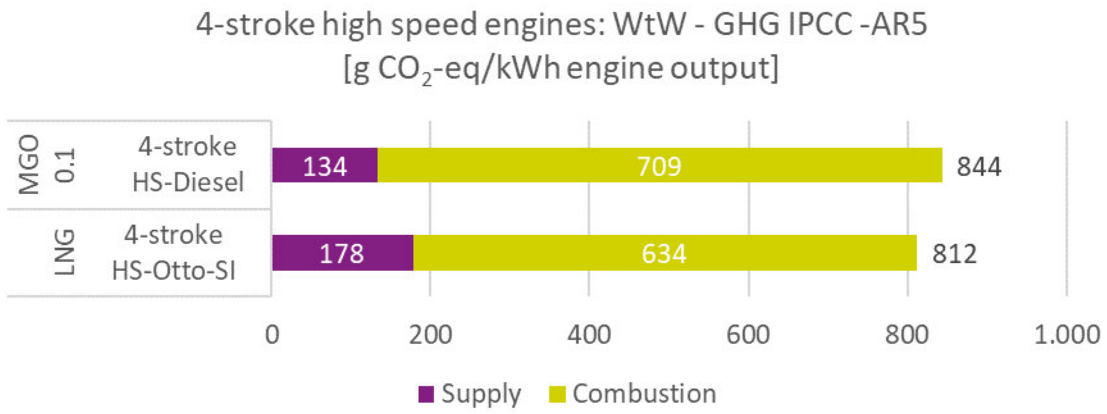


Figure G-5: Well-to-Wake - GHG emissions of 4-stroke high speed engines (Tier II) [23]

Influence of different NOX after-treatment systems on WtW GHG emissions

As described in the main body of the study, different technologies are available to decrease NO_X emissions. In this paragraph, the influence of SCR and EGR on WtW GHG emissions are described briefly. Typically, the reduction of NO_X comes at the expense of increased consumption of either urea solution (only applicable for SCR system) and/or engine fuel.

Taking into account the assumptions in Table 5-6 and assuming a HFO consumption without SCR of 160 g/kWh, the additional WtW GHG emissions due to the operation of a SCR system are 16.1 g CO_2-eq/kWh for the 4-stroke engines and 14.0 g CO_2-eq/kWh for the 2-stroke engines.

Some engine manufacturers develop exhaust gas recirculation system (EGR) that enable higher engine efficiency and hence lower fuel consumption, even in Tier II operation. Evaluating the Tier II data of the MAN 6G70ME-C10.5 engine [71], the overall fuel consumption is decreased by 3 % (IMO E2/E3 cycle) when the engine runs on the MAN EcoEGR setting compared with a standard Tier II setting. In Tier III operation, the fuel consumption is 1 % higher than when operating the SCR system, however no urea is needed. Assuming a fuel consumption of 160 g/kWh (see above), the 1 % increase leads to additional 5.8 g CO_2-eq/kWh compared with the 14.0 g CO_2-eq/kWh calculated above, showing the benefit of the EcoEGR system.

Well-to-Wake – GHG Emissions of Methanol and LPG

In addition to the oil-based marine fuels, methanol and LPG can be considered as reference marine fuels. The fuels are briefly described in Table G-1.

Table G-1: Overview on other marine fuels considered in this study

Marine Fuel	Description
LPG	In this study, the liquefied petroleum gas (LPG) mix is a blend of 40 wt.% LPG from refinery and 60 wt. % LPG from Natural gas processing: • LPG from refinery consists of 70 wt. % propane and 30 wt. % butane. Propane and butane are both refinery products and data include the supply chain from crude oil production and processing, transport and refinery to distribution (same distribution as for oil-based fuels assumed). • Data on LPG from natural gas processing cover the whole supply chain, including conventional natural gas production and processing and distribution (same distribution as for oil-based fuels assumed). Data on LPG are taken from *thinkstep's* GaBi LCI databases [14].
Methanol	In this study, the methanol is produced considering a mix of large-scale technologies and integrated technologies. Methanol is produced from natural gas via synthesis gas. Synthesis gas is a mixture of hydrogen and carbon monoxide. The two industrially important processes for its production are steam reforming and partial combustion. Methanol is formed from synthesis gas and purified by distillation. Data on methanol are taken from *thinkstep's* GaBi LCI databases [14].

Figure G-6 shows the GHG results in g CO_2-eq/MJ (LHV) fuel for the LPG and methanol supply. LPG is calculated with 8.3 g CO_2-eq/MJ (LHV), which can be divided into 79 % CO_2 and 21 % CH_4 emissions. The methanol supply has an impact of 31.3 g CO_2-eq/MJ (LHV). CO_2 is the main contributor (90 %). The other 10 % are caused by CH_4. N_2O emissions are negligible for both fuel supply chains. The results are compared with the results of the JEC-WtW study [3] and show similar results (LPG supply in JEC-WtW study: 8.0 g CO_2-eq/MJ (LHV) LPG; methanol supply in JEC-WtW study: 24.9-32.2 g CO_2-eq/MJ (LHV) methanol).

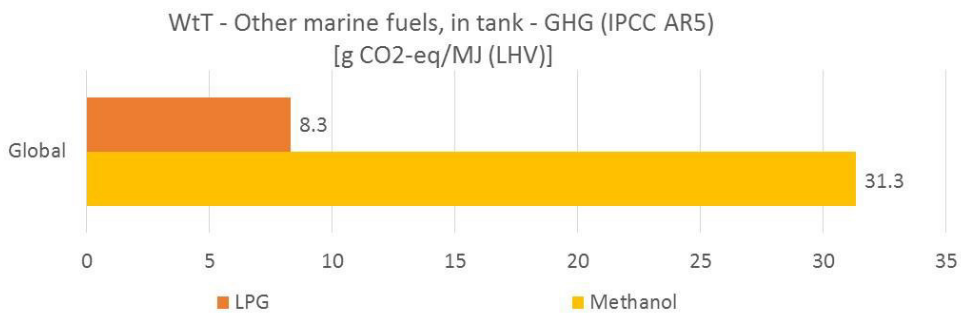


Figure G-6: Well-to-Tank – GHG Emissions: Other marine fuel supply [23]

Data of the combustion of LPG and methanol was provided by MAN and Wärtsilä for 2-stroke slow speed and 4-stroke medium speed engines [54] [71] and weigthened accoridng to the IMO E2/E3 cycle. Due to data availability, this is limited to Tier II consumption data with $MGO_{0.1}$ as a pilot fuel. Local pollutant emissions are not investigated.

Table G-2 shows the Tier II inventory.

Table G-2: Tier II fuel consumption data (primary) for 2- and 4-stroke engines running on LPG and Methanol based on the IMO E2/E3 cycle [71], [54]

g/kWh	LPG	Methanol	DSI
2-stroke slow speed			
Main fuel consumption	147.9	345.7	primary
Pilot fuel consumption	8.3	10.5	primary
4-stroke medium speed			
Main fuel consumption	-	373.2	primary
Pilot fuel consumption	-	9.8	primary

Figure G-7 and Figure G-8 show the WtW GHG emissions for 2-stroke slow speed engines and 4-stroke medium speed engines for LNG, methanol and LPG operation respectively broken down by fuel supply and combustion.

The WtW GHG emissions of 2-stroke slow speed engines running on LPG are calculated to 535 g CO_2-eq/kWh and 748 g CO_2-eq/kWh when running on methanol. The emissions resulting from the combustion (TtW) are in the same order of magnitude (473 respectively 524 g CO_2-eq/kWh) with the supply of methanol having significantly higher GHG emissions. Compared with LPG – depending on the engine – LNG show a marginal reduction or up to a 12 % increase in GHG emissions. Compared with methanol both LNG engines offer a GHG benefit with the Diesel-DF engine reaching a 29 % reduction and the Otto-DF engine reaching 20 %.

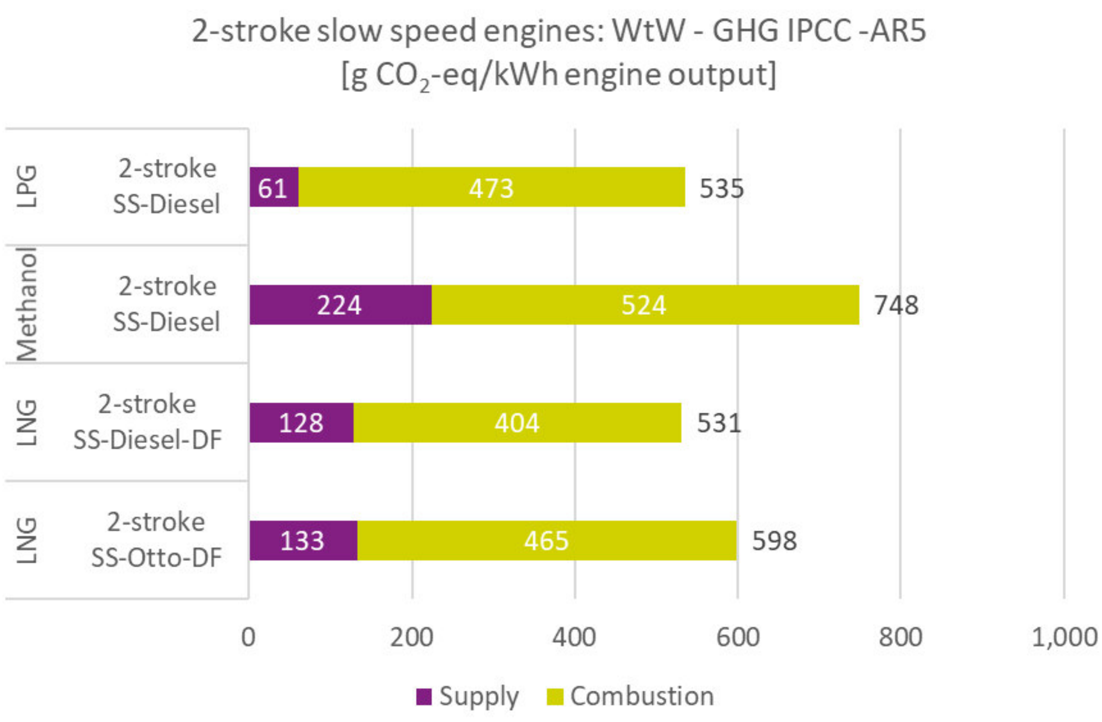


Figure G-7: WtW GHG emissions of 2-stroke slow speed engines using Methanol and LPG [23]

For 4-stroke medium speed engines, only methanol is investigated as an alternative fuel. The WtW GHG emissions result in 802 g CO_2-eq/kWh with both the GHG emissions of the supply and the combustion being higher for the respective LNG engine as shown in Figure G-8. The GHG benefit of LNG compared with methanol is 14 % for the Otto-DF engine and 22 %for the Otto-SI engine.

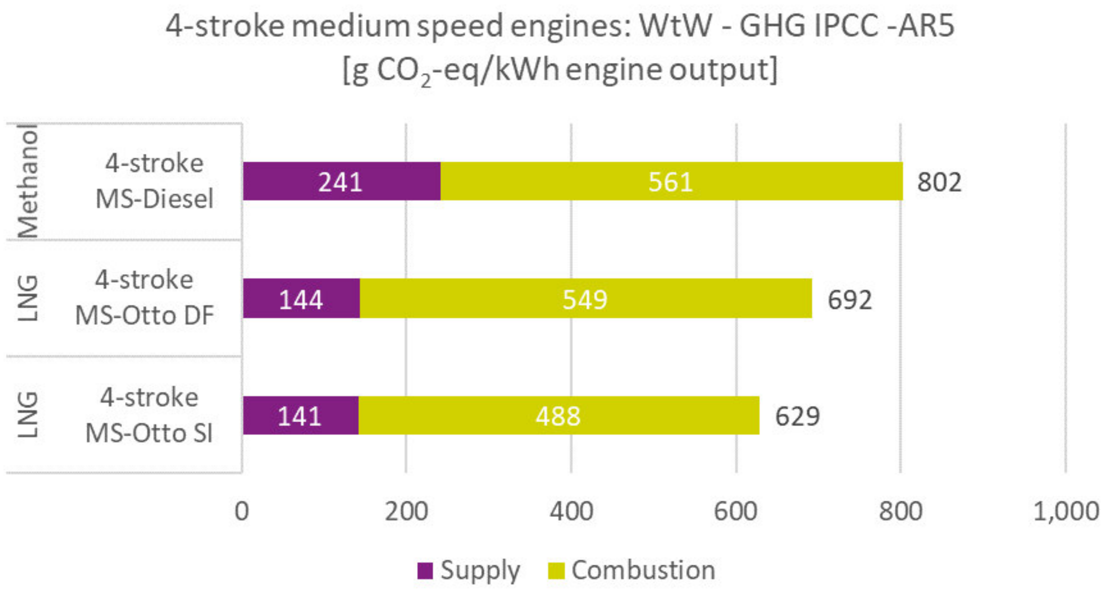


Figure G-8: WtW GHG emissions of 4-stroke medium speed engines using Methanol [23]

Annex H: Sensitivity Analysis on Technical Parameters

Well-to-Wake – Sensitivity Analysis on Technical Parameters for LNG

Figure H-1 to Figure H-4 illustrate the results of the sensitivity analysis on technical parameters for LNG. A detailed description of the sensitivity analysis and the results can be found in section 6.8.2.

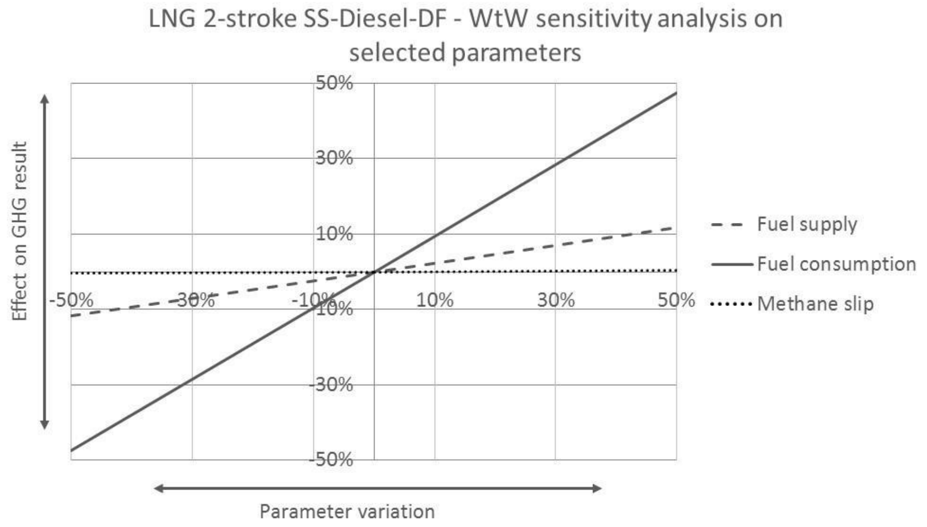


Figure H-1: Sensitivity analysis on selected parameters from the WtW GHG model of LNG 2-stroke slow speed Diesel-DF [23]

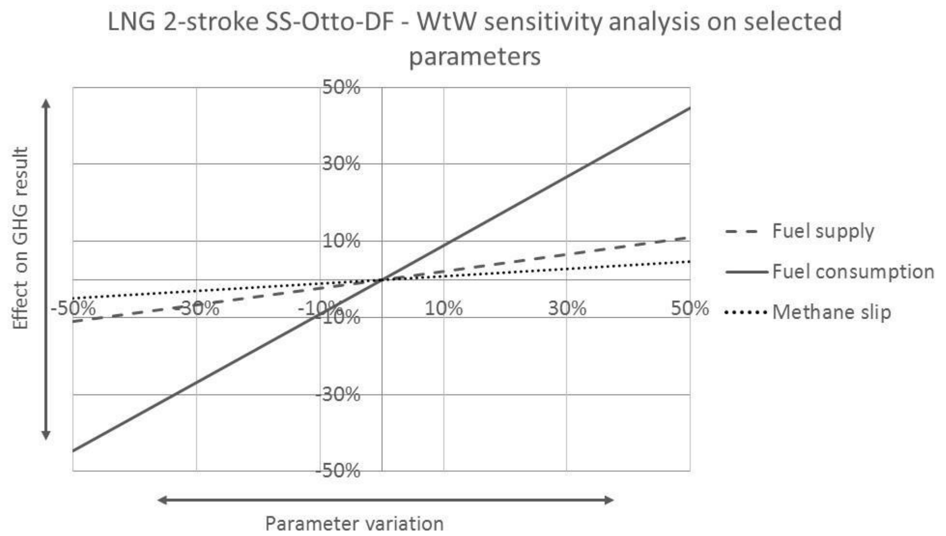


Figure H-2: Sensitivity analysis on selected parameters from the WtW GHG model of LNG 2-stroke slow speed Otto-DF [23]

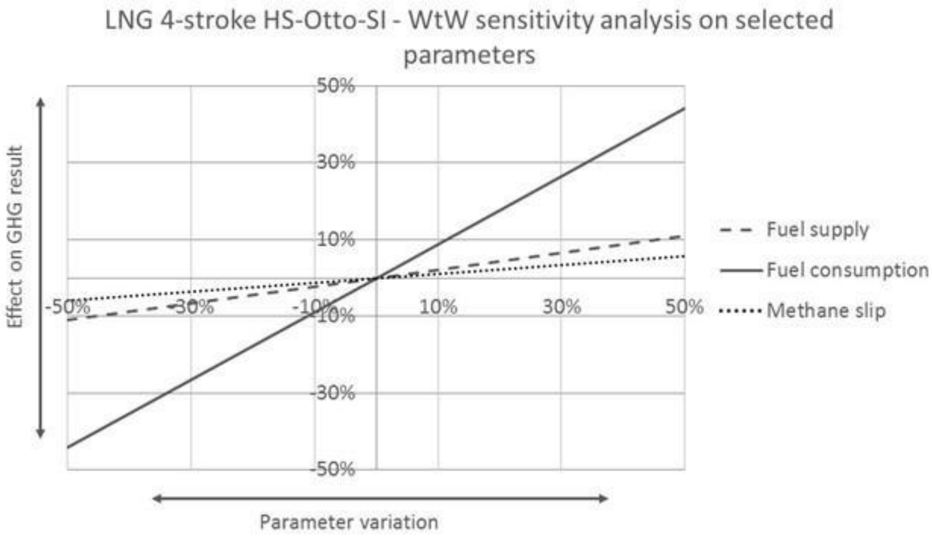


Figure H-3: Sensitivity analysis on selected parameters from the WtW GHG model of LNG 4-stroke medium speed Otto-DF [23]

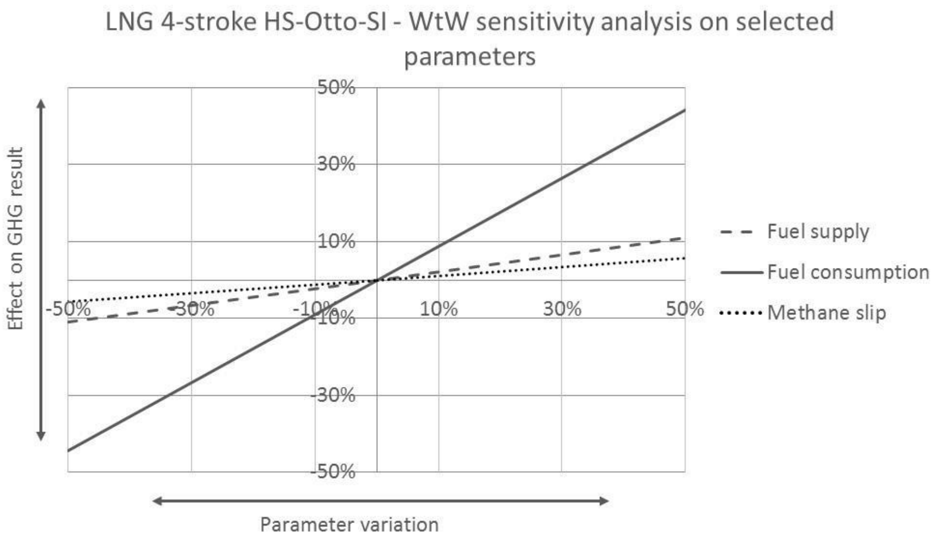


Figure H-4: Sensitivity analysis on selected parameters from the WtW GHG model of LNG 4-stroke high speed Otto-SI [23]

Well-to-Wake – Sensitivity Analysis on Technical Parameters for $HFO_{2.5}$

Figure H-5 illustrate the results of the sensitivity analysis on technical parameters for $HFO_{2.5}$ 2-stroke Diesel slow speed. Please see section 6.8.3 for a description of the results.

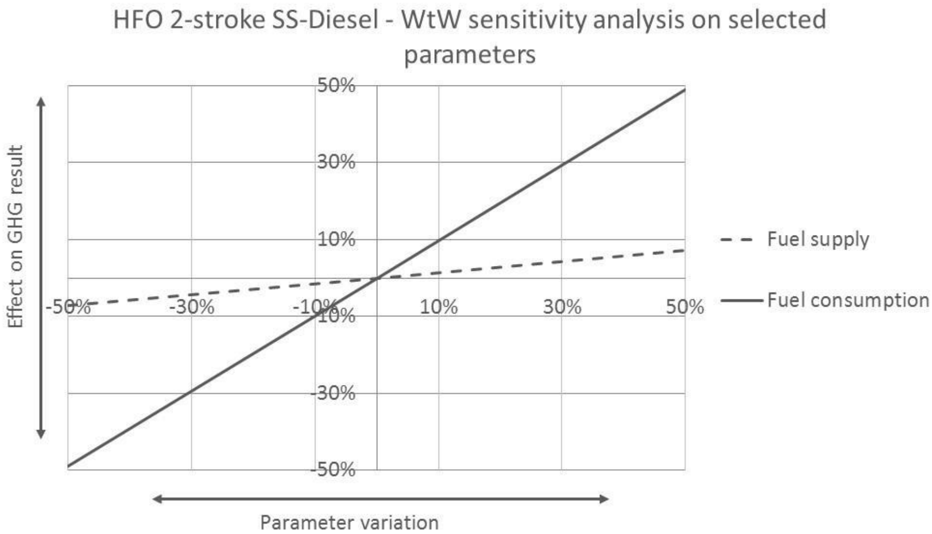


Figure H-5: Sensitivity analysis on selected parameters from the WtW GHG model of $HFO_{2.5}$ 2-stroke slow speed Diesel [23]

Annex I: Critical Review Statement

Critical Review Statement of the report "Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel"

dated 10 of April 2019

ISO 14 040 & ISO 14 044
ISO/TS 14071

SOL 18-060.1

10 of April 2019

for

SEA\LNG and SGMF

1 Introduction

thinkstep has prepared a third-party report "Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel" dated 10 of April 2019. The goal of the third-party report was to "to provide an accurate report of the life cycle GHG emissions on the use of LNG as a marine fuel compared with conventional marine fuels".

This study states that ISO 14040:2006 and ISO 14044:2006 requirements have been applied in order to get reliable transparent GHG results for LNG as marine fuel. To fulfill the ISO requirements, SEA\LNG and SGMF have requested a critical review (CR) panel to conduct a critical review of the third-party report (this "third-party report" is called "the LCA report" in the following of the text).

The present report is the "Final CR report", including the detailed tables prepared by the CR panel under the direction of Philippe Osset (Solinnen). This CR report is dedicated to being integrated, as a whole, within the final LCA report of SEA\LNG, SGMF and thinkstep.

2 Composition of the panel

The CR panel consisted of the following members, independent from the overall study content, and external to SEA\LNG and SGMF, thinkstep and the related business interests:

- Dipl. Eng. Philippe Osset, Solinnen, LCA expert (France). Philippe has acted as the chair of the Critical Review panel,
- Prof. Dr. Atsushi Inaba, Department of Environmental and Energy Chemistry at Kogakuin University (Japan),
- Prof. Dr. Friedrich Wirz, Head of Working Group Marine Engineering at Technical University of Hamburg (Germany),
- Dr. Michael Wang, Director of the Systems Assessment Department, Energy System Division at Argonne National Laboratory (USA).

The intention of the panel set up was to make available competencies which cover the studied topic. The reviewers were not engaged or contracted to represent officially their organization but acted as independent expert reviewer.

3 Nature of the CR work, CR process and limitations

The CR panel has worked according to the requirements of ISO 14040:2006 and 14044:2006 concerning CR. They have taken into account ISO/TS 14071 requirements too.

According to ISO 14044, the critical review process has been undertaken in order to check if:

- the methods used to carry out the LCA in the LCA report are consistent with ISO 14044 requirements,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified in the study and the goal of the study, and
- the study report is transparent and consistent.

The first task of the CR was *to provide thinkstep* with detailed comments in order to allow thinkstep to improve its work. These comments have covered methodology choice, results and reporting. The panel has checked the *plausibility* of the data used, including sample tests in the database regarding data implementation, system modeling, and LCI and LCIA results. Additionally, this final CR report *provides the future reader* of the LCA report and user of the LCI with information that will help understand the LCA report, its results, and the LCI data used in this study.

The CR was performed after completion of the draft study. The analysis and the verification of individual datasets are outside the scope of the CR. Nonetheless, a plausibility check of the software model was performed on the 29 of March 2019.

The CR work started in March 2019 and ended in April 2019. During this period, various oral and written exchanges have been held between the CR panel, SEA\LNG, SGMF and thinkstep, including clarification exchanges regarding the CR initial comments, and the production of one set of detailed comments by the CR panel, and a new version of the LCA report by thinkstep. Nevertheless, no new LCA calculations have been done after the comments of the panel, according to the answer brought to the panel by thinkstep regarding upstream LCI data used and the model itself, apart from specific corrections of identified issues and clarifications on certain questions brought by the CR panel.

The panel prepared 264 comments on the draft LCA report. They covered the following areas:

- General (21 key comments),
- Methodology (20 key comments),
- Technical (61 key comments),
- Data (49 key comments),
- Other miscellaneous comment (113 comments).

thinkstep has taken into account most of the comments and modified and improved their LCA report. In fact, a significant work has been done by SEA\LNG, SGMF and thinkstep to provide a final LCA report integrating answers to the CR comments, and the final result and the report have improved as compared to the draft version, towards the requirement of the reference standards.

This final CR report is the synthesis of the final comments by the reviewers. The remaining detailed comments are provided within this final CR report, together with the full detailed exchanges as appendices.

This final CR report is delivered to SEA\LNG and SGMF by the panel. The CR panel cannot be held responsible of the use of its work by any third party. The conclusions of the CR panel cover the full LCA report from SEA\LNG and SGMF. They do not cover any other report, extract, extrapolation or publication which may eventually been done. The CR panel conclusions have been made given the current state of the art and the information which has been received for the covered topics in the LCA report. These CR panel conclusions could have been different in a different context.

4 Conclusions of the Review – Critical Review Statement

As a whole, the CR panel considers that the requirements of the reference standards have been met.

The final LCA report answers the goal which has been set up, within the scope of the limitations that are mentioned in the LCA report and the detailed panel comments which are provided in the next chapter.

It must be clearly understood that the study does not allow to assess the advantages and disadvantages of the natural gas ships vis-à-vis non fossil fuels resources ships.

Additionally, it must be clearly understood that only GhG emissions have been assessed in the LCA report over the whole life cycle, and some local emissions were assessed for the ship operation only, and therefore that no conclusion should be taken regarding the overall environmental impacts (or benefits) associated to the studied life cycles – reductions of GHGs do not imply reduction of other environmental impacts, sometimes a reduction of GHGs is accompanied by an increase of other impacts – this is called "pollution transfer" in LCA.

5 Detailed comments

The following lines bring some highlights that a reader of the final LCA report may use to assist his reading and understanding of the LCA report. It includes also some critical comments which were not addressed, or which were addressed in a way which is different from what the CR panel expected. The comments which have been fully addressed no longer appear here. The reading of the detailed comments and answers (see the table in appendices at Chapter 6) is recommended.

5.1 Consistency of methods used with ISO 14044 requirements

The final structure of the LCA report presents the content of the ISO standard requirements. The methods that have been selected for reference calculations are clearly presented. The choice of functional unit for the well to wake comparison should be understood with care when communicating the conclusions of the LCA study.

5.2 Scientific and technical validity

As stated in the LCA report, "*methane slips have been included. They play an important role in addition to the emission from supply chain*". Their value is highly variable depending on the engines, and the LCA has assessed methane slips values which are globally appropriate. The panel recommends, on a case by case basis, to consider specific methane slips to ensure that the conclusions of the report applies to a given model of engine, as stated in the conclusions of the LCA report. Additionally, a combination of variability of methane slips and CH4 characterization factor could show higher variability which were not assessed in the sensitivity analyses at the same time.

5.3 Appropriateness of data used in relation to the goal of the study

The data used in the report are appropriate as far as the selected functional unit is concerned. In fact, the LCA study has benefited from data provided by major ship makers related to ship operation, and a 2017 study for data related to natural gas supply chain. The modeling in the GaBi software and its databases reflects what is described in the LCA report. A lot of data have been implemented manually from the Excel file in the GaBi software by copy and paste, with a risk of error. Nevertheless, the overall results look plausible to the panel.

Annex B presents the table of Characterization Factors that have been used, which covers the broad expectations of ISO 14067.

As mentioned in the LCA report, the European DG JRC recommends the use of 36,75 as characterization factor for methane for GWP 100 years direct in the PEF Guide, as currently published in Europe – this PEF guide presents requirements which are used by thinkstep as described in the presentation chapter of thinkstep (together with the link where to download the PEF guide). This characterization factor has not been used in the present report, which limits the application of the comparison results in the scope of the scheduled PEF applications. Indeed, answering PEF requirements was not part of the goal of the commissioners.

5.4 Validity of interpretations in the scope of the limitations of the study

The results of GHG emission changes on the life cycle basis are complete by including all key stages of the natural gas supply chain and ship operations. In particular, the LCA study identifies key methane leakages and test their importance for LCA results o LNG as a marine fuel. As mentioned in the LCA report, "*Black Carbon emissions are not considered, though potentially contributing to the global warming potential. Due to the uncertainty of the evaluation of its effect (between 0,3 and 15%), the GHG effect of black carbon emissions have not been taken into account. This choice can be seen as a likely conservative*". The panel recommends including black carbon effect in further LCA concerning marine transportation to improve the comparisons, as stated in chapter 9.2. of the LCA report. It would take into account improvements in the assessment of the effect of black carbon on global warming

5.5 Transparency and consistency

The overall level of transparency and consistency of the report is high, and in line with the ISO 14044:2006 expectations. Some duplications exist in the report which may confuse the reader. After checking, these duplications do not introduce inconsistencies in the LCA report and might help to get the appropriate information when readers do not read the entire report.

6 Appendices

The detailed critical review tables exchanged during the CR are the appendices of the present CR report. They recap the detailed exchanges between the CR panel and SEA\LNG, SGMF and thinkstep.