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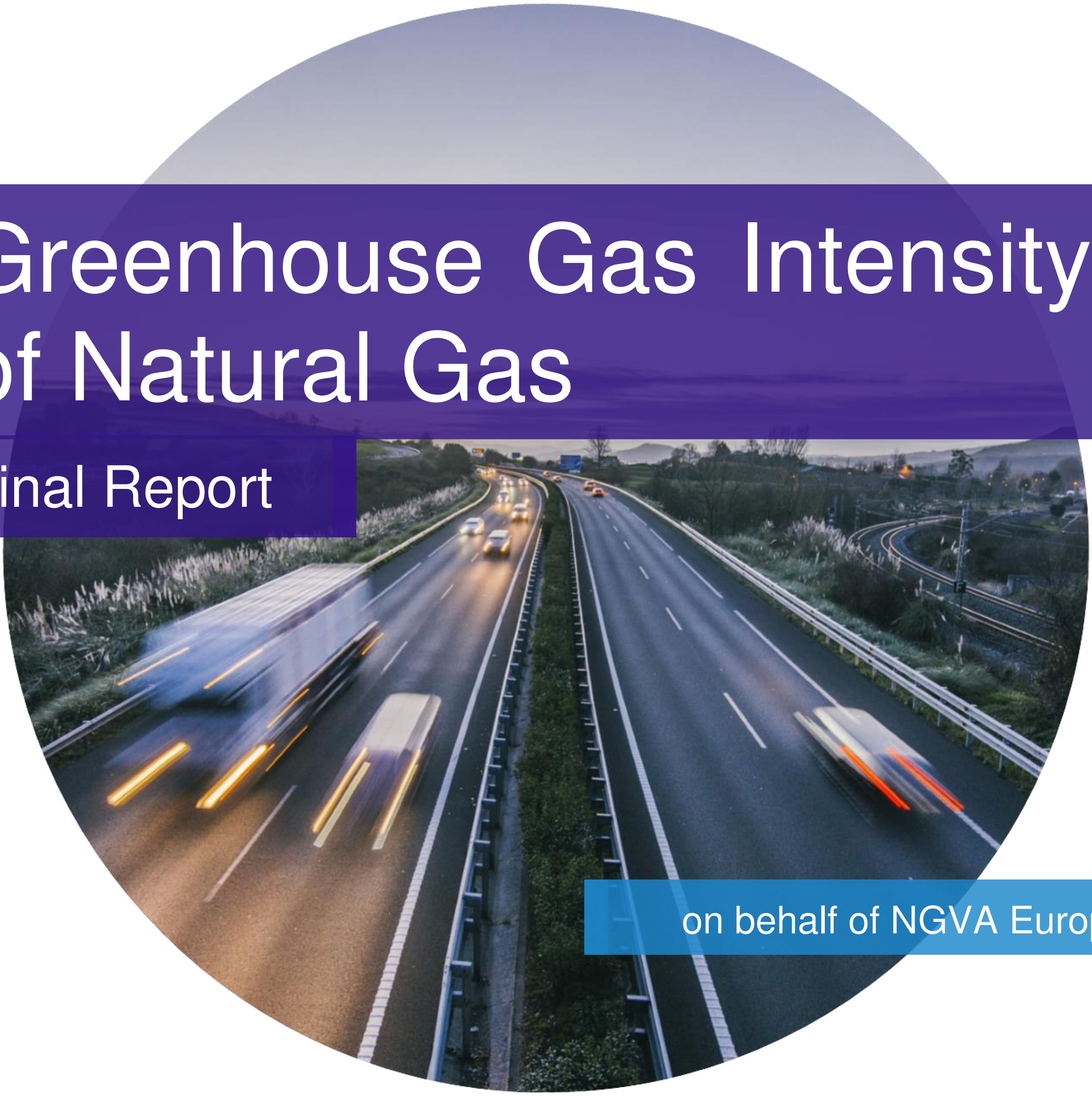
Greenhouse Gas Intensity of Natural Gas

Final Report



on behalf of NGVA Europe

Title: Greenhouse Gas Intensity of Natural Gas

Client: Natural & Bio Gas Vehicle Association (NGVA) Europe

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On behalf of thinkstep AG and its subsidiaries

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BEV	Battery Electric Vehicle
bioCNG	Compressed Natural Gas from Renewable Sources, e.g., from anaerobic digestion of organic waste and manure
bioLNG	Liquefied Natural Gas from Renewable Sources, e.g., from anaerobic digestion of organic waste and manure
bioSNG	Synthetic Natural Gas from Renewable Sources, e.g., from lignocellulose gasification (wood, straw, etc.)
BREF	Best Available Techniques Reference
BOG	Boil-Off Gas
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
CO_2	Carbon Dioxide
CNG	Compressed Natural Gas
DBI	DBI Gas- und Umwelttechnik GmbH (company, based in Germany)
DFDE	Dual-Fuel Diesel Electric Propulsion (e.g., LNG Carrier)
DISI	Direct Injection Spark Ignition
DSI	Data Source Indicator (labelling primary, calculated, literature or estimated data)
EoL	End of Life
EU	European Union
Euro 5,6	European Union Emission Standard for passenger vehicles
Euro V,VI	European Union Emission Standard for Heavy-Duty vehicles
EU-28	European Union with its 28 Member States
FQD	Fuel Qualitative Directive
g CH_4	Grams Methane Emissions
g CO_{2}-eq	Grams Carbon Dioxide-Equivalent Emissions
GaBi	dt. “Ganzheitliche Bilanzierung”, engl. Life Cycle Engineering Software
GIE	Gas Infrastructure Europe. European Association for Infrastructure Industry of Natural Gas Transmission System Operators, Storage System Operators and LNG Terminal Operators

GHG	Greenhouse Gas(es)
GTP_{100}	Global Temperature Change Potential at a 100 year time horizon
GWP_{100}	Global Warming Potential at a 100 year time horizon
HDV	Heavy-Duty Vehicle
HFO	Heavy Fuel Oil
HHV	Higher Heating Value
HPDI	High Pressure Direct Injection
H_2S	Hydrogen Sulphide
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
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	Kilo Watt 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
MDO	Marine Diesel Oil
MJ	Mega Joule
MW	Mega Watt
N_2O	Nitrous Oxide (Laughing Gas)
NEDC	New European Driving Cycle
NGL	Natural Gas Liquids
NGV	Natural Gas Vehicle
Nm^3	Normal Cubic Metre
OEM	Original Equipment Manufacturer
PAH	Polyaromatic Hydrocarbons
PCF	Product Carbon Footprint
PISI	Port Injection Spark Ignition
ppmv	Parts per Million Volume

PV	Photovoltaic
PtG	Power-to-Gas
Q_{Flex}	Q-Flex is a Type of Ship, carrying Liquefied Natural Gas
RDE	Real Driving Emissions
RED	Renewable Energy Directive
RoRo	Roll-on, Roll-off Ships
SI	Spark Ignited Engine
SNG	Synthetic Natural Gas
SSD	Slow Speed Diesel
SSO	Storage System Operator
TFDE	Tri-fuel Diesel Electric Propulsion (e.g., LNG Carrier)
TJ_{in}	Tera Joule related to Input
TSO	Transmission System Operator
ts	thinkstep
TtW	Tank-to-Wheel
Vol.%	Volume Percentage
WHTC	World Harmonised Transient Cycle (Heavy-Duty engines)
WLTC	Worldwide Harmonised Light Vehicles Test Cycles (for passenger vehicles and light commercial vans)
WLTP	Worldwide Harmonised Light Vehicles Test Procedure (for passenger vehicles and light commercial vans)
WtT	Well-to-Tank
WtW	Well-to-Wheel
WtX	Well-to-X (i.e. Well-to-Wheel, Well-to-Wake, and Well-to-Grid)
wt.%	Weight Percentage

Glossary

Carbon Footprint – Carbon Intensity – GHG intensity

Total emissions of greenhouse gases (GHG) following the life cycle approach. By characterising each single GHG emission by its individual characterisation factor, all GHG emissions can be aggregated to 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.

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)

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)

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)

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)

Functional unit

“Quantified performance of a product system for use as a reference unit” (ISO 14040:2006, section 3.20)

Allocation

“Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14040:2006, section 3.17)

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).

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 2,500 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 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 LCA database provider, *thinkstep* has gathered considerable experience in modelling emissions along the entire supply chain of Natural Gas for 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 greenhouse gas assessments.

Our LCA data and tools are used by major vehicle manufactures 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 data sets to the European Commission's LCA data network (ILCD - see http://eplca.jrc.ec.europa.eu/) and 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-Wheel 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, focusing 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.

Our consulting teams consist of about 150 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

The Natural & bio Gas Vehicle Association (NGVA) Europe commissioned *thinkstep* to perform an industry-wide GHG intensity analysis of supplying and using Natural Gas at European level, mainly focussing on the road transportation (Well-to-Wheel) sector, but also considering ship transport (Well-to-Wake), as well as power generation (Well-to-Grid).

The report provides a complete analysis of the current scenario based on the most recent data, most of them referring to the year 2015 and provided through the NGVA members. The report also provides a prospective outlook to 2030 looking to potential future technological evolutions, i.e. more efficient technologies for natural gas supply, improved electricity production in the future, and an integration of bioCNG and SNG into the Natural Gas supply.

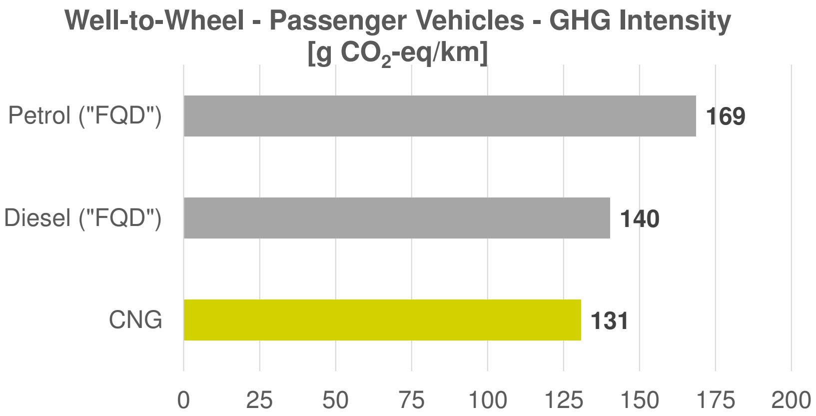
The goal of the study is to provide high quality, reliable, and up-to-date industry-based life cycle data on Natural Gas to inform the public and to support dialogue with external stakeholders and policy makers. It is also intended to contribute to an informed debate during the revision process of the different Directives dealing with clean and efficient mobility (e.g. Fuel Quality Directive, CO_2 emission regulations, Clean Vehicle Directives, etc.). This study assesses the use of Natural Gas in detail following ISO 14040/44, and is not a comparative assertion according to its LCA definition. Nevertheless, the determined GHG results are discussed alongside estimates for other fuels as reported in other sources.

This assessment builds on previous studies conducted in this field, e.g. the Exergia study, the DBI study, and the JEC-WtW study. It aims to further develop and advance those results based on using more recent data, and a comprehensive collection of primary data, as well as the integration of an external critical review.

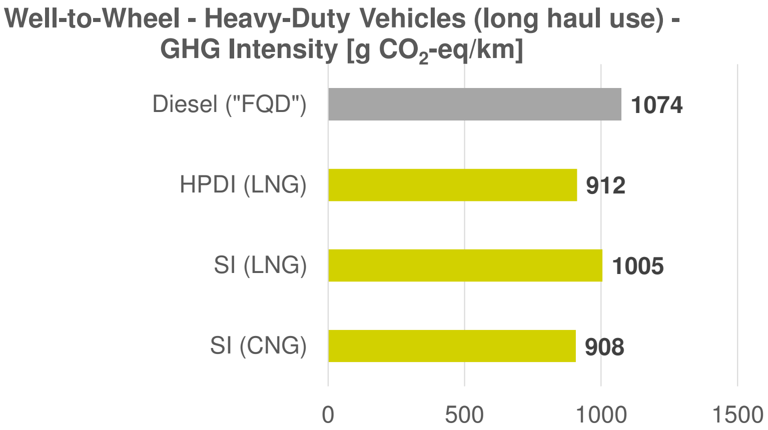
The key findings are:

Well-to-X Results

- On a life cycle basis, including all emissions from production and processing, through to supply and use, the main results are as follows: The **Well-to-Wheel** greenhouse gas (GHG) emissions of a **Passenger Car** (vehicle from the C segment being used according to the New European Driving Cycle) powered by CNG (130.7 g CO_2-eq/km) are **23 % lower** than those determined for an equivalent passenger car powered by petrol (168.7 g CO_2-eq/km) and **7 % lower** than those of an equivalent passenger vehicle powered by Diesel (140.4 g CO_2-eq/km). The petrol and diesel powertrain technologies were assessed based on primary fuel consumption data collected within this study in combination with the GHG intensity default values that are provided by the Council Directive (EU) 2015/652 pursuant to the Fuel Quality Directive (FQD). The GHG emissions determined for passenger vehicles were also compared with the estimates determined in the JEC-WtW study.



- The **Well-to-Wheel** GHG emissions for **Heavy-Duty Vehicles** (40 t tractor + trailer combination with 75% payload in long haul use) are **16 % lower** than the Diesel baseline determined when considering **CNG** SI engines (908 g CO_2-eq/km vs. 1 074 g CO_2-eq/km). When using **LNG** in a SI engine, which requires more energy on the Well-to-Tank side, the overall WtW result shows a **GHG reduction of 6 %** (1 005 g CO_2-eq/km). Taking into account new incoming HPDI engine technology for LNG applications, the benefit increases **to 15 %** (912 g CO_2-eq/km). The emissions of the Diesel HDV are based on the GHG intensity default values provided in the Council Directive (EU) 2015/652.



Considering maritime applications, **Well-to-Wake** GHG emissions for an **LNG powered ship** are lower than those determined for a ship powered by either heavy fuel oil or marine diesel oil: LNG fuelled 2-stroke engines with high pressure injection show a **benefit of 21 %** compared with HFO vessels, while 4-stroke engines emissions are **11 % lower** than HFO. The emissions caused by HFO and MDO were modelled based on the Council Directive (EU) 2015/652 and the JEC-WtW study.

The **Well-to-Grid** GHG emissions for electricity generation based on a Natural Gas power plant mix (direct and CHP electricity generation) are 475 g CO_2-eq/kWh (**53 % less** than hard coal). A combined cycle Natural Gas power plant (best available technology) emits only 404 g CO_2-eq/kWh (**60 % less** than hard coal). (In comparison: Lignite 1 156 g CO_2-eq/kWh, Hard Coal 1 008 g CO_2-eq/kWh)

The results for Passenger Cars and Heavy-Duty Vehicles have been confirmed to be very robust through sensitivity and uncertainty analyses (see sections 7.5 and 7.6). The use of a more recent life cycle impact assessment methodology, such as the Global Warming Potential according to the 5th

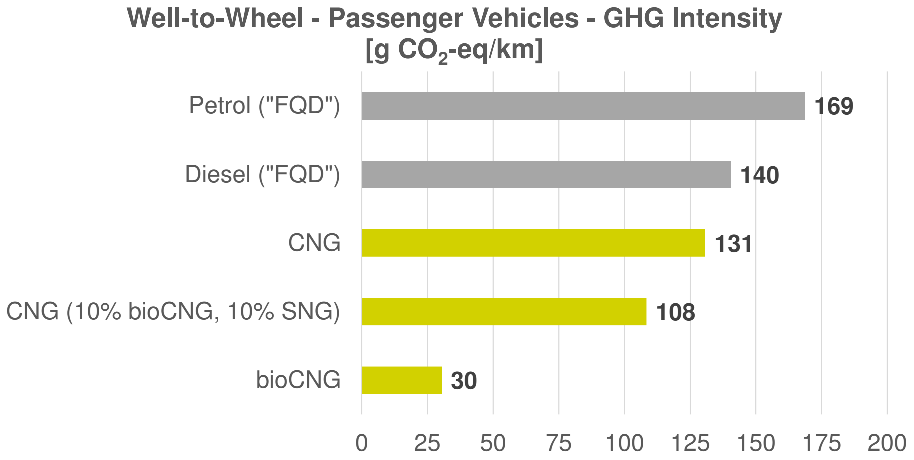
Assessment Report (GWP AR5) gives very similar results to the assessment conducted according to the 4th Assessment Report. Using the Global Temperature Change Potential (GTP) reduces the determined impact due to a lower weighting factor for methane. As expected, among the technical parameters considered in the model, the vehicles' fuel consumption has the greatest influence, and the impact of all other parameters assessed is far less.

Introducing Renewable Methane

The study focussed also on the current and future contribution from **Biomethane (bioCNG)** produced from renewable sources. From the technical standpoint, Biomethane has the key property to be **100 % compatible with Natural Gas**, being easily blended or used directly as a neat fuel in engines.

Current conventional production of Biomethane based on waste organic biomass contributes to a virtuous circular economy approach where a waste material is transformed into a clean fuel, locally produced, while at the same time producing high quality bio co-products (e.g. fertilisers). On the other hand, new processes based on direct CO_2 conversion and methanation, like e.g. Power-to-Gas, offer a complementary solution to store renewable energies (green methane from renewable electricity) as **Synthetic Natural Gas (SNG)**.

The following figure shows the Well-to-Wheel impact for a Passenger Car using a 20 % renewable methane blend (10 % bioCNG, 10 % SNG produced from a 50 / 50 rate of wet manure and organic waste conversion), as well as 100 % bioCNG, based on local fuel consumption on specific fleets.



Well-to-Tank Results

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

- The EU Total carbon footprint of **CNG is 12.5 g CO_2-eq/MJ** (LHV) in tank (full details provided in section 5.3.1). Over the total life cycle, contributions are:
    - production, processing and liquefaction (37 %)
    - fuel dispensing (27 %)
    - feedstock transportation (23 %)
    - gas transmission, storage and distribution (13 %)
- The EU Total carbon footprint of **LNG is 19.9 g CO_2-eq/MJ** (LHV) in tank (full details provided in section 5.3.2. Over the total life cycle, contributions are:
    - production, processing and liquefaction (77 %)
    - feedstock transportation (15 %)

  - fuel dispensing (6 %)
  - storage and distribution (2 %)

Large variations (± 30 %) were identified and considered for both CNG and LNG supply chains among the four defined regions (North, Central, South East, South West) in order to provide an average weighted EU figure. Major reasons for this variation are:

- different electricity grid mixes,
- different transmission energy intensities, and related methane emissions,
- different Natural Gas countries of origin, with different supply routes and technologies, and consequent GHG intensities,
- different GHG intensity of production and processing.

The EU LNG imports from Algeria, that account for 22.1 % of the overall LNG supply (2015), strongly affect the overall results, as only few data are available for current LNG plants in Algeria. Assuming only state of the art plants in Algeria, the EU Total LNG supply GHG intensity results reduced by 16 %, from 19.9 g CO_2-eq/MJ down to 16.8 g CO_2-eq/MJ.

Methane Emissions to the Atmosphere

The study has also carried out a deep analysis on methane emissions to the atmosphere from the entire Natural Gas chain, since methane is the largest component of Natural Gas.

For the **CNG supply chain**, the methane contributions from the different steps are:

- production, processing and liquefaction (45 %)
- gas transmission, storage and distribution (32 %)
- long distance transportation (15 %)
- dispensing (8 %)

For the **LNG supply chain** the methane contributions from the different steps are:

- gas production, processing and liquefaction (78 %)
- fuel distribution and dispensing (20 %)
- feedstock transportation (2 %)

Considering the **vehicle technologies**, it is important to note that:

- No Natural Gas leakage occurs on the engine / vehicle side.
- All crankcase ventilation systems for road vehicles are based on closed blow-by circuit, directly connected to the engine air intake manifold, so there are no CH_4 emissions.
- CH_4 emissions from boil-off and dynamic venting are not released into the atmosphere.
- Only CH_4 from exhaust unburned hydrocarbons occur from the combustion process, and they are taken into account as CO_2-equivalent through GHG characterisation factors.

The **Well-to-Wheel methane emissions** are summarised in the following table for Heavy-Duty vehicles. Methane emissions include vented, pneumatic, and fugitive emissions as well as CH_4 unburnt emissions. The wt.% values are related to the mass of CNG and LNG combusted.

	CNG Vehicles (SI) [wt.%]	LNG Vehicles (HPDI) [wt.%]
Vehicle	0.131 wt.%	0.155 wt.%
Fuel dispensing	0.051 wt.%	0.210 wt.%
Gas transmission, storage and distribution	0.209 wt.%	0.002 wt.%
Feedstock transport (Pipeline, LNG-carrier)	0.100 wt.%	0.021 wt.%
Gas production, processing and liquefaction	0.291 wt.%	0.840 wt.%
TOTAL	**0.782 wt.%**	**1.228 wt.%**

Key Messages from the Study

The collaboration and support from the large number of NGVA members working across the entire natural gas supply chain enabled the collection of up-to-date and high quality data. Multiple iterations of data collection were conducted with the data providers in order to close data gaps and eliminate inconsistencies and hence improve the overall data quality. The draft report was circulated twice among the consortium partners, who were invited to verify data and provide feedback and remarks. This internal stakeholder process has provided the basis for a complete and accurate analysis of the Natural Gas GHG intensity for Europe expressed in terms of CO_2-equivalents. Methane emissions (CH_4) from each step of the life cycle have been carefully calculated and included, as well as N_2O emissions and other relevant emissions that impact on climate change. From this analysis, the key messages are:

- The use of Natural Gas to fuel both Passenger Cars and Heavy-Duty vehicles ensures a large WtW GHG reduction compared with the estimates for conventional diesel and petrol fuels that are based on the Council Directive (EU) 2015/652 pursuant to the Fuel Quality Directive (FQD).
- The development of LNG as a transportation fuel is extending the application of Natural Gas from the typical urban / inter-city mission profile, towards the long haulage task. As a result of this use, manufacturers are developing dedicated engine units with equivalent performance to diesel engines in terms of torque and power output.
- bioCNG, produced from a range of organic waste biomasses, as well as SNG (Synthetic Natural Gas) provide a supplementary and substantial benefit in terms of WtW GHG intensity. This benefit is enhanced by the fact that both bioCNG and SNG can be easily blended with Natural Gas or used directly in their own right.
- Results show considerable regional variations with GHG intensity being strongly correlated to the specific regional conditions in terms of distances and plant technologies. This demonstrates the importance of analysing local data. Local analysis is already indicating best practice technologies that can be progressively adopted, closing the gaps between local GHG performances.
- Vehicle / engine technology improvements in the future are expected to provide a supplementary reduction in fuel consumption due to the introduction of fully dedicated natural gas engines. According to the NGVA members, this is likely to result in -20 % reduction for Passenger Cars, and -10 % for Heavy-Duty vehicles. The improvements will include Direct Injection system for CNG applications, currently under development for both Passenger Cars and Heavy-Duty applications.
- For maritime applications, Natural Gas provides better GHG intensity figures than the estimates for conventional fuels. In particular, modern 2-stroke engines with High Pressure Injection system offer an effective reduction of CH_4 unburnt emissions compared with other Natural Gas engines used in ships.
- When used for power generation, Natural Gas Power Plants offer GHG reduction of -53 % compared with hard coal.
- All these environmental and efficiency benefits strongly support current European Union policies around these issues. The use of bioCNG and SNG and also supports policies encouraging energy self-sufficiency, and regional economic development because of the ability to use local inputs and generate local employment.

1. Introduction

To support Europe's activities in developing a sustainable mobility, it is fundamental to have accurate and reliable GHG inventory data from the mobility and fuel supply sector.

For this reason, the Natural & bio Gas Vehicle Association (NGVA) Europe commissioned an industry-wide Well-to-X analysis of supplying Natural Gas to Europe and using it in the European Union. The analysis includes a prospective outlook to the year 2030 on the potential future shares and blends of renewable Natural Gas (Biomethane, Synthetic Natural Gas). Natural Gas Vehicle improvements, such as expected efficiency improvements, are also discussed along with improvements in the Natural Gas supply chain, e.g., reduction of methane emissions, liquefaction efficiency, etc.

Thanks to wide support from over 50 associated companies operating in the Natural Gas field, this study is based on very consistent and high quality data sources, most of them referring to updated 2015 year figures.

The overall goal of the study is to provide high quality, reliable, and up-to-date industry-based life cycle data and to inform and improve the open and transparent communication with external stakeholders and policy makers.

This study analyses the GHG emissions along the supply chain of Natural Gas and its usage in the transportation sector in both road vehicles (i.e., Well-to-Wheel) and shipping vessels (i.e., Well-to-Wake). In addition, the usage in other applications, like power generation (i.e., Well-to-Grid), are considered.

The results are compared with existing studies. The goal and scope of previous studies differ from each other and from the present study. However, the outcome of the study at hand is put into context of the other studies' results taking into account the differences in boundary conditions. The analysis is conducted on a country-by-country basis, but the GHG results are aggregated to four EU regions and the European average.

Legal Context

The study is in line with the EU's objectives to monitor and calculate lifecycle emissions in accordance with the Fuel Quality Directive (FQD)[1] [1], [2], and Renewable Energy Directive (RED) [3]. The Council Directive (EU) 2015/652 [4] describes calculation methods and reporting requirements pursuant to the FQD (Directive 98/70/EC of the European Parliament and of the Council [1]). It provides a list of average life cycle greenhouse gas (GHG) intensity default values[2] for fuels other than biofuels, and electricity, to be used by suppliers for calculating and reporting the GHG intensity of fuels they place on the market. This study is intended to contribute to an informed debate during the revision process of the Directive and the definition of new default values for the GHG intensity of Natural Gas as a vehicle fuel.

The FQD builds on work that has been carried out by the JEC consortium (JRC, EUCAR, CONCAWE). This study also aims to contribute to the scientific discourse with updated and consolidated data of future revisions of the JEC-WtW Study.

Most life cycle assessment studies, including the FQD, have so far only looked at either natural or renewable gas, without considering blends of natural and renewable gas. The Renewable Energy

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[1] Directive 98/70/EC of the European Parliament and of the Council of 13 October 1998 relating to the quality of petrol and diesel fuels.

[2] See Annex I Part 2 (5) of the Council Directive (EU) 2015/652

Directive (RED) has recently been amended and prescribes a mandatory share of biofuels (including Biomethane and Synthetic Gas) by the year 2030. This will also affect the mobility sector. Hence, the study considers an 80/20 blend of Natural Gas and bio-based / Synthetic Gas for the year 2030 in order to inform future policy making.

Life Cycle Assessment (LCA)

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 [5], [6] 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 addresses the goal of the study. Section 3 summarises the findings of the literature survey and section 4 the general scope of the study. In the subsequent sections 5, 6, and 7, the Well-to-Tank, Tank-to-Wheel, and Well-to-X analyses are described. Section 8 addresses the interpretation of the results and section 9 provides the conclusions and recommendations.

2. Goal of the Study

2.1. Goal of the Study

The goal of the study is to provide high quality, reliable and up-to-date greenhouse gas (GHG) emission factors for the Natural Gas supply and use chains of the European Union using life cycle assessment in accordance with ISO 14044[3]. This is done by performing an industry-wide Well-to-X analysis. In addition, Natural Gas from renewable sources (Biomethane, Synthetic Natural Gas) is analysed based on publicly available data. This analysis also includes a prospective outlook to the year 2030 on the potential future shares and blends of renewable gas, and supply chain improvements are considered.

An intensive data collection activity was initiated to gather primary industry information about the energy consumption, methane emissions, etc., along the different value chains supplying Natural Gas to Europe, including the production, transportation, and distribution of Natural Gas up to the consumption in vehicles or other applications, e.g. electricity generation. Based on the data collected, the GHG intensity, also known as carbon footprint, was calculated.

2.2. Reasons for carrying out the Study

The reason for carrying out this project was to provide reliable and up-to-date data about the GHG intensity of Natural Gas, in particular the use of energy and methane emissions of the Natural Gas industry in Europe. Another key motivation was to incorporate the latest vehicle technologies and performance attributes for Natural Gas supply and use. Having reliable GHG inventory data, based on industry information, is key to supporting Europe's activities in developing sustainable mobility initiatives, as well as reducing potential climate change impacts.

2.3. Intended Application

The intended application of the study outcome is mainly to support the open and transparent communication with external stakeholders such as policy makers.

Through the provision of a detailed and transparent GHG report, this project is intended to contribute to an informed debate during the revision process of the different Directives dealing with clean and efficient mobility (e.g. Fuel Quality Directive, CO_2 emission regulations, Clean Vehicle Directives, etc.).. It also aims to potentially support the future Well-to-Wheel analysis activities (JEC – Joint Research Centre - EUCAR - CONCAWE collaboration) of the European Commission.

Note: The results of the study are intended to support comparative assertions 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. Nevertheless, the study does not represent a comparative assertion in its LCA definition (see section 8.2).

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[3] ISO/TS 14067:2013 "Greenhouse Gases - Carbon footprint of products – Requirements and guidelines for quantification and communication" is currently under revision and therefore not considered for this study

2.4. Intended Audience

The report is prepared to be used for public dissemination and the dialogue with external stakeholders, particularly those involved in policy development (governmental, NGOs, and decision makers). The results are also expected to provide a sound data basis for responses to any external inquiries.

2.5. Objectives

The main objective of this study was to provide information about the life cycle GHG emissions of Natural Gas consumed in the European Union, based as much as possible on the collection of current primary data. Several pathways were analysed.

The following objectives were met with this study:

- Conduct a literature survey to identify relevant documents and studies to be used as the basis for comparison and benchmarking, and summarise them.
- Analyse the European Natural Gas consumption mix by origin of supply.
- Develop specific LCA models for the different Natural Gas supply chains, taking into account the country of origin, technology used and its technical parameters, and giving detailed consideration to venting, flaring and fugitive emissions along the supply chain. The differences between old and new LNG liquefaction plants (trains) have to be considered.
- Collect high quality primary data as far as GHG-relevant (e.g., energy and mass flows data, methane emissions, etc.) concerning the EU Natural Gas supply from NGVA members and associated partners.
- Synthesise the collected data taking into account origin and technologies in place.
- Calculate GHG emission results within the ISO 14040/44 framework using established methods for the following different transport systems:
    - Compressed Natural Gas in passenger vehicles,
    - Compressed Natural Gas in heavy-duty vehicles,
    - Liquefied Natural Gas in heavy-duty vehicles.
- Analyse the GHG emission results for vessel transport fuelled by LNG
- Compare Natural Gas supply/use in vehicles with the conventional fuels petrol and diesel, as well as electricity.
- Benchmark the developed GHG data sets with published Natural Gas GHG data sets.
- Compare Natural Gas supply and use in a combined cycle gas turbine (CCGT) for power generation with conventional power generation systems, such as lignite and hard coal.
- Consider future supply sources of gas, including Biomethane and Synthetic Gas, based on results from other publicly available reports. Include a qualitative description of key levers in the report to change the results in future.

3. Literature Survey

The first task of the project was to perform a literature survey for benchmarking purposes. In a first step, documents of relevance to the Natural Gas life cycle GHG emissions were identified and reviewed. In a second step, the most relevant studies were analysed and summarised in brief.

The literature survey focussed on identifying the most relevant and up-to-date information regarding Natural Gas life cycle GHG emissions on production, supply and usage, in particular as transport fuel in addition to the legal framework documents “Fuel Quality Directive (FQD)” [1], [2], “Council Directive (EU) 2015/652” (2015/652) [4] and “Renewable Energy Directive (RED)” [3].

Due to the large amount of publications in the oil and gas sector, e.g., reports, studies, research papers, etc., only relevant ones – in the sense of being close to the subject of the study – were taken into consideration. This means the literature review was limited to documents which:

- focussed on the European Natural Gas market and its supply chains,
- investigated GHG emissions,
- addressed the legal framework and policy aspects (energy supply, fuels, transportation), and
- were published in recent years (generally within the last 5 years, if relevant within the last 10 years).

The literature survey was performed with input from the stakeholders of the project consortium, covering the major European Natural Gas production, transport and transmission companies as well as the major European vehicle manufactures. The survey was performed within the first few weeks of the project. Due to the industry involvement, an impressive number of relevant documents were identified within a short timeframe. These were then supplemented by extensive online research by *thinkstep* staff and additional sources were added throughout the project, as appropriate.

The identified documents were reviewed and the most relevant studies were discussed among the consortium members to determine best available references for comparison and benchmarking purposes.

The literature survey resulted in an overview of recent documents and studies regarding the GHG intensity and methane leakage of the Natural Gas industry. The best available references identified for comparison and benchmarking are briefly described and presented in Annex A.1 and the literature overview in Annex A.2.

The authors of this study gratefully acknowledge all the work performed by others (e.g. Exergia [7], JEC-WtW [8], DBI [9]). Hence, this present study should be seen as further development and advancement based on using more recent data, the collection of primary data as well as conducting an external critical review, and not as counter assessment.

Special attention is given to the DBI study (“Critical Evaluation of Default Values for the GHG Emissions of the Natural Gas Supply Chain”) [9], commissioned by Zukunft Erdgas e.V.. Since some companies providing data for the DBI study were also supporting this study, there was close cooperation between DBI and *thinkstep*.

4. General Scope of the Study

4.1. System Boundary

The study is divided into three main parts, the:

- Well-to-Tank analysis (section 5)
- Tank-to-X analysis (section 6), and, the
- Well-to-X analysis (section 7), summarising the first two parts.

The Well-to-Tank analysis describes the Natural Gas supply, the Tank-to-X analysis the usage of Natural Gas. If Natural Gas is used as a road transport fuel than x refers to wheels. When used as maritime fuel x stands for wake and if Natural Gas is used as energy carrier for Natural Gas power plants, x refers to the grid. A Well-to-X analysis combines the Well-to-Tank and Tank-to-X components. Each of the three elements are independent from each other, and are framed by section 4 (this section) and section 8 and 9 (“Interpretation” resp. “Conclusions, Recommendations”).

An overview of the general system boundary of the study is displayed in Figure 4-1. A more detailed illustration of the system boundaries for the different products, CNG and LNG, is given later in section 5.1.3.

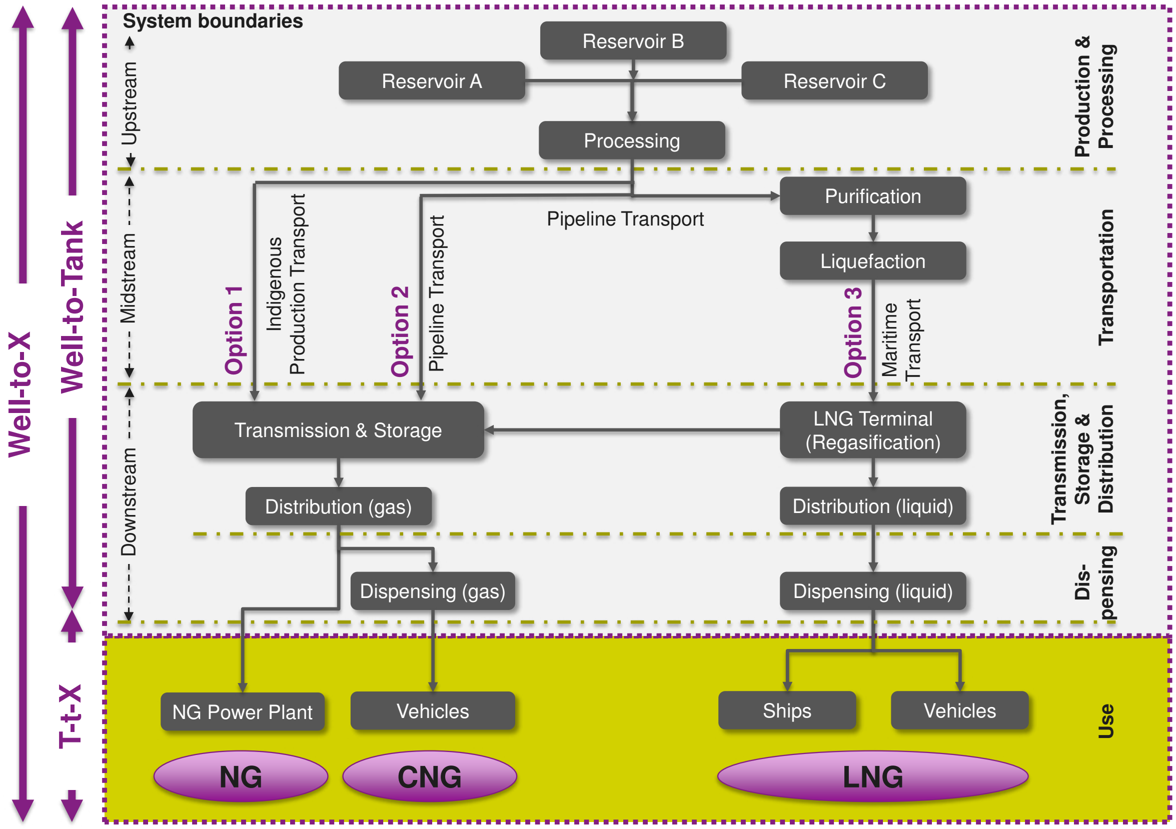

Figure 4-1: Overview – Well-to-Tank, Tank-to-X and Well-to-X Analysis[4] [10]

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[4] The Reservoirs A, B, C indicate that in some cases several gas fields are providing gas to one processing facility.

This section outlines the general scope of the project to achieve the stated goals. This includes, but is not limited to, 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.

4.2. Selection of the Global Warming Potential (GWP)

The energy sector and the sectors interlinked with the application of Natural Gas, like building, electricity generation, and mobility, are currently driven by policy makers, NGOs and the public towards carbon reduction to mitigate the effects and consequences of climate change as far as possible.

Because of this external focus, this study is not a complete LCA. This would have had to include a selection of different 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 effect that is called "climate change" and is caused by a number of substances emitted into the air, mainly CO_2, CH_4 and 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 ($CO_{2\text{-eq}}$).

The impact category climate change is assessed based on the IPCC characterisation factors taken from the 4th Assessment Report (AR4, 2007) for a 100-year timeframe (GWP_{100})[5] [11] as this metric has been used as a mandatory source for the National Inventory Reports since the United Nations Climate Change Conference in Warsaw in 2013. In addition, the carbon footprints calculated by the Exergia study, by the DBI study and by the JEC-WtW study were also based on the GWP_{100} from the 4th Assessment Report. This increases the comparability of the results of this study with the results of other studies.

The most current factors from the 5th Assessment Report (AR5, 2013) for a 100 year timeframe (GWP_{100})[6] [12] are applied in a sensitivity analysis to check the influence of any changes to the different factors on the overall GHG results.

In a further sensitivity analysis, the results are calculated following the global temperature approach for a 100-year timeframe (GTP_{100})[7]. This metric is also based on the IPCC characterisation factors taken from the 5th Assessment Report [12]. 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. Nonetheless, according to the 5th Assessment Report (AR5), the GTP is seen as more suitable for target-based policies.

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[5] GWP_{100} (AR4): CO_2-eq factors: carbon dioxide 1, methane 25, nitrous oxides: 298
[6] GWP_{100} (AR5): CO_2-eq factors: carbon dioxide 1, methane 28, nitrous oxides: 265
[7] GTP_{100} (AR5): CO_2-eq factors: carbon dioxide 1, methane 6, nitrous oxides: 234

It must be noted that the impact categories represents 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 was not applied. Weighting and grouping were also not included, because only one impact category was chosen for the present study.

4.3. Interpretation to be used

The results of the life cycle inventory analysis and the GWP 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.

4.4. 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.
- 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 resp. 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 employed.

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

4.5. Type and Format of the Report

In accordance with the ISO 14044 requirements [6] this document aims to report the results and conclusions of the GHG intensity completely, accurately and without bias. The results, data, methods, assumptions and limitations are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

It is intended to make the final report publicly available after the completion of the critical review process.

4.6. Software and Database

The LCA software system GaBi 7[8] was used to synthesise the collected data and information and to build the basis for the GHG model. The associated LCI databases (GaBi databases 2016) [13] provides the life cycle inventory data for the background data sets, like country-specific electricity grid mixes, steel, concrete and other construction materials. For the comparison and benchmarking with petrol and diesel vehicles, the GHG intensity values for the Well-to-Wheel diesel and petrol supply chains are taken from Council Directive (EU) 2015/652 [4]. Within the outlook section, the Biomethane and Synthetic Gas GHG values come from the Renewable Energy Directive (RED) [3] and Fuel Quality Directive (FQD) [1]. The licensed GHGenius model was used for comparisons.

4.7. Critical Review

The results of the study are intended to support comparative assertions intended to be disclosed to the public. While comparative assertions are not possible based on GHG intensity considerations alone, it is intended to inform and support such comparative assertions performed by third parties in the future, whether disclosed to the public or not. The study was therefore subjected to a critical review by a panel of independent experts according to ISO 14044, section 6.

The critical review statement can be found in Annex I. The critical review report containing the comments and recommendations by the independent expert(s) as well as the practitioner's responses is available upon request from the study commissioner in accordance with ISO/TS 14071 [14].

Members of the critical review panel are:

Table 4-1: 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. Stefan Hausberger	TU Graz, Graz (Austria) *Institut für Verbrennungskraftmaschinen & Thermodynamik*	Reviewer
Jean-Arnold Vinois	Jenergrid BVBA, Kraainem (Belgium), *former Director at the European Commission, DG Energy*	Reviewer

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[8] GaBi is an LCA software and one of the largest consistent LCA database 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 [20]), based on collected primary data during *thinkstep* global work with companies, associations and public bodies including all relevant industry sectors. The data sets are updated annually. More than 2000 professionals work with GaBi on a daily basis.

5. Well-to-Tank Analysis

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

The following sections describe the scope of the Well-to-Tank 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(s), 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 study covers two product systems: The supply of gaseous Natural Gas ("Product system CNG") and of Liquefied Natural Gas ("Product system LNG"). Definitions of the terms CNG and LNG as well as characteristics of these two products are given in Annex B. In the following paragraphs, all single process steps are described, and in section 5.1.3 the single processes are assigned either to the CNG, LNG or to both product systems.

The supply chains can be divided into the process steps below.

Natural Gas Production (incl. Well Drilling)

Natural Gas occurs in nature in gas fields or in connection with other hydrocarbons such as crude oil. Conventional Natural Gas is commonly found in underground sandstone and limestone formations, whereas unconventional gas refers to coal bed methane, shale gas, gas hydrates and tight gas, see Annex B. Once the drilling is completed and the wells are installed, raw Natural Gas is produced. The effort for the extraction depends on the type of Natural Gas, the formation characteristic and the location of the field (onshore or offshore).

Natural Gas Processing

After production, raw Natural Gas (rich-gas) is processed to remove Natural Gas Liquids (NGL) and impurities such as carbon dioxide, hydrogen sulphide, and water. Processed gas is often called dry gas. Processing facilities are usually built in gas producing regions, and a plant may process gas from several production wells within a specific region. The processing is necessary due to the corrosive nature of these substances. Because most collected data describe production and processing as one, and the companies do not have separate information, production and processing is treated as one in this study.

Natural Gas Pipeline Transport

Natural Gas can be transported by high-pressure pipelines from the Natural Gas processing units to the consuming regions. These pipelines can be onshore and/or offshore. Typically, the pressure in offshore pipelines is higher (>200 bar) than onshore pipelines, since with offshore pipelines the distance between the compressor stations may be longer than for onshore transport (onshore typically between 100 - 200 km). Pipelines may also differ in compression efficiency and methane emissions, often defined by age. The pipelines utilised for subsea gas transport are welded high pressure steel pipes coated to decrease friction and pressure drop. Compressors are most often run on Natural Gas, sometimes with electricity from the grid, and occasionally with diesel fuel.

Natural Gas Purification (if any)

Before liquefaction, Natural Gas needs to be purified. This purification includes typically the:

- Removal of acid gas,
- Gas dehydration,
- Removal of mercury,
- Recovery of LPG.

Natural Gas Liquefaction (if any)

To transport Natural Gas economically over longer distance or across the ocean, Natural Gas is liquefied. The basis of all liquefaction processes is the same. The Compressed Natural Gas enters the liquefaction plant to be cooled down by gaseous refrigerants to approximately -162°C. The volume is reduced by a factor of approx. 600. Different technologies have been developed which uses different cooling cascades and different refrigerants. These technologies are:

- AP-C3MR (Air Product and Chemicals, Inc.),
- AP-C3MR/SplitMR (Air Product, Inc.),
- AP-X (Air Product and Chemicals, Inc.),
- Optimized Cascade (ConocoPhillips),
- DMR (Shell),
- MCR (Linde), and
- Propane pre-cooled mixed refrigerant design (Shell).

LNG Transport (if any)

Liquefied Natural Gas is transported by dedicated LNG carriers. These vessels are equipped with steam turbine, DFDE[9], TFDE[10], or SSD[11] 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 (boil-off gas). This boil-off gas either is used as propulsion fuel (steam, DFDE, TFDE) or is re-liquefied on-board (SSD).

LNG Terminal (Regasification, if any)

LNG terminals are marine terminals where LNG carriers unload or reload the Liquefied Natural Gas. Often after storage, the LNG is either further distributed by means of trucks and trains to LNG consumers, or warmed-up to its gaseous state and fed into the Natural Gas transmission network. Typically, open rack vaporisers (ORV) using seawater are installed, or sometimes ambient air vaporisers.

Natural Gas Transmission & Storage

Natural Gas transmission describes the trans-regional transport of Natural Gas. Again, high-pressure pipelines are used. Underground storage caverns are often integrated into the transmission network, guaranteeing a continuous supply within Natural Gas networks.

Natural Gas and LNG Distribution

Gaseous Natural Gas is supplied to the final consumer via the low-pressure distribution network. Liquefied Natural Gas is typically transported by ship, truck or train.

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[9] Dual-Fuel Diesel Electric
[10] Tri-Fuel Diesel Electric
[11] Slow Speed Diesel

Natural Gas (CNG) and LNG Dispensing

Dispensing describes the operation to fuel a vehicle or ship with either Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG). At the filling station, the Natural Gas compression, and in the case of LNG, the storage take place.

5.1.2. Product Function and Functional Unit

The product function is the provision of energy into the European Natural Gas system to be used as fuel for CNG and LNG vehicles as well as LNG fuelled ships. The lower heating value (LHV) of Natural Gas is the main property to be used to describe the functional unit. More information on Natural Gas properties is provided in Annex C.

The functional unit is defined as 1 MJ (LHV) of energy in the European Natural Gas system, in tank. The two reference flows related to the defined functional unit are[12]:

- 1 MJ (LHV) Compressed Natural Gas (CNG), in tank,
- 1 MJ (LHV) Liquefied Natural Gas (LNG), in tank.

The technical characteristics of the Natural Gas from different sources is taken into consideration.

5.1.3. System Boundary

The system boundaries for both product systems include the extraction of Natural Gas from natural resources, starting with the production & processing up to the tank at the filling stations.

Figure 5-1 shows the Well-to-Tank system boundary for the Compressed Natural Gas (CNG) supply.

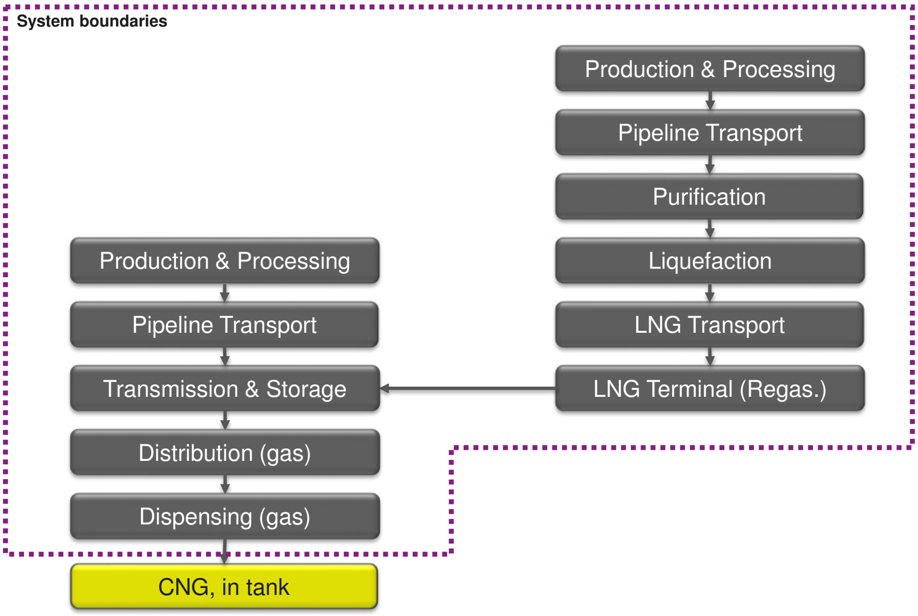

Figure 5-1: Well-to-Tank – Product System: Compressed Natural Gas (CNG) [10]

Analogous to Figure 5-1, Figure 5-2 displays the system boundary for the Well-to-Tank product system for the supply of Liquefied Natural Gas (LNG).

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[12] If Natural Gas is used as an energy carrier in Natural Gas power plants, dispensing and distribution are not part of the product system, and hence the reference flow is 1 MJ (LHV) Natural Gas, at the transmission network exit point.

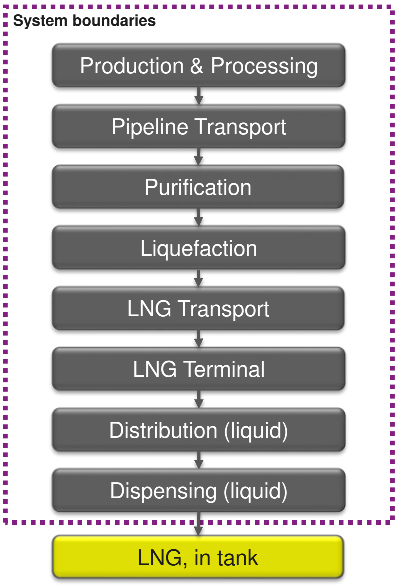

Figure 5-2: Well-to-Tank – Product System: Liquefied Natural Gas (LNG) [10]

As outlined, the objective of the study was the analysis of Natural Gas consumed in the European Union. The source of this Natural Gas is quite diverse in terms of country of origin. While more than 25 countries are supplying gas to the European market, only a few countries are contributing the major portion of the European Natural Gas consumption mix and the study focuses on those. The European Natural Gas consumption mix 2015 is presented in Figure 5-3. [15].

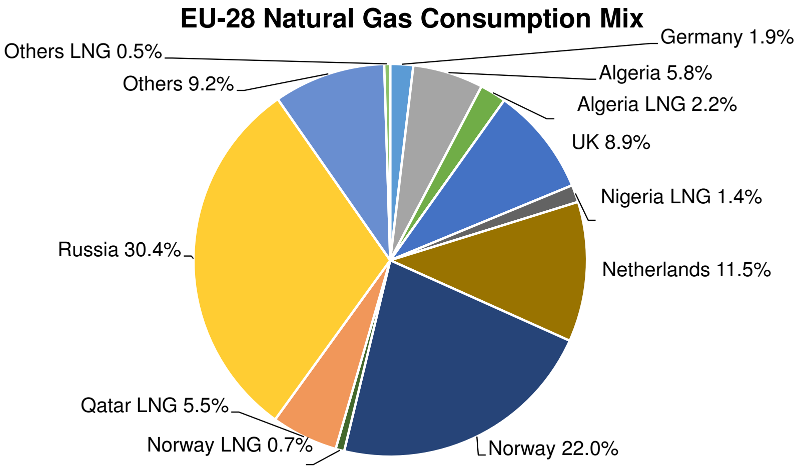

Figure 5-3: EU-28 Natural Gas Consumption Mix 2015p, based on IEA – Natural Gas Information 2016 [15]

As shown in Figure 5-3, eight countries provide 90.3 % of the EU Natural Gas consumption mix. Hence, the data collection activities of the present study focused on the following eight countries:

- Algeria,
- Germany,
- The Netherlands,
- Nigeria,
- Norway,
- Qatar,
- Russia,
- United Kingdom (UK).

It was intended to gather data for each process step in the supply chains for these countries.[13]

The Natural Gas production and transport pathways to Europe that were analysed are illustrated in Figure 5-4.

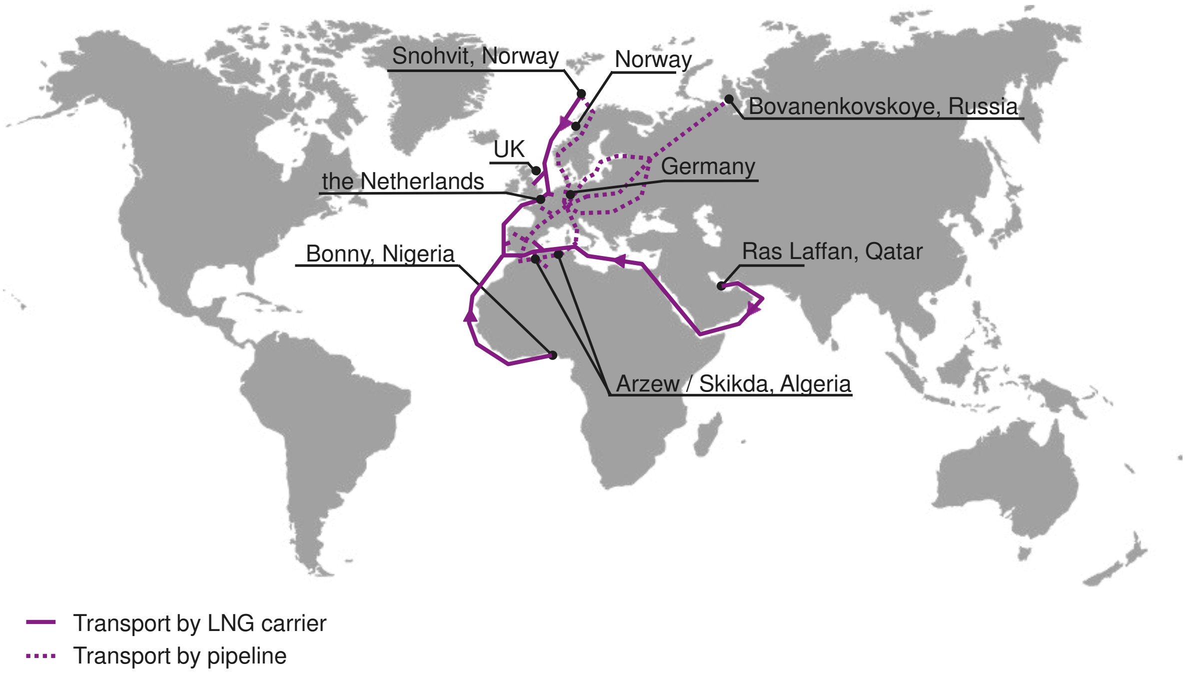

Figure 5-4: Analysed Natural Gas production and transport pathways to Europe [10]

Natural Gas Production & Processing (incl. Well Drilling)

The sub-system "Natural Gas Production & Processing" includes all the steps necessary to extract the resource, process the raw gas to pipeline quality as well as all accompanying processes to operate the system, like electricity supply. In detail, the following GHG emission relevant processes resp. emission sources are considered:

- Well drilling and well installation efforts (infrastructure),
- Extraction of the hydrocarbons itself (e.g., Natural Gas, associated gas) at the reservoir,
- Separation facilities (including high and low pressure 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 and other methane emissions.

GHG emissions are released to the atmosphere through the combustion of fuels such as Natural Gas or diesel, and through methane emissions. In this study, methane emissions comprise vented, pneumatic, and fugitive emissions as well as other unburnt emissions.

Carbon dioxide and nitrous oxides mainly occur in combustion processes associated with the energy supply or in flaring. Energy is needed to run the system, and flares are installed for safety reasons to prevent accidents. The only exception where CO_2 emissions are not related to energy supply is CO_2 separated from the Natural Gas in the gas processing and purification unit as described below. This CO_2 is released to the atmosphere whenever there are no economic benefits or penalties that would

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[13] Originally, it was planned to collect data for the top seven countries. However, for Germany, the DBI institute was collecting up-to-date data within their study [9], and hence the consortium decided to include Germany.

justify capturing the CO_2. Methane, as the main component of Natural Gas, is mainly released as fugitive and unburnt emission.

GHG emissions in all subsequent processes, including emission sources, can be described similarly.

Since unconventional gas (shale gas, tight gas, coal bed methane, etc.) is not produced in any considerable[14] amount in any of the countries under consideration, it is not analysed in this study.

Natural Gas Pipeline Transport

The sub-system "Natural Gas Pipeline Transport" comprises all processes necessary to transport Natural Gas via pipeline. These are:

- Pipeline and compressor manufacturing,
- Energy supply units (diesel generator, gas turbine, electricity from the grid).

Similar to the Exergia study, the pipeline transport considers the transport of the Natural Gas from the processing plant to the border of the European Union, e.g., from Bovanenkovskoye to Greifswald[15], and from any offshore field to the shore, e.g., Netherlands, UK. Transport within the European Union is addressed by the transmission processes. For instance, Natural Gas produced in Germany is not part of the pipeline transport, but rather of the transmission.

GHG emissions are released by energy conversion processes and from fugitive emissions. Compressors are mostly powered by Natural Gas, sometimes by electricity, with diesel used as backup. Methane emissions primarily occur at the compressors and at the valves.

Offshore pipelines, like the Norwegian exporting pipelines or the Nord Stream, run with high pipeline inlet pressure and no further intermediate compression is necessary on the way to Europe, and hence no methane emissions are released. In general, by having high-pressure levels and hence having longer distances between compressor stations, typically less methane emissions are released.

Natural Gas Purification (if any)

While Natural Gas processing is removing Natural Gas impurities to achieve pipeline quality, Natural Gas purification achieves higher qualities by lowering impurities levels even further. For instance, the H_2S and mercury concentration is lowered to the ppmv range. The following process steps and emission sources are taken into account:

- Plant / unit construction (addressed together with Natural Gas liquefaction),
- Removal of acid gas and sulphur recovery unit (Claus process),
- Gas dehydration,
- Removal of mercury,
- Liquefied petroleum gas (LPG) recovery,
- Energy supply units (diesel generator, gas turbine, electricity from the grid),
- Natural Gas methane emissions.

The LCA model further allows the application of CCS technology (carbon capture and storage) to sequester the CO_2 separated in the purification process, and hence reduce the carbon footprint. CCS is a quite new technology and currently only applied in a few plants worldwide. Within this assessment, CCS technology is only relevant for Norway.

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[14] estimated to be >3 %

[15] The import of Natural Gas from Russia via the Ukrainian and Belarussian Corridors are considered as well, see Annex D.

Natural Gas Liquefaction (if any)

The Natural Gas liquefaction sub-system includes the:

- Plant construction (addressed together with Natural Gas purification),
- Liquefaction process itself, incl. 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.

The country-specific technology, including the technology mix is modelled, considering efficiencies, and average ambient temperature.

LNG Transport (if any)

The LNG transport is modelled as the:

- LNG carrier construction,
- Transportation process itself, specifying the fuel demand,
- Boil-off rates[16],
- Energy supply processes (HFO, MDO, 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 all taken into account:

- The utilisation rate of the LNG fleets depends on short-term versus long-term trade contracts, distance of the trip as well as utilisation rates of the liquefaction plants.
- A utilisation rate of 100 % means there are no idling times of the vessels, no delay during sailing or non-operative in-port time. This means the carrier is loaded, sails, is unloaded, sails, is loaded, etc.
- 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. The time the vessels spend sailing is defined as sailing factor, i.e., the sailing factor describes the rate at which a defined vessel (e.g., speed, capacity) is at sea during a defined trip (e.g., distance) with a defined in-port time per roundtrip. In consequence, the sailing factor is per definition below the utilisation rate. At a vessel utilisation rate of 100 %, the sailing share is typically around 70-80 % based on the discussions with operators.

LNG Terminal (Regasification, if any)

The sub-system “LNG terminal (Regasification)” includes the:

- LNG terminal construction,
- Regasification itself,
- Storage and unloading activities,
- Energy supply units (diesel generator, submerged combustion vaporisers, boilers, electricity from the grid),
- Natural Gas methane emissions.

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[16] Due to generally higher outside temperature (compared with the LNG boiling temperature at -162°C), LNG is usually warmed leading to some LNG evaporating to gaseous Natural Gas (boil-off gas)

Natural Gas Transmission & Storage

The Natural Gas transmission and storage contains the trans-regional transport of Natural Gas, regulating and metering stations and underground storage and. This includes:

- Pipeline and compressor manufacturing,
- Energy supply units (diesel generator, gas turbine, electricity from the grid),
- Natural Gas methane emissions.

Again, GHG emissions occur in particular due to the operation of the compressors and from methane emissions mainly at the compressors, valves and welding seams.

Natural Gas and LNG Distribution

For the Natural Gas distribution pipeline network, the pipeline manufacturing and methane emissions of the operation are considered. There is no energy demand assumed to transport the gas to the final consumer since the distribution network is operated at lower pressure levels (<25 bar) compared with the transmission network. Sometimes, gas pressure regulating and metering stations are integrated into the system to reduce pressure.

Liquefied Natural Gas supply considers truck transport (diesel) from the LNG terminal to the filling station.

Natural Gas (CNG) and LNG Dispensing

Natural Gas dispensing (CNG) to passenger vehicles and trucks typically takes place at fillings stations with quick filling technology. These stations consume electricity to run the compressors and methane emissions may occur. It is assumed that the electricity is provided from the local grid and that the pipeline outlet pressure is at 4 bar, as derived from data provided by GrDF (Gaz Réseau Distribution France) [16]. The 4 bar outlet pressure are seen as representative among consortium partners.

Similarly, a certain amount of electricity for operating the filling stations for Liquefied Natural Gas dispensing (LNG) of trucks and ships is required. Since state-of-the-art LNG fuelling stations are equipped with a boil-off-gas (BOG) treatment, such a fuelling station is taken into consideration. The infrastructure of the fuelling station itself was not taken into consideration due to the low relevance expected[17].

Infrastructure

The infrastructure is part of the system and considered in the analysis. This study considers as infrastructure mainly the materials used to build the facilities and, if relevant, the processes of the construction work (e.g., excavation, etc.).

The infrastructure is modelled, and the total environmental impact associated with the construction / manufacturing is related to 1 MJ Natural Gas. For an assumed period of 30 years the total throughput of each modelled infrastructure is determined, and the GHG emissions are divided by that and scaled down to 1 MJ (LHV). This means that for each MJ produced or transported, a small share of environmental impact is due to the infrastructure. A period of 30 years is chosen since most plants and installations have a minimum lifetime of 30 years, e.g., LNG plants, LNG carriers, and LNG terminals as well as Natural Gas pipelines, see [17]. For well drilling and well installation an average proxy was used to estimate the well drilling and well installation impacts. The relevance of the infrastructure on the overall GHG results is evaluated in the interpretation section 8.

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[17] Based on previous work [18].

For processing, liquefaction, and regasification plants as well as LNG carriers, the End-of-Life (EoL) of the infrastructure is also considered. Pipelines are assumed not to be recycled at EoL. The infrastructure consists largely of concrete and different metal alloys. Metals are generally recyclable and/or re-usable as long as they are recovered. The recycling and re-use of metals typically leads to environmental benefits in LCA studies as the usability of waste in one product system is considered as valuable secondary material in another product system, due to substitution of primary material[18].

Table 5-1: System boundary – included and excluded elements or activities

Included	Excluded
✓ Well drilling and well installation	× Seismic exploration and exploratory drilling
✓ Production & processing (CO_2 removal, water removal, H_2S removal)	× Maintenance efforts for infrastructure (e.g., pipeline, LNG carriers, liquefaction plants)
✓ Pipeline transport	× Auxiliary materials, like lubricants
✓ Purification	× Overhead of production plants, e.g., personnel lodging and transport, employee commute, administration
✓ Liquefaction	× Accidents
✓ LNG transport	
✓ LNG terminals (Regasification)	
✓ Transmission & Storage	
✓ Distribution (CNG and LNG)	
✓ Dispensing (CNG and LNG)	
✓ Energy supply: gas turbine, gas engines, diesel generators, grid electricity	
✓ Methane emissions	
✓ Consideration of co-products (crude oil, NGLs, and LPG)	
✓ Life cycle burdens of infrastructure (e.g., pipelines, LNG carriers, liquefaction plants, etc.)	

Previous work conducted demonstrated that the excluded points do not have a relevant influence on the overall GHG results [7], [18]. Seismic exploration and exploratory drilling activities may have, (due to 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

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[18] Depends on the choice of recycling allocation method. However, this is the most common approach.

not covering, e.g., impacts from accidents, spills, and similar[19]", as outlined in the European Commission's ILCD handbook on LCA [19]

Time Coverage

The intended reference year for all primary data collected is 2015. However, because of some data not being available, some data, such as the country-specific electricity grid mixes are based on statistics of the International Energy Agency (IEA) from 2014.

Technology Coverage

The technology covered in the study is described in detail in section 5.2 for all processes and for all supply chains under consideration. It is intended to cover all relevant technologies.

Geographical Coverage

As outlined, the data collection for the upstream activities focused on eight countries covering 90.3 % of the European Natural Gas market. However, the analysis will have more granularity. It was agreed to use literature data for the remaining ~9.7 % (see "Others" and "Others LNG" in Figure 5-3), in particular from the Exergia study [7], as far as available. In the Exergia study, data for Denmark, Hungary, Italy, Libya, Poland and Romania are provided. The still missing "Others" (0.9 %) and missing "Others LNG" (0.5 %) were neglected and the remaining mix was scaled to 100 %. The mix, as it is used in the present study, is shown in Figure 5-5.

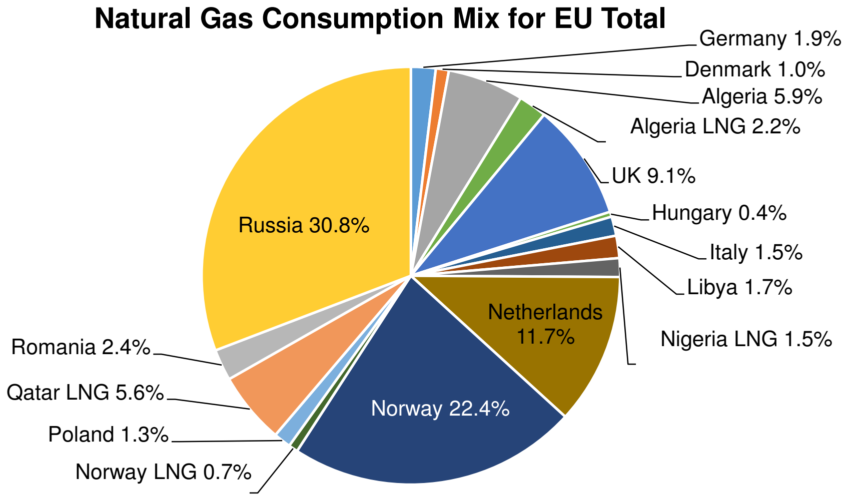

Figure 5-5: EU Total Natural Gas consumption mix[20] 2015p, own calculations based on IEA – Natural Gas Information 2016 [15]

Analogous to the Natural Gas consumption mix 2015 for Europe, the LNG consumption mix was calculated by only taking the LNG supply chains into account and by scaling the imports up to 100 %. The result is presented in Figure 5-6.

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[19] „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." [20].

[20] The EU Natural Gas consumption mix displays the share of Natural Gas consumed in the EU by its country of production. It considers the domestic Natural Gas production (within the EU) as well as the Natural Gas imports to the EU.

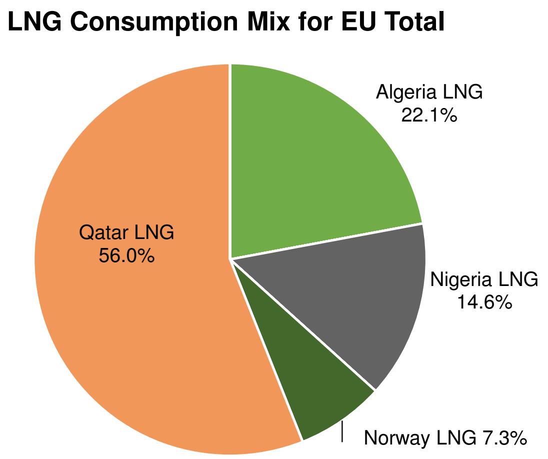

Figure 5-6: EU Total Liquefied Natural Gas (LNG) consumption mix 2015p, own calculations based on IEA – Natural Gas Information 2016 [15].

In addition to the analysis of the European Natural Gas consumption mix (EU Total), the analysis was performed for four EU regions. The definition corresponds to the Exergia study [7].

EU North	Denmark, Ireland, Finland, Sweden, United Kingdom
EU Central	Austria, Belgium, Czech Republic, Estonia, Germany, Hungary, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Slovakia
EU South East	Bulgaria, Croatia, Cyprus, Greece, Italy, Malta, Romania, Slovenia
EU South West:	France, Portugal, Spain

Note that Malta and Cyprus do not have Natural Gas markets and therefore were not considered in this study.

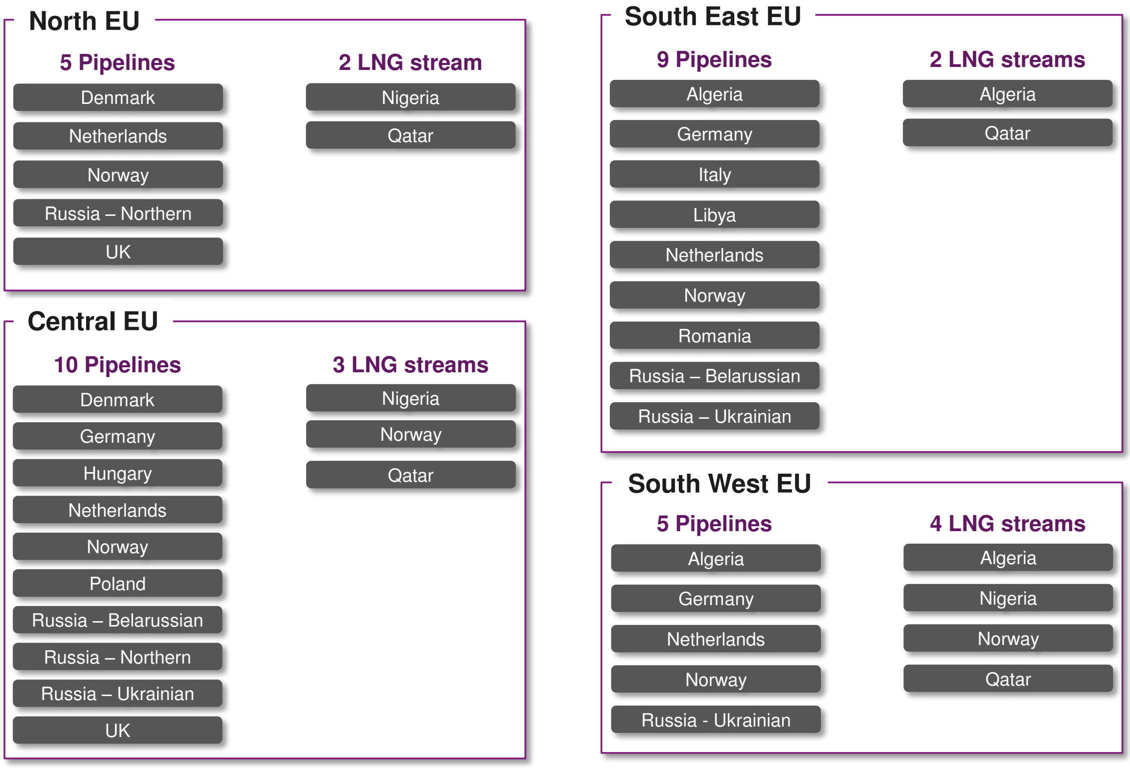

Figure 5-7: Natural Gas consumption by country per considered region 2014 [10].

The Natural Gas imports from Russia are further broken down by the three main pipeline corridors, Northern (Baltic sea), Belarussian, and Ukrainian due to different technical parameters, including distance, and energy demand. For details on the breakdown, see Annex D.

In Figure 5-8, the Natural Gas and LNG consumption mixes by region are displayed. These mixes were used in the GHG calculations.

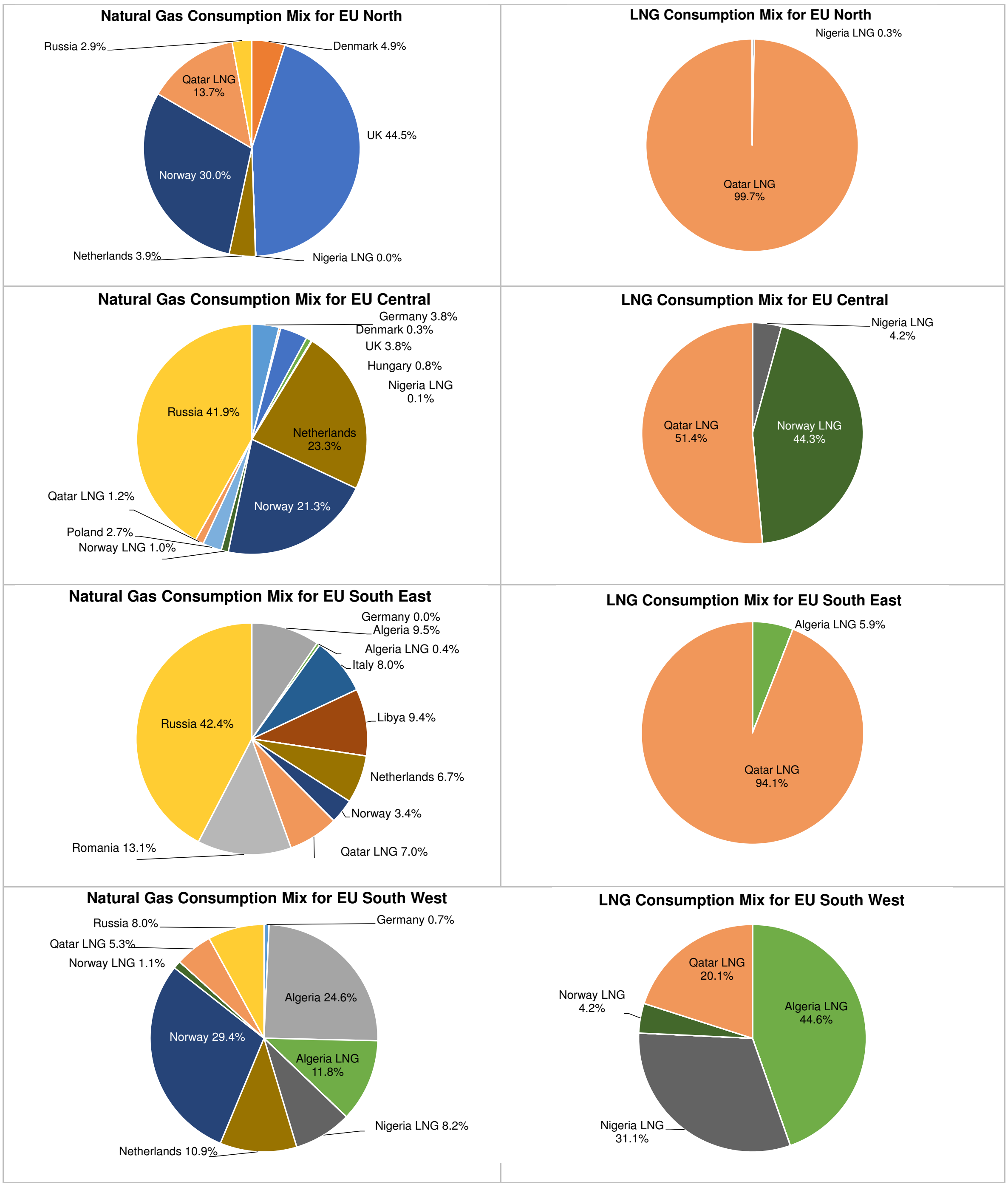

Figure 5-8: **Natural Gas and Liquefied Natural Gas (LNG) consumption mixes 2015p by country per region as used in the study, own calculations based on IEA – Natural Gas Information 2016 [15].**

Coverage of the modelled mixes aligns closely with that of the actual mixes. For EU North and EU Central, the analysed countries cover 99 % of the actual Natural Gas mix and 93 % of the actual LNG mix. For EU South East it is 96 % and 96 %, while in EU South West 98 % of the actual Natural Gas mix and 93 % of the actual LNG mix is covered.

5.1.4. 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 done on the basis of the energy content (MJ LHV) as is common practice in modelling oil and gas supply chains.

In Table 5-2, 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 5-2: Allocation factors for purification step based on energy content (based on mass for comparison)

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 relevance. Hence, no further sensitivity analysis was performed.

Allocation of background data (electricity and materials) taken from the GaBi 2016 databases is documented in [20] . Relevant for this study, the products and co-products of “combined heat and power generation (CHP, co-gens) units”, namely: thermal energy and electricity, are allocated based on exergy in accordance with the IPPC - BREF document on large combustion plants [21], one of the Best Available Techniques (BAT) reference documents related to the Industrial Emissions Directive.

5.1.5. Cut-off Criteria

No cut-off was applied within the system boundaries. The system boundaries were defined based on the relevance to the goal of the study (all included and excluded processes are listed in Table 5-1). 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. The influence of these proxy data on the results of the assessment has been carefully analysed and is discussed in section 8.

5.2. Well-to-Tank – Inventory Analysis

5.2.1. Data Collection Procedure

The data collection procedure is displayed in Figure 5-9.

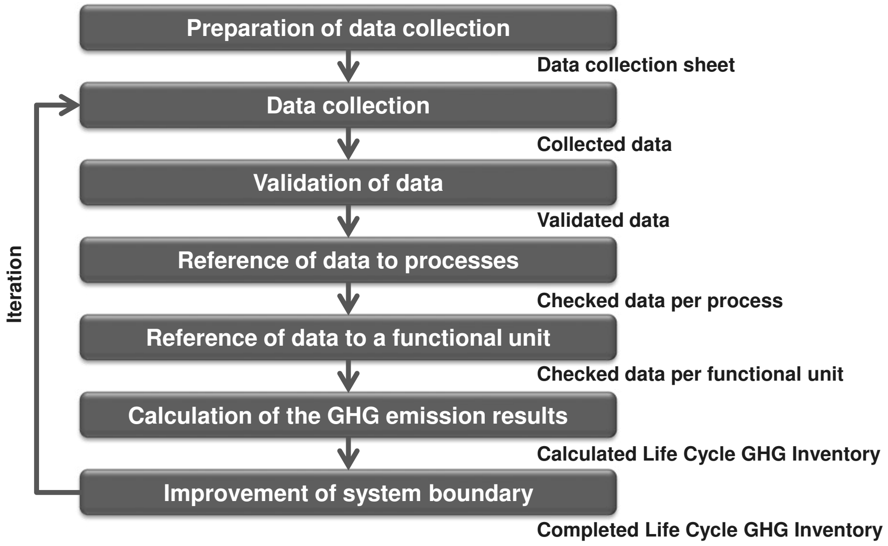

Figure 5-9: Data Collection Procedure applied by *thinkstep* [10]

Custom data questionnaires (spreadsheets) were developed for each process step within the supply chain. These questionnaires were introduced to the consortium in two webinars and then circulated via email among the consortium members and other associated partners who were providing data. The primary data were collected from the data providers at the participating companies. Each questionnaire was crosschecked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. If gaps, outliers, or other inconsistencies occurred, *thinkstep* engaged with the data provider to resolve any open issues.

Because not all partners were able to provide data in the requested format, additional effort was undertaken to adapt the data received to fit the requested format. In this respect, several iterations were conducted with some data providers in order to improve the quality of data. Furthermore, the draft report was circulated two times among the consortium partners (internal stakeholder process), who were invited to provide feedback and remarks.

Wherever feasible, data were compared with each other and with literature.

The data collection for upstream was performed for the following eight countries:

- Algeria,
- the Netherlands,
- Nigeria,
- Norway,
- Qatar,
- Russia,
- United Kingdom (UK)
- Germany.

The following companies or associations provided primary Well-to-Tank data, supported with providing appropriate literature sources, or gave advice based on their individual expertise.

- Adriatic LNG
- Bahia de Bizkaia Gas
- Bohlen-Doyen
- ELENGY
- Enagás
- Energinet.dk
- ENGIE
- ENI
- Fluxys
- Gas Connect Austria
- Gas Natural Fenosa
- GASNAM
- Gassco
- Gasum Oy
- Gazprom
- GrDF - Gaz Réseau Distribution France
- GRTgaz
- Innogy Gas Storage
- Linde
- Norwegian Oil and Gas Association (NOROG)
- OLT Offshore LNG Toscana
- Podzemno skladište plina
- RAG Energy Storage
- Reganosa
- REN Armazenagem
- REN Atlântico
- REN Gasodutos
- SAGGAS
- Sedigas
- SNAM
- SNAM–GNL Italia
- Shell
- Statoil
- Stogit
- Storengy
- TIGF
- Trans Austria Gasleitung

Companies or associations that provided information to the DBI study [9] or supported that consortium, and hence indirectly to this study, are listed below. Companies are taken from page 20 of the DBI final report [9] and only listed if not already named as a direct data provider above.

- Bundesverband Erdgas, Erdöl, und Geoenergie e.V. (BVEG)
- E.ON
- ExxonMobil
- Fernleitungsnetzbetreiber Gas e.V. (FNB Gas) and the German TSOs
- Gasunie

- International Association of Oil & Gas Producers (IOGP)
- Naftogaz
- OMV
- Uniper
- Wingas
- Wintershall

If data conversion of collected primary data had to be performed, country-specific values for lower or higher heating values, density, etc. were used if offered by the data providers. If no country-specific conversion values were provided, default values, as listed in Annex C, were used.

The inventory analysis for Norway is described below as an example, since Norway provides both CNG and LNG. All other countries (i.e., Algeria, Germany, Netherlands, Nigeria, Qatar, Russia, and UK) are described in Annex D.

5.2.2. Norway

Production and Processing

In Norway, Natural Gas is primarily produced offshore as associated gas, i.e., together with oil and condensate. Exceptions are Troll A and Snøhvit fields, which are producing mainly gas. However, virtually all installations on the Norwegian Continental Shelf are part of the NG value chain. The primary data collected had already been allocated by lower heating value to represent Natural Gas only, before being provided. Table 5-3 summarises the energy use (LHV) and gas losses per metric tonne of Natural Gas produced. Since the same format of the inventory table was used for all countries investigated, some parameters are shown as zero in some cases. In Table 5-3, for instance no crude oil is used as fuel running the production process. Please note that totals may not agree with sum due to rounding throughout this report.

Table 5-3: Energy use (LHV) and gas losses for gas production in Norway 2015, NPD [22], Statistics Norway [23], and Statoil (all data provided by Statoil [24])

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	136 094	kJ/t	primary	NO: Electricity grid mix	ts
Diesel fuel	92 544	kJ/t	primary	EU: Diesel mix at filling station (proxy)	ts
Crude oil	0	kJ/t	primary	-	-
Natural gas	1 013 261	kJ/t	primary	-	-
TOTAL	**1 241 900**	**kJ/t**	**-**	**-**	**-**
Gas losses	4.58E-03	Vol.%[21]	primary	-	-

The DSI, data source indicator, describes whether the data are primary, calculated, taken from literature or estimated. Gas processing takes place in centralised facilities, like Kårstø, Kollsnes or Nyhamna, collecting so called rich-gas from several fields. These rich-gases contains methane, ethane, propane, iso and normal butane, naphtha (Natural Gasoline) and stabilised condensate.

Processed dry gas is then compressed and exported mainly through Draupner and Heimdal to the EU (high pressure pipelines). Separated Natural Gas liquids and condensate are exported by ship.

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[21] Very large and very small numbers need to be 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 x 10^{-3} = 0.0015. Similarly, 3.5E6 refers to 3 500 000.

Table 5-4: Energy use (LHV) and gas losses for gas processing in Norway 2015, primary data provided by Gassco [25]

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	0	kJ/t	primary	-	-
Diesel fuel	8	kJ/t	primary	EU: Diesel mix at filling station (proxy)	ts
Crude oil	0	kJ/t	primary	-	-
Natural gas	50 232	kJ/t	primary	-	-
TOTAL	**50 240**	**kJ/t**	**-**	**-**	**-**
Gas losses	4.22E-3	wt.%	primary	-	-
CO_2 vented	0.225	wt.%	primary	-	-

Pipeline Transport

The compressing units are largely powered with Norwegian grid electricity. The Carbon intensity is provided in Annex C (mainly hydropower). Table 5-5 outlines the key parameters per metric tonne of pipeline-grade Natural Gas. There are several subsea exporting pipelines from the processing facilities to EU Central (Germany, Belgium), EU North (UK) and EU South West (France). The distances were determined together with Gassco, see Table 5-5.

Table 5-5: Distance, onshore share of pipeline, energy use (LHV) and gas losses for gas pipeline transport from Norwegian offshore gas production and processing fields to corresponding transmission network, primary data taken from Gassco [25].

Parameter	Value	Unit	DSI
Distance to EU Total	1 000	km	estimated
Distance to EU North	925	km	estimated
Distance to EU Central	925	km	estimated
Distance to EU South West	1 200	km	estimated
Onshore share of pipeline	0	%	primary
Electricity	3.26E-06	J/(J*km)	primary
Diesel fuel	1.17E-09	J/(J*km)	primary
Natural gas	4.42E-06	J/(J*km)	primary
Gas losses	0	Vol.%	primary

For offshore pipeline transport, the gas losses are zero, since the pipeline is a closed system and there is no re-compressing taking place. Potential methane emissions of the initial compression unit are included in the processing data.

5.2.3. Norway (LNG)

Production

Data on production are shown in section 5.2.2. Natural Gas produced in Snøhvit is processed at the LNG plant.

Pipeline Transport

The well stream from the offshore field, with Natural Gas, CO_2, Natural Gas liquids (NGL) and condensate, is transported in a 160 km pipeline to the Hammerfest LNG facility, see Table 5-6. The same energy use (LHV) values are used as described above.

Table 5-6: Distance, onshore share of pipeline, energy use (LHV) and gas losses for gas transport from Norwegian gas fields (Snøhvit) to liquefaction plant (Hammerfest), primary data provided by Statoil [24] and Gassco [25]

Parameter	Value	Unit	DSI
Distance	160	km	estimated
Onshore share of pipeline	0	%	estimated
Electricity	3.26E-06	J/(J*km)	literature
Diesel fuel	1.17E-09	J/(J*km)	literature
Natural gas	4.42E-06	J/(J*km)	literature
Gas losses	0	Vol.%	estimated

Purification and Liquefaction

Natural Gas purification involves three stages in Hammerfest: CO_2 removal, dehydration and mercury removal. CO_2 is removed in an amine unit, dewatered, compressed, liquefied before being piped back to the field in a dedicated line and re-injected into an aquifer below the gas cap. The heavier gas components, the NGLs, are removed in a fractionation column to be sold separately. The lighter gas fraction, consisting of methane and some ethane, is cooled to -163°C and liquefied. The Mixed Fluid Cascade (*MFC*®)-Process by Linde is highly efficient due to the use of the three mixed refrigerant cycles. Part of the nitrogen (N_2) in the gas is extracted in order to meet the LNG sales specifications. The LNG is stored in tanks before being shipped.

Hammerfest LNG had a gas production close 6 000 million Nm^3 gas in 2015. Energy consumption is covered by own production. The main production of electricity is generated by five LM6000 dry low emissions gas turbines. Each generator has a capacity of 45 MW, resulting in a maximum of 225 MW. Seawater (3-9°C) is used for cooling of the process and this is a strong competitive advantage compared with other LNG plants, bringing the energy consumption down. Only a small amount of electricity comes from the grid.

The liquefaction technology shares installed in Norway are presented in Table 5-7.

Table 5-7: Technology mix of liquefaction in Norway 2015, based on GIIGNL [26], IGU [27]

Technology	Value	Unit	DSI
Linde MFC	100	%	primary

Table 5-8 shows the key inputs and outputs per metric tonne of LNG[22].

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[22] Since *thinkstep's* own GaBi LNG model was used to model the facility, the boil-off rate has been set to 1.8 wt.%, of which 1 % is released as methane emissions to the atmosphere to meet actual methane emission data provided by Statoil [26].

Table 5-8: Energy use (LHV) and boil-off gas rate and recovery for gas purification and liquefaction in Norway 2015, primary data provided by Statoil [24]

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	68 076	kJ/t	primary	NO: Electricity grid mix	ts
Diesel fuel	0	kJ/t	primary		ts
Natural gas	3 559 059	kJ/t	primary		ts
TOTAL	**3 627 135**	**kJ/t**	**-**		**-**
Boil-off gas rate	1.8	wt.%	primary		ts
of which: BOG recovery	99	wt.%	primary		ts
of which: CH_4 emissions	1	wt.%	primary		ts

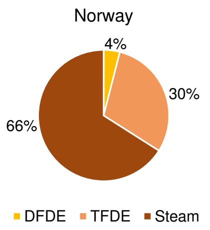
Re-injection of CO_2 which has been separated from the Natural Gas (CCS technology), is considered in the model.

LNG Transport

Norwegian Liquefied Natural Gas is supplied to several regions in Europe. Table 5-9 summarises the sea distances [25].

Table 5-9: Sea distances for LNG imports from Norway [25] and share of LNG carriers by vessel type for LNG imports from Norway

Country of origin	Destination	Distance [km]	DSI
Norway (Hammerfest)	EU Total	4 257	literature
Norway (Hammerfest)	EU North	-	literature
Norway (Hammerfest)	EU Central	2 570	literature
Norway (Hammerfest)	EU South East	7 600	literature
Norway (Hammerfest)	EU South West	5 310	literature



The share of the LNG carriers by vessel is assumed based on GIIGNL [21] and IGU [22] global fleet and expert adjustment. The fuel consumption of the LNG transport is further described in section 5.2.4.

5.2.4. General Information on LNG Transport

Table 5-10 summarises the fuel consumption and methane emissions of LNG transport applied to all LNG imports independent of country of origin.

Table 5-10: LNG carrier fuel consumption (LHV) and methane emissions, taken from GaBi databases [18]

[MJ/MJ*km]	small DFDE	small Steam	Steam	TFDE	DFDE	SSD
Capacity [m^3]	**81 000**	**65 000**	**140 000**	**160 000**	**174 000**	**216 000[23]**
fuelled by HFO	-	4.10E-07	2.99E-07	4.97E-08	-	1.71E-06
fuelled by MDO	1.57E-07	-	-	6.64E-08	9.24E-08	-
fuelled by BOG	3.29E-06	3.69E-06	2.71E-06	2.44E-06	2.02E-06	-
TOTAL FUEL[24]	**3.45E-06**	**4.10E-06**	**3.01E-06**	**2.55E-06**	**2.11E-06**	**1.71E-06**
CH_4 emissions[25]	3.29E-09	3.69E-09	2.71E-09	2.44E-09	2.02E-09	1.21E-09

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 also considers that 93 % of the LNG is unloaded. The remaining 7 % stays in the vessel. The data are taken from *thinkstep's* GaBi databases [18], crosschecked with [28], [29] and were considered good proxies for LNG transport by representatives of ENGIE and Shell.

5.2.5. Natural Gas Supply from other Countries

Other countries modelled are: Denmark, Hungary, Italy, Libya, Poland and Romania.

Production and Processing (incl. well drilling)

Production and Processing data were taken from the Exergia study [7] to get the breakdown of the GHG results into the three main GHG emissions: CO_2, CH_4, and N_2O, from the GHGenius model [30].

Pipeline Transport

As outlined previously, pipeline transport describes the transport from the natural production fields to the border of the EU. Since Libya is the only country outside the EU for which no primary data were collected, the transport from Libya to EU has to be estimated.

5.2.6. LNG Terminals (Regasification), Natural Gas Transmission, Storage, Distribution and Dispensing inside the EU

LNG Terminals (Regasification)

The inventory data, i.e., energy use (LHV) and methane losses (see Table 5-11) are based on information from 10 data providers covering 15 LNG terminals out of 21 in operation in Europe. The 15 terminals were identified to be representative for Europe. The data were weighted and averaged based on the technical capacities of the LNG terminals by GIE [31]. GIE is the European association for the infrastructure industry in the Natural Gas business, and includes Transmission System Operators, Storage System Operators and LNG Terminal Operators.

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[23] Corresponds with Q_{Flex} vessel size

[24] All fuel consumption values refer to regular sailing and do not include port operations.

[25] The methane emissions: Methane emissions are released to the environment and are assumed to be 0.1 % of the boil-off gas.

To guarantee data confidentiality, an EU Total value was calculated and no breakdown into the four different EU regions was performed. The following companies provided data: Adriatic LNG, Bahia de Bizkaia Gas, ELENGY, Enagás, Fluxys, OLT Offshore LNG Toscana, Reganosa, REN Atlântico, SAGGAS, SNAM–GNL Italia.

Table 5-11: Energy use (LHV) and methane losses for LNG terminals in EU Total 2015, primary data provided by GIE members [31]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Natural gas	8.5E-04	J/J	primary		GIE
Electricity	4.8E-04	J/J	primary		GIE
Diesel fuel	2.0E-06	J/J	primary		GIE
Total energy	**1.3E-03**	**J/J**			
Methane Losses[26]	3.3E-05	J/J	primary		GIE

For the methane losses, some companies provided measured data, while some data were estimated and some were calculated data.

Transmission and Storage

In Table 5-12 to Table 5-18, the energy use and methane losses data for EU Total and the four different EU regions are presented. The data were collected from the transmission system operators (TSO) as well as storage system operators (SSO) on a company basis per country. Some TSOs are also operating underground gas storages; so data from the transmission grid has been provided separately from the storage data. Some of the SSOs are operating facilities in more than one country. In those cases, they have provided the information on a country basis. The following companies provided data: Enagás, Energinet.dk, Fluxys, Gas Connect Austria, Gas Natural Fenosa, Gasum Oy, GRTgaz, Innogy Gas Storage, Podzemno skladište plina, RAG Energy Storage, Reganosa, REN Armazenagem, REN Gasodutos, SNAM, Stogit, Storengy, TIGF, Trans Austria Gasleitung. Via the DBI study [9], the German association FNB and the Dutch Gasunie also supported with primary data.

The data collection and the weighted averaging of the data was performed by GIE [31]. Data for EU Central (Germany, and Netherlands) were provided by the DBI [9].

The collected data were first averaged to get representative weighted averages per country if more than one company operates the network systems in a particular country. This averaging was done based on the quantities transported. In a second step, transmission and storage numbers were aggregated. In a third step, the country values calculated above were averaged based on the Natural Gas consumption of the respective countries of a region [32]. All calculations were performed by GIE except those data provided via DBI.

Generally, primary data taken from the DBI study (Germany and the Netherlands) and primary data provided by GIE (all other EU countries) were used whenever available. If GIE did not provide any data for a certain country, data from the Exergia study [7] were used to close these data gaps.

It should be also noted that the companies have provided the best data available. In some cases, it came from measurements, while in other cases data were extrapolated from measurements. Some data have been calculated based on methodology approaches. However, since the majority of the primary data are measured data, the data source indicator (DSI) for the aggregated data sets is labelled as “primary” for three regions and as “primary / literature” for two others.

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[26] Methane Losses comprise vented, pneumatic, and fugitive emissions as well as other emissions.

Since the data collection and the calculation is based on a country-by-country basis, data gaps (if operator(s) of a certain country do not provide data) were filled by using literature data taken from the Exergia study [7]. This can be seen as a worst-case approximation, since most collected primary data show less losses than the literature data.

In contrast to pipeline transport, the transmission data are not related to a certain distance (e.g., km). While dedicated transport pipelines can be viewed as single pipes, having compressor stations every 100 - 150 km and frequent reduction and regulating stations, it is considered that transmission takes place in a highly complex network of multiple compressors and gas entry and exit points. Therefore, the whole network has to be taken into consideration, even if an individual gas molecule is only transported a short distance. What has been included is the total energy demand and total losses to run the system as a whole in relation to the gas transported. The same logic applies for the distribution network described later.

Table 5-12: Energy use (LHV) and methane losses for Transmission and Storage in EU Total 2015, primary data provided by GIE [31] and DBI [9]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Natural gas	4.2E-03	J/J	primary	84% primary data	GIE, DBI
Electricity	3.2E-04	J/J	primary	84% primary data	GIE, DBI
Diesel fuel	1.2E-04	J/J	primary	84% primary data	GIE, DBI
Total energy	**4.7E-03**	**J/J**	**-**	**-**	**-**
Methane losses	5.8E-04	J/J	primary	84% primary data	GIE, DBI

Table 5-13: Energy use (LHV) and methane losses for Transmission and Storage in EU North 2015, primary data provided by GIE [31]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Natural gas	2.3E-03	J/J	primary	94% primary data	GIE
Electricity	2.4E-04	J/J	primary	94% primary data	GIE
Diesel fuel	1.7E-07	J/J	primary	94% primary data	GIE
Total energy	**2.5E-03**	**J/J**	**-**	**-**	**-**
Methane losses	8.7E-05	J/J	primary	94% primary data	GIE

Table 5-14: Energy use (LHV) and methane losses for Transmission and Storage in EU Central 2015, primary data provided by GIE [31] and DBI [9]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Natural gas	4.2E-03	J/J	primary/lit	76% primary data	GIE, DBI
Electricity	2.8E-04	J/J	primary/lit	76% primary data	GIE, DBI
Diesel fuel	2.4E-04	J/J	primary/lit	76% primary data	GIE, DBI
Total energy	**4.7E-03**	**J/J**	**-**	**-**	**-**
Methane losses	5.3E-04	J/J	primary/lit	76% primary data	GIE, DBI

Table 5-15: Energy use (LHV) and methane losses for Transmission and Storage in EU South East 2015, primary data provided by GIE [31]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Natural gas	6.5E-03	J/J	primary/lit	76% primary data	GIE
Electricity	7.9E-05	J/J	primary/lit	76% primary data	GIE
Diesel fuel	6.2E-07	J/J	primary/lit	76% primary data	GIE
Total energy	**6.6E-03**	**J/J**	**-**	**-**	**-**
Methane losses	1.4E-03	J/J	primary/lit	76% primary data	GIE

Table 5-16: Energy use (LHV) and methane losses for Transmission and Storage in EU South West 2015, primary data provided by GIE [31]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Natural gas	2.8E-03	J/J	primary	100% primary data	GIE
Electricity	6.6E-04	J/J	primary	100% primary data	GIE
Diesel fuel	3.4E-06	J/J	primary	100% primary data	GIE
Total energy	**2.8E-03**	**J/J**	**-**	**-**	**-**
Methane losses	3.3E-04	J/J	primary	100% primary data	GIE

As indicated in the previous tables, the amount of energy required for the transmission and storage as well as the methane losses differ between the assessed regions. Between the EU North, where emissions are low, and the EU South East, where emissions are high, the main impact is due to the lack of primary data and that the missing data had to be taken from the Exergia report (national inventories 2012, with an unknown uncertainty). In the North those countries/companies who have not provided primary data have very low methane emissions (below 1E-4 J/J). In the South East the countries/companies that have not provided primary data have methane emissions higher than 1E-3 J/J and in one case even higher than 1E-2 J/J. It is important to keep in mind the potential differences in the quality of the national inventories with a lack of standards and methodologies for collecting the information for pipeline transport.

The percentage values presented in the comment column, were calculated based on the amount of gas consumed in the data providing countries, in relation to the amount of gas consumed by the whole region.

As mentioned, data gaps were closed by literature data (Exergia study [7]), 14 % of the data in EU Central and EU South East are based on literature. It is important to highlight that the data taken from the Exergia study for these two regions were very high values, and this substantially affects the weighted average. In EU North, only 6 % are based on literature data. For EU South West, all information is based on primary data.

Considerable amounts of Natural Gas are transported through EU Central, mainly Natural Gas coming from the North Sea and Russia being transported to the regions South East and South West. Since this transit transport represents an important part of the energy demand and losses in EU Central, a split of the energy demand and losses in EU Central was performed by *thinkstep*. The EU Central energy and methane losses values were slightly reduced by the amount which was allocated to the transit (already considered in Table 5-14) and the same amount was added as “transit fee” to the regions South East and South West (not included in Table 5-15 and Table 5-16). These “transit fees” are shown in Table 5-17 and Table 5-18, and were calculated on the basis of the amount of gas transported across a region, e.g. from Natural Gas from Russia to EU South West.

Using this transit approach leads to a small increase of 5.0E-04 J/J in the energy demand and methane losses of 6.3E-06 J/J in the region South East. In South West the numbers are 1.4E-04 J/J and 4.6E-06 J/J respectively. The corresponding amounts of energy and methane losses (in absolute numbers) were subtracted from EU Central to arrive at the values shown in Table 5-14.

Table 5-17: Energy use (LHV) and methane losses for Transit EU Central to South East 2015, own calculation based on primary data [33]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Natural gas	4.4E-04	J/J	calculated	-	-
Electricity	3.7E-05	J/J	calculated	-	-
Diesel fuel	2.3E-05	J/J	calculated	-	-
Total energy	**5.0E-04**	**J/J**	**-**	**-**	**-**
Methane losses	6.3E-06	J/J	calculated	-	-

Table 5-18: Energy use (LHV) and methane losses for Transit EU Central to South West 2015, own calculation based on primary data [33]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Natural gas	9.6E-05	J/J	calculated	-	-
Electricity	2.4E-05	J/J	calculated	-	-
Diesel fuel	2.1E-05	J/J	calculated	-	-
Total energy	**1.4E-04**	**J/J**	**-**	**-**	**-**
Methane losses	4.6E-06	J/J	calculated	-	-

Distribution (gaseous)

In Table 5-19, the gas losses related to the distribution are shown. Marcogaz and Eurogas (both industry associations related to Natural Gas distribution), recommended using the “representative average” value from the Marcogaz survey [34]. Subsequently it was agreed to use this value for all regions in Europe.

Table 5-19: Gas Losses for Natural Gas Distribution in EU 2014-2015, taken from [34]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Gas losses	0.15	wt.%	primary	representative average	Marcogaz

Distribution (liquid)

The distribution of LNG was assumed to be performed by a 44 tonnes long haul diesel fuelled truck with 16.5 tonnes payload capacity. The average distance from the terminal to the filling station was assessed to be ~200 km (one way). The gas losses are covered by the dispensing process. The LNG distribution process modelled is not country or region-specific.

Dispensing (gaseous)

CNG passenger vehicles and trucks are typically refuelled by quick filling technology. The following information was gathered for the CNG dispensing.

Table 5-20: Energy use (LHV) and Gas Losses for CNG Dispensing in EU 2016, primary data provided by GrDF [16]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Electricity	0.32	kWh/kg	primary	based on an inlet pressure of 4 bar	GrDF
Gas Losses	0.022	wt.%	primary	-	GrDF

The CNG dispensing data were provided by Gaz Réseau Distribution France (GrDF) and are based on averaged European industry data for the year 2016. In addition, the data were discussed with an industry expert of the NGVA and are considered a reasonable proxy for all countries and regions. Some consortium partners plan further measurement campaigns for 2017.

Dispensing (liquid)

LNG trucks and ships are refuelled at LNG filling stations. The modelled station is equipped with boil-off gas (BOG) treatment. The electricity demand and gas losses are displayed in Table 5-21.

Table 5-21: Energy use (LHV) and Gas Losses for LNG Dispensing in EU 2016, primary data provided by GrDF [16]

Parameter	Value	Unit	DSI	Comment	Dataset provider
Electricity	0.015	kWh/kg	primary		GrDF
Gas Losses	0.2	wt.%	primary	incl. all emissions from the LNG terminal exit gate to the tank	GrDF

The LNG dispensing data were also provided by GrDF and are based on averaged industry data for the year 2016. In addition, the data were discussed with industry experts of the NGVA and Shell and are considered as technology representative industry average. The modelled LNG dispensing process is not country or region-specific.

5.2.7. Background Data

Background data (e.g., fuel, electricity, raw materials, transportation) are taken from GaBi 2016 LCI databases [13]. Some relevant background data are explained in more detail below.

Electricity Grid Mixes

In country-specific operations, e.g., at Natural Gas production in Norway, country-specific electricity grid mixes are used, e.g., the Norwegian electricity consumption mix.

However, since the European Natural Gas transmission, storage, distribution and dispensing activities are modelled on a regional level (EU Total, EU North, EU South East, EU South West), region representative electricity mixes for the transportation of natural gas in those regions were calculated. The share of each country-specific electricity mix in a region is based on the Natural Gas consumed in this region. In consequence, if a country consumes a lot of Natural Gas, e.g., the Netherlands, its share in the regional electricity grid mix is higher compared with a country with a low Natural Gas consumption, e.g., Luxembourg. The Natural Gas consumption data are taken from "IEA – Natural Gas Information 2016" and refer to 2014 [15]).

The electricity consumption mixes per region used in the model are shown in Table 5-22. Note that for each individual country-specific electricity consumption, the corresponding shares of fuels (e.g., coal, Natural Gas, oil, wind, biomass, etc.), combustion technologies, (e.g., direct, combined heat and power), combustion efficiencies, emissions factors, fuel gas cleaning technologies, power plant own energy consumption, electricity transmission losses as well as the specific energy carrier supply chains were modelled (e.g., import mixes, own production).

Table 5-22: Electricity consumption mixes by country for EU Total and the four EU regions (own calculation [33], based on the IEA statistics [15])

	EU Total	EU North	EU Central	EU South East	EU South West
Denmark	1.0%	5.5%			
Finland	0.6%	3.2%			
Ireland	0.8%	4.6%			
Sweden	0.2%	0.9%			
United Kingdom	15.1%	85.7%			
Austria	2.1%		4.2%		
Belgium	3.1%		6.2%		
Czech Republic	1.4%		2.8%		
Germany	18.5%		36.4%		
Estonia	0.1%		0.2%		
Latvia	0.2%		0.3%		
Lithuania	0.5%		1.0%		
Luxembourg	0.2%		0.4%		
Hungary	2.0%		4.0%		
Netherlands	18.4%		36.3%		
Poland	3.3%		6.6%		
Slovak Republic	0.9%		1.8%		
Bulgaria	0.5%			3.4%	
Croatia	0.5%			3.4%	
Cyprus	0.0%			0.0%	
Greece	0.5%			3.5%	
Italy	11.7%			74.9%	
Malta	0.0%			0.0%	
Romania	2.2%			13.9%	
Slovenia	0.1%			0.9%	
France	8.4%				52.7%
Portugal	0.8%				4.8%
Spain	6.8%				42.5%
TOTAL	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

The GHG intensity of each country specific electricity grid mix is presented in Annex C.

Natural Gas Turbines, Natural Gas and Diesel Engines; Crude Oil Combustion

Table 5-23 shows the emission factors for the main combustion processes, which convert the reported amount of fuel into GHG emissions along the Natural Gas supply chain.

Table 5-23: Emission factors used in GHG calculations [35], [13]

Emissions [g/GJ (LHV) fuel]	Natural Gas Turbine	Natural Gas Engine	Diesel Fuel Engine	Crude Oi Combustion
CO_2	56 100	54 393	74 066	73 300
CH_4	3.34	483.66	3.31	3.02
N_2O	1.16	1.16	0.37	1.6

5.2.8. The GHG model in the GaBi Software System

The GHG model was set up in the LCA software system GaBi 7. 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 an hierarchical system of modules representing the complete supply chain. As an example, single unit processes, like a Natural Gas turbine, a gas processing unit, and an electricity mix (each containing the relevant emissions data) are combined to form one module, called “Natural Gas processing”. This module is then combined with other modules to represent the complete supply chain. Each module can be set up and maintained independently. A screenshot of the module “Natural Gas Mix (CNG)” is shown in Figure 5-10 (Sankey diagram) as an example, with each box representing yet 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.

The EU Total Well-to-Tank - inventory results by emission for the CNG and LNG supply are shown in section D.8.

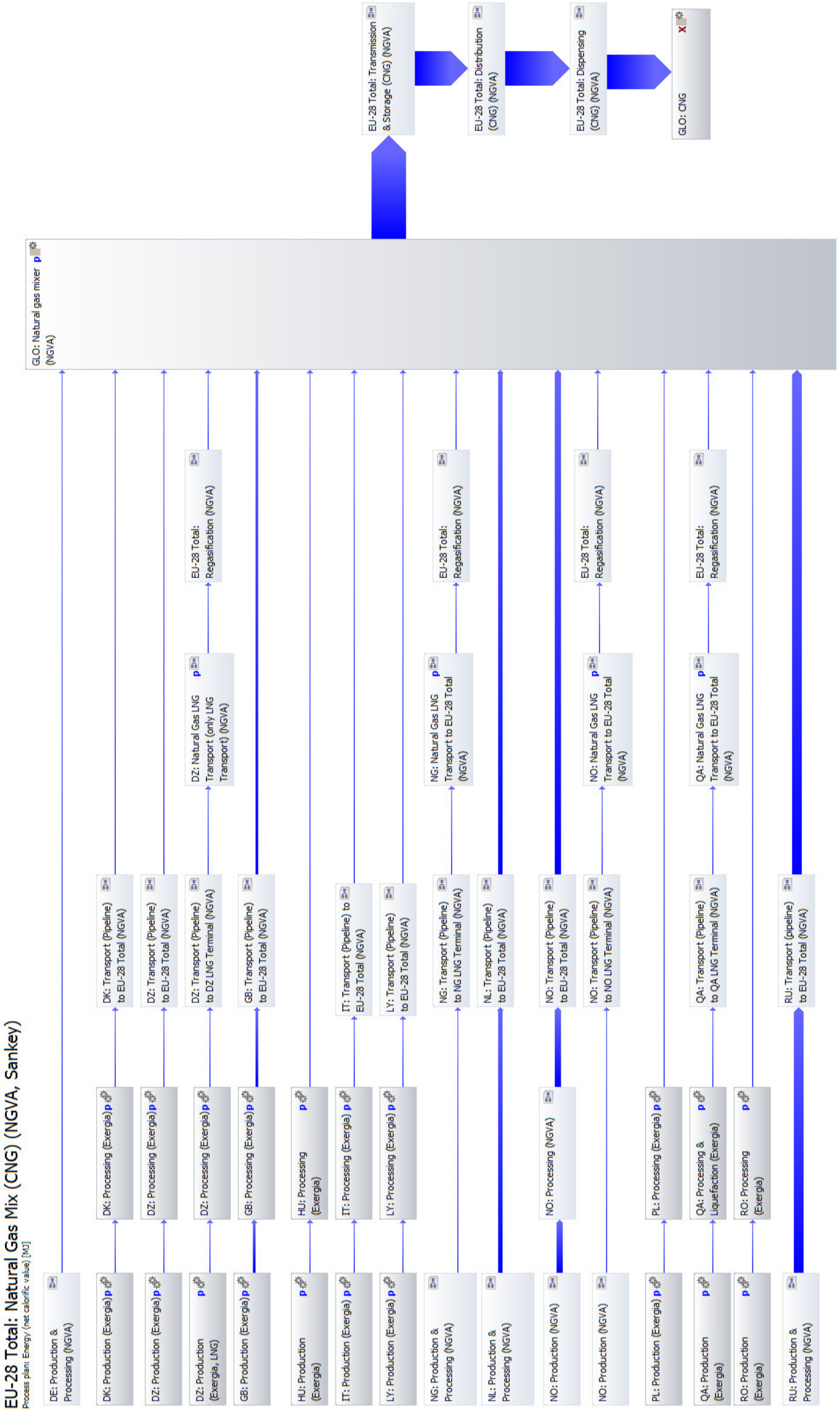

Figure 5-10: **GaBi Screenshot of the Natural Gas Mix (CNG) Supply as modelled (Sankey diagram) [10]**

5.3. Well-to-Tank – GHG Emissions

This section contains the results for the Well-to-Tank GHG emissions. 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. Further, they do not express an effect on any other environmental impacts, i.e. other than global warming.

5.3.1. Well-to-Tank – GHG Emissions for the CNG Product System

Figure 5-11 provides an overview of the GHG results in grams of CO_2-equivalents per MJ of lower heating value (LHV) delivered to the tank. They are displayed as the weighted average values for the EU as well as for the four different EU regions. Additionally, they are broken down by the main process steps in the supply chain.

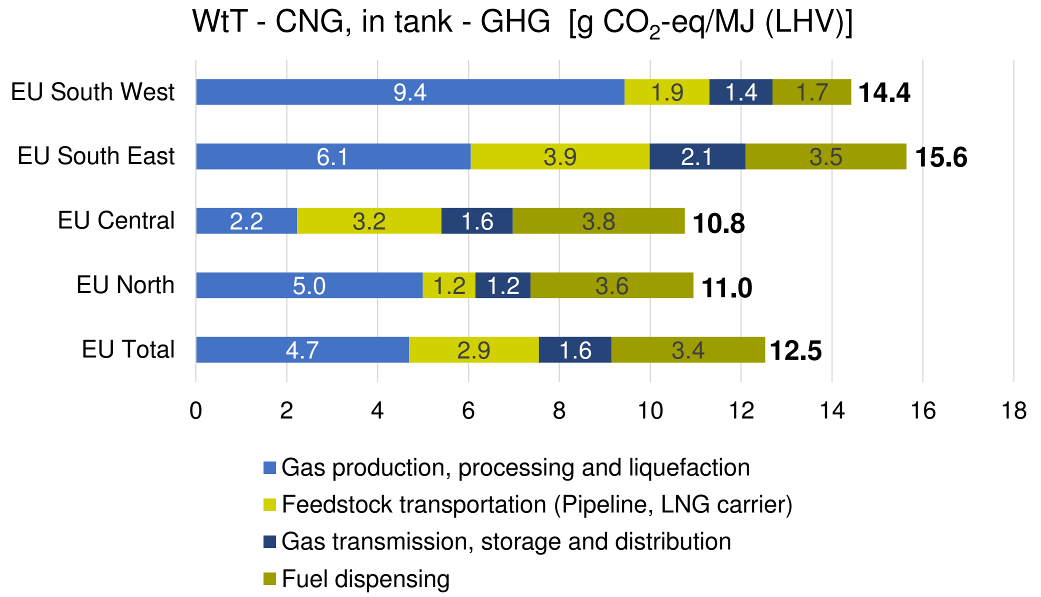

Figure 5-11: Well-to-Tank – GHG Emissions: CNG supply – breakdown by main process steps

Table 5-24 presents GHG emissions of the CNG supply chain in a corresponding table.

Table 5-24: Well-to-Tank – GHG Emissions: CNG supply – breakdown by main process steps

[g CO_2-eq/MJ (LHV)], in tank	EU Total	EU North	EU Central	EU South East	EU South West
Fuel dispensing	3.4	3.6	3.8	3.5	1.7
Gas transmission, storage and distribution	1.6	1.2	1.6	2.1	1.4
Feedstock transportation (Pipeline, LNG carrier)	2.9	1.2	3.2	3.9	1.9
Gas production, processing and liquefaction	4.7	5.0	2.2	6.1	9.4
TOTAL CNG	**12.5**	**11.0**	**10.8**	**15.6**	**14.4**

Key Findings of the CNG Product System:

- The EU Total carbon footprint of CNG, in tank is 12.5 g CO_2-eq/MJ (LHV).
- The EU Total result is dominated by Natural Gas production, processing and liquefaction (37 %), fuel dispensing (28 %), feedstock transportation (23 %) and gas transmission, storage and distribution (13 %).
- EU North is comparable with EU average GHG results in order of magnitude, but the relative contributions are different. It has low GHG values resulting from feedstock transportation due to short pipeline distances from UK and Norway.
- EU Central compared with EU Total: 14 % lower GHG values resulting from Natural Gas production and processing, as the main Natural Gas sources are Russia and the Netherlands, and minor imports of LNG.
- EU South East and EU South West compared with EU Total have overall higher GHG results and higher contributions to the results from gas production and processing including liquefaction. For South West, the main reason is the contribution of Natural Gas from Algeria (imports via pipeline and LNG that is later regasified) and Nigeria. For EU South East the supply of Algerian and Libyan Natural Gas are relevant.
- The comparatively low share of dispensing in EU South West (1.7 g CO_2-eq/MJ) is related to the low GHG intensity of the French electricity grid mix (mainly nuclear power plants), and the share of 53 % in the EU South West electricity grid mix, see Table 5-22

Figure 5-12 and Table 5-25 display the same overall results as Figure 5-11 and Table 5-24 above, but are broken down into the main individual emissions CO_2, CH_4, and N_2O. 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 excluded from the chart.

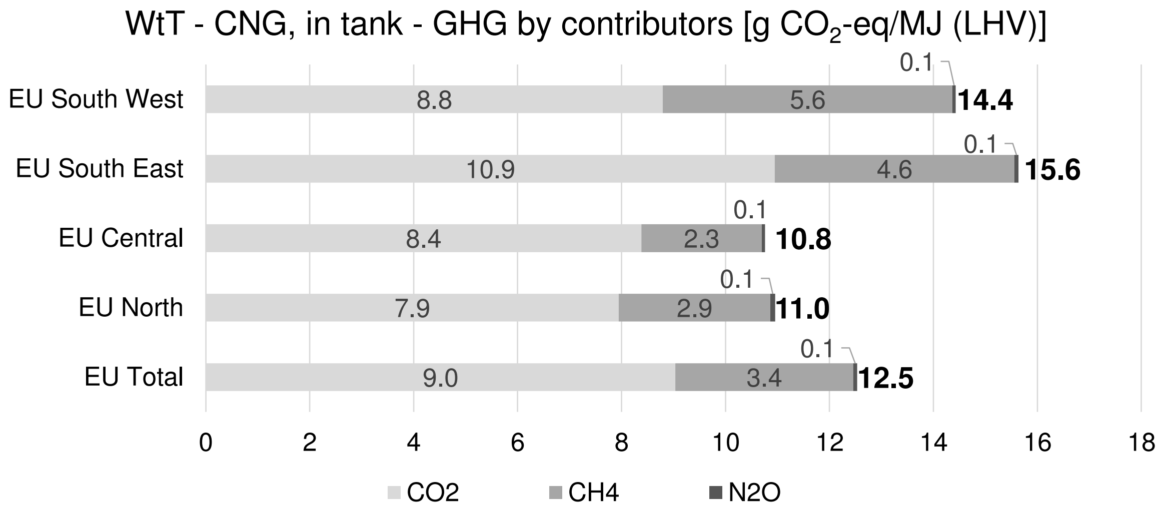

Figure 5-12: Well-to-Tank – GHG Emissions: CNG supply – breakdown by main individual emissions [33]

CO_2 emissions mainly come from fuel combustion, and very small amounts (< 1 %) are vented during processing and purification of Natural Gas (CO_2 removal). CH_4 emissions were from vented, pneumatic, and fugitive emissions as well as other unburnt emissions.

Table 5-25: Well-to-Tank – GHG Emissions: CNG supply – breakdown by main individual emissions [33]

[g CO_2-eq/MJ (LHV)], in tank	EU Total	EU North	EU Central	EU South East	EU South West
CO_2	9.0	7.9	8.4	10.9	8.8
CH_4	3.4	2.9	2.3	4.6	5.6
N_2O	0.1	0.1	0.1	0.1	0.1
TOTAL CNG	**12.5**	**11.0**	**10.8**	**15.6**	**14.4**

Contribution Analysis Methane Emissions (EU Total)

As outlined earlier, the methane emissions include vented, pneumatic, and fugitive emissions as well as other unburnt emissions.

Figure 5-13 illustrates the Well-to-Tank methane emissions in CO_2-eq broken down by the different main process steps for the EU Total CNG supply. These are the Natural Gas production, processing and liquefaction (45 %), as well as gas transmission, storage and distribution due mainly to fugitive emissions (32 %). Dispensing only contributes 8 % of the total Well-to-Tank methane emissions, and feedstock transportation 15 %.

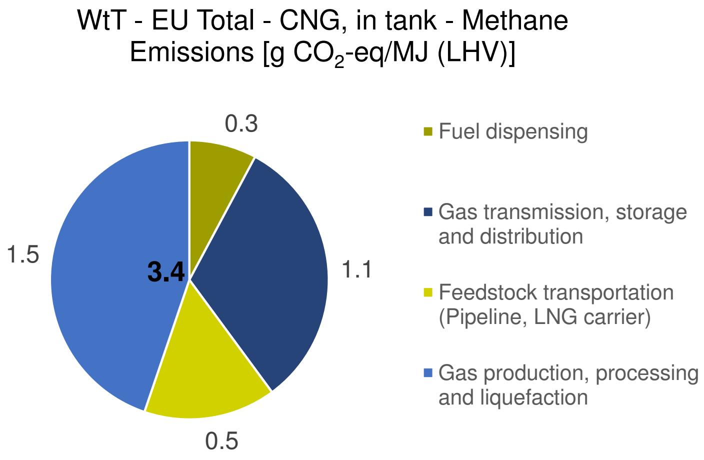

Figure 5-13: Well-to-Tank – Methane Emissions (EU Total): CNG supply – breakdown by main process steps [33]

In Table 5-26 the CH_4 emissions are expressed in weight percentage related to CNG fuelled in a tank.

Table 5-26: Well-to-Tank – Methane Emission (EU Total): CNG supply – weight percentage (wt.%) related to CNG dispensed in the tank [33]

[g CH_4 / g $CNG_{in\ tank}$]	CNG Supply [wt.%]
Fuel dispensing	0.051 wt.%
Gas transmission, storage and distribution	0.209 wt.%
Feedstock transportation (Pipeline, LNG carrier)	0.100 wt.%
Gas production, processing and liquefaction	0.291 wt.%
TOTAL	**0.651 wt.%**

Well-to-Tank methane emissions for the CNG supply are 0.651 wt.%.

5.3.2. Well-to-Tank – GHG Emissions for the LNG Product System

This section describes and explains the GHG results for the LNG product system. Figure 5-14 gives an overview of the results in grams of CO_2-equivalents per MJ of lower heating value (LHV) delivered to the tank for the European average and the related four EU regions, as well as the breakdown of the total results in the main process steps of the value chain.

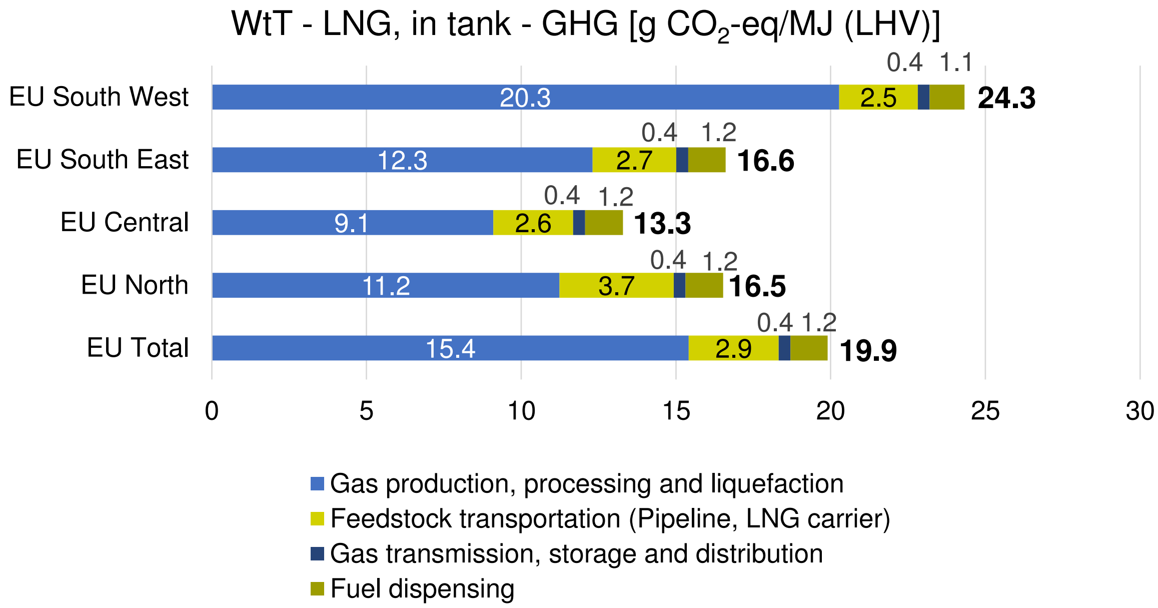

Figure 5-14: Well-to-Tank – GHG Emissions: LNG supply – breakdown by main process steps

Table 5-27 presents GHG emissions of the LNG supply chain in a corresponding table.

Table 5-27: Well-to-Tank – GHG Emissions: LNG supply – breakdown by main process steps

[g CO_2-eq/MJ (LHV)], in tank	EU Total	EU North	EU Central	EU South East	EU South West
Fuel dispensing	1.2	1.2	1.2	1.2	1.1
Gas transmission, storage and distribution	0.4	0.4	0.4	0.4	0.4
Feedstock transportation (Pipeline, LNG carrier)	2.9	3.7	2.6	2.7	2.5
Gas production, processing and liquefaction	15.4	11.2	9.1	12.3	20.3
TOTAL LNG	**19.9**	**16.5**	**13.3**	**16.6**	**24.3**

Key Findings of the LNG Product System:

- The EU Total carbon footprint of LNG, in tank is 19.9 g CO_2-eq/MJ.
- The EU Total GHG result, as well as all other regional results, is dominated by Natural Gas production, processing and liquefaction (77 %), followed by feedstock transportation (15 %), fuel dispensing (6 %) and storage and distribution (2 %).
- EU North result are close to the EU average due to the nearly exclusive LNG supply from Qatar.
- Comparatively low GHG results for EU Central are due to LNG supply from Norway (44 %).

- EU South East GHG results are close to the EU average due to LNG supply mainly from Qatar (94 %).
- Comparatively high GHG results for EU South West due to the share of 45 % of LNG coming from Algeria and its high GHG intensity.
- The Algerian LNG supply route to Europe has a large influence on the EU Total GHG result, even though only 22.1 % of the LNG imports are sourced from Algeria. Hence, the Algerian situation is analysed in more detail in the subsection “Scenario Analysis Algeria” below.

Figure 5-15 and Table 5-28 display the same overall results as Figure 5-14 and Table 5-27 above, but are broken down into the individual emissions CO_2, CH_4, and N_2O. 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 excluded from the chart.

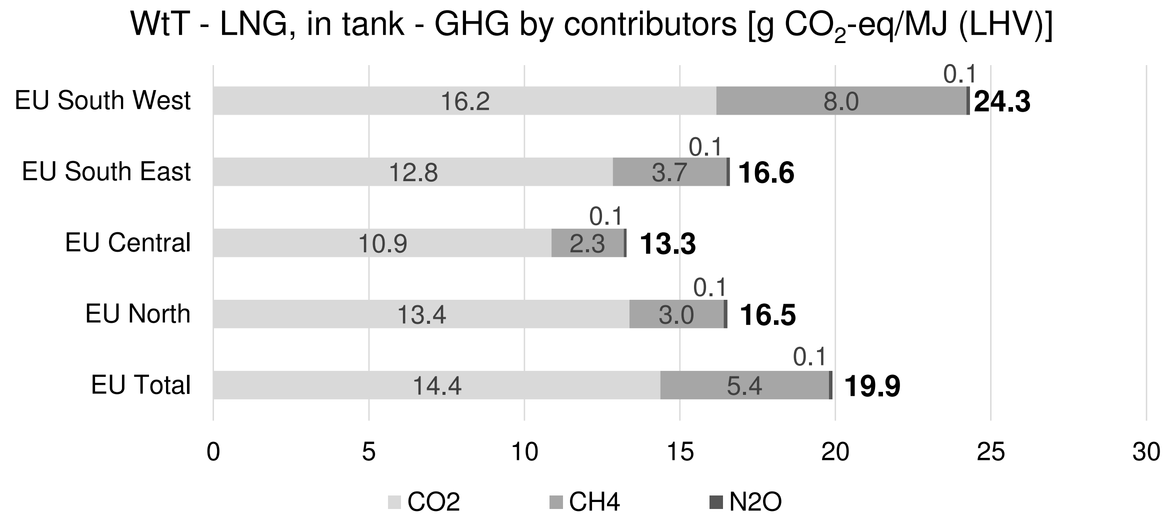

Figure 5-15: Well-to-Tank – GHG Emissions: LNG supply – breakdown by main individual emissions [33]

CO_2 emissions mainly come from fuel combustion and very small amounts (< 1 %) are vented during processing and purification of Natural Gas (CO_2 removal). The main sources for the CH_4 emissions are fugitive and unburnt emissions. Again, the high contribution of the Algerian Natural Gas production and processing and liquefaction is explaining the high results for South West and in consequence for EU Total.

Table 5-28: Well-to-Tank – GHG Emissions: LNG supply – breakdown by main individual emissions [33]

[g CO_2-eq/MJ (LHV)], in tank	EU Total	EU North	EU Central	EU South East	EU South West
CO_2	14.4	13.4	10.9	12.8	16.2
CH_4	5.4	3.0	2.3	3.7	8.0
N_2O	0.1	0.1	0.1	0.1	0.1
TOTAL LNG	**19.9**	**16.5**	**13.3**	**16.6**	**24.3**

Contribution Analysis Methane Emissions (EU Total)

Figure 5-16 illustrates the Well-to-Tank methane emissions broken down by the different main process steps for the EU Total LNG supply. The main contributors for the LNG supply chain are the gas production, processing and liquefaction (78 %) followed by the fuel distribution / dispensing (20 %). Feedstock transportation accounts for 2 %.

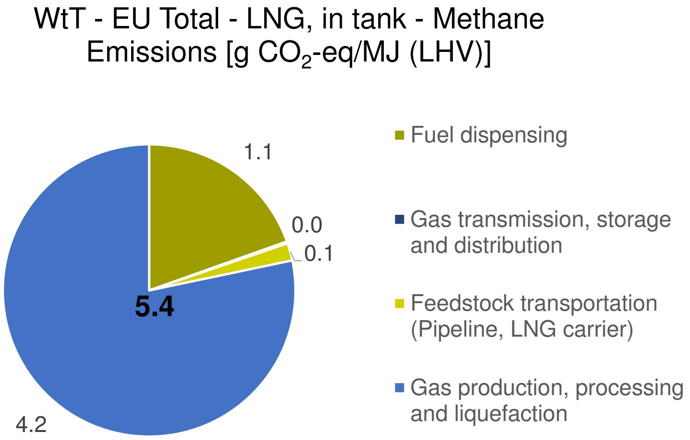

Figure 5-16: Well-to-Tank – Methane Emissions (EU Total): LNG supply – breakdown by main process steps [33]

In Table 5-29 the CH_4 emissions are expressed in weight percentage related to LNG fuelled in a tank.

Table 5-29: Well-to-Tank – Methane Emission (EU Total): LNG supply – weight percentage (wt.%) related to LNG dispensed in the tank [33]

[g CH_4 / g $LNG_{in\ tank}$]	LNG Supply [wt.%]
Fuel dispensing	0.210 wt.%
Gas transmission, storage and distribution	0.002 wt.%
Feedstock transportation (Pipeline, LNG carrier)	0.021 wt.%
Gas production, processing and liquefaction	0.840 wt.%
TOTAL	**1.073 wt.%**

Well-to-Tank methane emissions for the LNG supply are 1.073 wt.%.

Scenario Analysis Algeria

As described in section 5.2 and the corresponding Annex D, some of the Algerian data are based on the Exergia study [7]. Some of the provided data may be outdated. Nevertheless, they are considered to be the most recent data available. Therefore, a scenario analysis was conducted to see the influence on the EU regional LNG mixes, if:

- LNG is only liquefied in new state of the art LNG liquefaction plants (Scenario 1), and
- LNG is produced in LNG liquefaction plants and the GHG intensity of the production and processing is cut by half (Scenario 2), which is still higher than for Qatar and Nigeria.

Table 5-30: Well-to-Tank – GHG Emissions: LNG supply – Algerian Scenario Analysis [33]

[g CO_2-eq/MJ (LHV)], in tank	EU Total	EU North	EU Central	EU South East	EU South West
TOTAL LNG – base case	19.9	16.5	13.3	16.6	24.3
TOTAL LNG – Scenario 1	18.5	16.5	13.3	16.2	21.4
Reduction to base case	*-7%*	*0%*	*0%*	*-2%*	*-12%*
TOTAL LNG – Scenario 2	16.8	16.5	13.3	15.8	18.1
Reduction to base case	*-16%*	*0%*	*0%*	*-5%*	*-26%*

As Table 5-30 shows, GHG emissions of the EU Total would be reduced by ~7 % if only new liquefaction plants were in operation in Algeria. Adding further upstream improvements, would result in GHG emissions of the EU Total LNG supply mix reducing to 16.8 g CO_2-eq/MJ (-16 % less than the base case). The improvements in the region EU South West are even larger (-26 %).

5.4. Well-to-Tank – Comparison with other Studies

The GHG results presented above were compared with the GHG intensity reported in the Exergia study [7] and the JEC-WtW study [8] as well as with the DBI study [9].

Figure 5-17 shows the comparison for CNG and Figure 5-18 for LNG. The reference periods are different for the three studies. The JEC-WtW study is based on data mainly from 2010, while the Exergia study is based mainly on data from 2012 and this study mainly on data from 2015. The DBI study refers to 2012, 2013 and 2014.

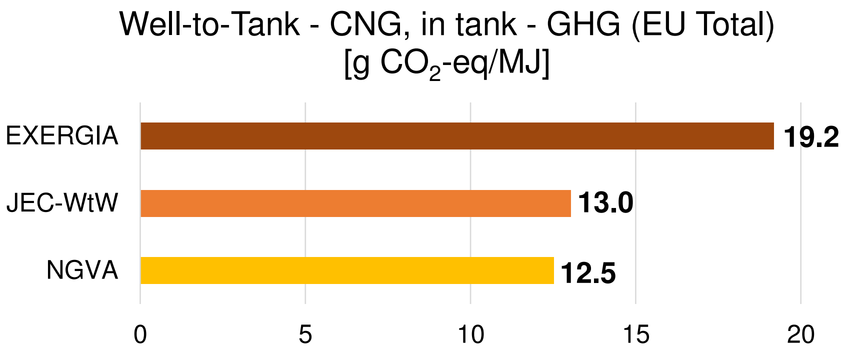

Figure 5-17: Well-to-Tank – GHG Emissions: CNG supply – benchmarking [33], [8], [7]

The GHG emission results of the present study are considerably different from the Exergia study – about 35 % less for the CNG supply chain. Many of these differences are related to the Natural Gas imports from Russia, Norway, and Algeria (LNG). While primary data were collected for Russia and Norway, for Algeria only primary data on shares of new and old LNG plants in operation were gathered. Taking the share of old plant data from Exergia, and modelling the carbon footprint based on average technical parameters of new plants, reduced the carbon intensity remarkably (see section 5.3). The results of the JEC-WtW study are 4 % higher than those of this study.

While the Exergia study gives methane emissions in the order of 1.56 wt.%[27], this study calculates a value of 0.65 wt.%.

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[27] Since the Methane losses as outlined in the Exergia study (table 5-21) [16], do not take distribution and transmission losses into account for the region EU Total, but for the other EU regions, and since for all EU regions the distribution and transmission

The comparison of the GHG emissions calculated in the DBI study is limited to EU Central. The DBI calculated GHG emissions of 7.9 g CO_2-eq/MJ (without dispensing). The corresponding GHG emissions of this study are 7.0 g CO_2-eq/MJ, also without dispensing (see Table 5-24, without dispensing). The main differences can be explained as follows:

- The present study refers to 2015, DBI to 2014[28], i.e. different Natural Gas consumption mixes used.
- Russian values from 2015[29] are used in this study and more up-to-date primary data were collected for Norway.
- Smaller differences are due to different model assumptions and background data information.

The value given in the Exergia study for EU Central is 14.6 g CO_2-eq/MJ (without dispensing) [7].

The comparison of the GHG emission by contributors between the DBI study (CO_2 = 62 %, CH_4 = 38 %, N_2O = 0.1 %, values for 2012) and this study (CO_2 = 70 %, CH_4 = 30 %, N_2O = 0.5 %) show quite similar results (both without dispensing). Note, including dispensing, this study delivers the following result: CO_2 = 78 %, CH_4 = 22 %, N_2O = 0.6 %.

Looking at the LNG supply, the differences between the three studies are smaller. This study calculates a 19 % lower GHG emissions compared to the Exergia study and a 3 % higher result compared with the JEC-WtW study. Considering only new LNG plants and lower upstream emissions for the Algerian supply chain (i.e. expected to reflect the situation in 2020), would lead to a total GHG emissions of 16.8 g CO_2-eq/MJ for this study, which would represent a -32 % decrease from the Exergia study and a -13 % decrease compared to the JEC-WtT study.

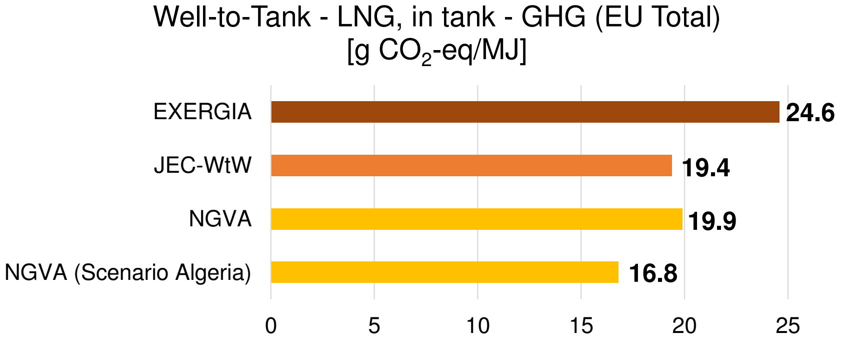

Figure 5-18: Well-to-Tank – GHG Emissions: LNG supply – benchmarking [33], [8], [7]

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losses for the 2030 scenario are the same as for 2012, the EU Total distribution and transmission losses from 2030 are added to the 2012 losses (1.103 % + 0.401 % + 0.057 %, resulting in 1.561 %).

[28] The DBI study refers to 2012, 2013 and 2014.

[29] In principle, no other data source than the DBI study was used. The 2015 Russian values were compiled by DBI, even if they used in their study only 2012, 2013 and 2014 values due to the comparability reasons.

6. Tank-to-X Analysis

6.1. Tank-to-X – Scope of the Study

6.1.1. Product System

The two product systems that were addressed in the Well-to-Tank section, i.e., the supply of CNG and LNG, are extended by combining them with four different applications of Natural Gas use. The applications considered are the use of Natural Gas in passenger vehicles and heavy-duty vehicles (HDV), maritime ships, and power plants. While the Natural Gas is used in the engines of road vehicles and ships to provide propulsion energy, power plants use Natural Gas as an energy carrier for the generation of electricity that is fed into the local grid.

The product systems for the Well-to-Wheel, Well-to-Wake, and Well-to-Grid analysis are described in more detail in the following paragraphs.

6.1.2. Product Function and Functional Unit

The function of the extended product systems, i.e., including the four applications, is the transport of passengers and/or goods for the different road vehicles and for the maritime ships, and the generation of electricity.

The following functional units were chosen (equal to reference flows):

- 1 km driven by a passenger vehicle according to the conditions defined by the New European Driving Cycle (NEDC). The characteristics of the passenger vehicles assessed are chosen to be a 5-seater sedan from the C segment (compact car) with a curb weight in the range of 1 250 – 1 500 kg similar to the vehicles assessed in the JEC-WtW study,
- 1 km driven for the HDV by a 40 t tractor-trailer combination in long haul use with 75 % payload,
- 1 kWh of energy output, at the wake of a maritime ship assuming an engine load of 85 %,
- 1 kWh of electricity output (net), at the power plant grid connection.

Some further information on the primary data used is documented in Annex F.

6.1.3. System Boundary

Compared with the Well-to-Tank assessment, i.e. from the production of Natural Gas up to the tank, the Tank-to-X analysis is less complex, as illustrated in Figure 6-1 and Figure 6-2. Natural Gas is supplied to passenger vehicles and HDVs (CNG) as well as to a Natural Gas power plant. For Natural Gas used in power plants, the supply chain from the Natural Gas production field to the transmission network is considered. Distribution and dispensing (incl. Natural Gas compression) is not taken into consideration. LNG is used within some HDV technologies and in engines of maritime ships.

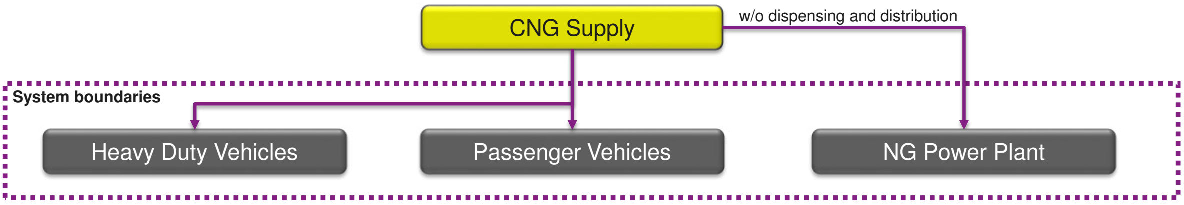

Figure 6-1: Tank-to-X – Product System: Compressed Natural Gas (CNG) [10]

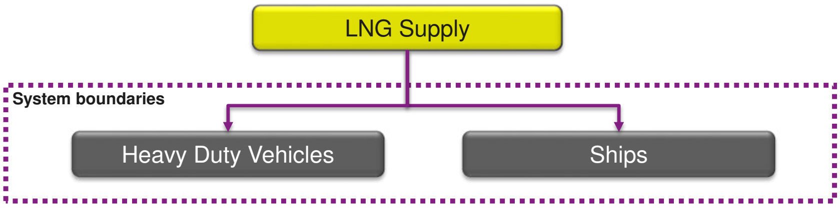

Figure 6-2: Tank-to-X – Product System: Liquefied Natural Gas (LNG) [10]

The study assessed all relevant GHG emissions, e.g., CO_2, CH_4, N_2O, that occur during the regular operation of the applications mentioned. All emissions from the vehicle were considered including gases from the complete or incomplete combustion process, as well as blow-by gases and emissions from the exhaust gas after treatment.

The production and the end-of-life (EoL) of the vehicles was not within the system boundary, since these can be assumed to be very similar between the alternatives that are compared, which is in accordance with the other studies used for benchmarking (JEC-WtW [8], but also Ricardo study [36]). However, the power plants include the construction, commissioning and EoL. Since the emissions caused by the pipeline infrastructure were found to be negligible in the overall WtT emissions, also the emissions related to potential additional infrastructure (to be build) were neglected.

Table 6-1 summarises the elements that are included and excluded in the Tank-to-X part of the analysis.

Table 6-1: System boundary for Tank-to-X Analysis

Included	Excluded
✓ Use of fuels in road vehicles, maritime ships, and power plants ✓ Emissions from (incomplete) combustion ✓ Other emissions that may occur during regular operations, e.g., from exhaust gas after treatment ✓ Construction, commissioning and EoL of power plants ✓ Auxiliary materials for the power plants, e.g., ammonia for the exhaust gas after treatment	× Service and maintenance activities or necessary repairs of the road vehicles and ships × Manufacturing and EoL of the road vehicles × Operating and auxiliary materials, e.g., urea used in the exhaust gas after treatment × Infrastructure for vehicle use, e.g., roads

Time Coverage

The data considered in this study reflect existing technologies that are available on the market today or within the near future (HDV with HPDI engine). Potential future improvements are considered in the outlook (see section 7.7).

The intended reference year for all primary data collected for road vehicles and maritime ships is 2016. The electricity generation uses 2014 as the reference year due to data availability limitations.

Technology Coverage

The technology covered in the study is described in detail in section 6.2 for all CNG and LNG applications under consideration. Nevertheless, the following paragraphs provide an introduction of the relevant technologies.

For all applications, a share of 100 % fossil fuels was considered in order to have an equal starting point for comparisons purposes with other studies. Hence, the currently existing bio-shares of each fuel were not taken into consideration, since all fuel types are able to contain a certain share of biofuel. Nevertheless, section 7.7 addresses the use of bioCNG and bioLNG as well as Synthetic Natural Gas (SNG).

Passenger Vehicles

This study assesses the use of Compressed Natural Gas (CNG) in passenger vehicles that are currently on the market. Since the C-segment is the largest vehicle segment (by vehicle sales) in Europe (see Roland Berger study [37]) and since it is expected to continue as such, this segment is used as the basis of comparison for the passenger vehicles assessed in this study. The use of CNG is compared with the use of diesel and petrol within technically similar (e.g., engine power, vehicle weight) passenger vehicles.

While the combustion of petrol and Natural Gas takes place in a spark-ignited (SI) engine using the Otto cycle, diesel is ignited by compression (CI) according to the diesel cycle. In general, passenger vehicle engines using the diesel cycle have a higher efficiency and lower energy consumption compared with engines using the Otto cycle. Currently, the combustion of Natural Gas takes place within stoichiometric combustion.

Heavy-Duty Vehicles (HDV)

For the heavy-duty vehicles (HDV), two different technologies that both use Natural Gas and that are currently and nearly on the market respectively, were assessed and compared with diesel HDV as a baseline. Unlike dual-fuel engine technologies that are not compliant with current Euro VI regulations, both technologies assessed within this study comply with the current Euro VI regulations.

The first uses gaseous methane in a SI Otto dedicated engine (SI engine) using stoichiometric combustion and is currently representative of most of the market applications. The second technology, named HPDI (High Pressure Direct Injection), coming on the market, uses a dedicated CI engine (Diesel cycle) using only a small fraction of diesel fuel to initiate the combustion process. Because of the methane high pressure injection this technology applies to LNG vehicles where methane can be easily pumped up to high pressures under liquid phase (see Figure 6-1 and Figure 6-2).

Depending on the HDV use patterns, LNG storage may be more convenient than CNG due to its higher energy density and the resulting longer range for a limited storage space on the HDV (see Annex C).

Ships

For maritime ships, two different engine types using Natural Gas were assessed and compared with engines using conventional fuels, i.e., Heavy Fuel Oil (HFO) and Maritime Diesel Oil (MDO). Both ships store LNG on board due to the related higher energy density (compared with gaseous Natural Gas). The first engine type is a four-stroke engine and uses gaseous Natural Gas according to the Otto cycle together with a small quantity of pilot fuel for the ignition (liquid spark plug). The second engine type is a two-stroke low-speed engine that also uses a small amount of pilot fuel besides the Natural Gas, which is injected at high pressure. Its combustion is according to the diesel cycle, its efficiency is higher than that of the earlier Natural Gas engine, and the loss of unburnt methane is reduced, see MAN Diesel & Turbo [38]. For both engines, the use of MDO was assumed as pilot fuel. For information on methane exhaust emissions, please see section 6.2.2. Within the assessment of this study, the effect of implementing an additional exhaust gas after-treatment, e.g. by a scrubber, were neglected.

Natural Gas Power Plant (Combined Cycle Gas Turbine, CCGT)

In thermal power plants, electricity is produced within an electricity generator that is usually driven by a turbine. Whereas coal and lignite are usually combusted for the generation of steam that is driving a steam turbine, Natural Gas is used in gas turbines, which generally reach higher thermodynamic efficiencies than steam turbines. If the heat remaining in the exhaust gas after the gas turbine is also used in a subsequent cycle for producing steam to drive a steam turbine (combined cycle gas turbine, CCGT), the overall power plant efficiency can be increased further.

The electricity production from power plants using Natural Gas, hard coal and lignite was assessed in this study on the basis of available information in the *thinkstep's* LCA GaBi databases [13]

Geographical Coverage

The use of Natural Gas, both for transport and for electricity generation, is considered to take place within the European Union.

6.1.4. Multifunctional Processes and Allocation Rules

There is no multifunctional process in the Tank-to-Wheel and Well-to-Wake part of the assessment for road transport and ships.

In combined heat and power plants (CHPs), electricity and thermal energy is produced. The allocation of the impacts coming from the operation of process, are allocated to the products by using its exergy content (in accordance the IPCC - BREF document on combustion plants [21]).

6.1.5. Cut-off Criteria

No cut-off criteria are defined for this study. As summarised in section 6.1.3, the system boundaries are defined based on relevance to the goal of the study. For the processes within the system boundaries, all available energy and material flow data have been included in the model.

6.2. Tank-to-X – Inventory Analysis

6.2.1. Data Collection Procedure

The data collection for the Tank-to-X analysis followed the procedure for the Well-to-Tank section (see section 5.2.1). Primary data for road transport were collected using customised data collection questionnaires (spreadsheets), which were distributed by email to the respective data providers in the participating companies. 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 reported data for passenger vehicles comprise absolute figures for the fuel consumption of Natural Gas, petrol and diesel vehicles. In addition, CO_2 and CH_4 emissions for Natural Gas Vehicles are reported. For the assessment of HDV in long haul use, the relative advantages of the two Natural Gas powertrain technologies (SI and HPDI) versus diesel HDV as baseline with respect to fuel or energy consumption, CO_2 emissions, and/or the overall GHG emissions were provided. More information on the primary data collected can be found in Annex F.

The following companies provided primary Tank-to-Wheel information directly and gave advice based on their individual expertise:

- Audi,
- Daimler,
- FCA,
- IVECO,
- Scania,
- Volkswagen,
- Volvo,
- Westport.

The primary data for the engines used in maritime ships were from different sources including primary data from a supplier [39] as well as public information [38], [40] (see also Annex F).

As mentioned, the comparisons of the electricity generation alternatives, were based on literature data.

6.2.2. Tank-to-Wheel – Inventory Analysis: Passenger Vehicles

An important aspect for modelling the emissions arising from the use of different fuels in passenger vehicles is the definition of the fuel properties. In accordance with European practices, the energy content of petrol and diesel fuel was defined as outlined in Annex C. The energy content of Natural Gas can vary significantly depending on its source due to different gas compositions and densities. For this reason, the G20 standard was chosen as the reference for the Natural Gas used in the combustion in passenger vehicles (according to the directives [41] and [42]). This reference gas consists almost entirely of methane leading to the respective heating value. As mentioned previously, Natural Gas engines that are used in passenger vehicles today are Otto engines, in which a spark plug ignites the fuel-air mixture.

For assessing the greenhouse gas emissions from passenger vehicles with different powertrain technologies, primary data were collected for different vehicles (see Annex F). This study focussed on currently available vehicles from the C segment, since this vehicle class represents the segment with most vehicles sales and this trend is expected to continue [37]. The collected data comprised the fuel consumption of all three powertrain technologies and for Natural Gas Vehicles the CO_2 and CH_4 emissions according to the official regulations of the New European Driving Cycle (NEDC) [43], [44]. This study modelled the assessed passenger vehicle using CNG by determining the mean value of the collected primary data of the appropriate vehicles.

The current European emission regulations for passenger vehicles (Euro 6) do not set specific emission limits for N_2O.[30] For this reason, primary data collection is difficult due to limited data availability on these emissions. Therefore, the emissions are often assessed by using approximations from the regulated emission groups, e.g., in the JEC-WtW study [8]. This approach was also applied within this study for determining the emission of N_2O from a passenger vehicle using Natural Gas. In order to comply with the chosen time reference, this study uses the average of the vehicle characteristics for the year 2010 and for 2020 and beyond (2020+) for approximating the N_2O emissions from spark-ignited Natural Gas engines. Table 6-2 summarises the emissions determined for a passenger vehicle using Natural Gas as well as the fuel consumption of all powertrain technologies assessed.

Data on the CO_2 emissions from several petrol and diesel vehicles are provided in Annex F. However, the emission estimates for petrol and diesel vehicles are not relevant for the emission inventory, since their emission performance is determined with estimates from the Fuel Quality Directive (FQD), Council Directive (EU) 2015/652 [4] (see section 7). More information on the characteristics of Natural Gas Vehicles in comparison with those using other fuels can also be found in the Well-to-Wheel Analysis of section 7.3. For more details see Annex F.

Table 6-2: Passenger vehicles: Fuel consumption, CO_2, CH_4, and N_2O emissions [33], based on [45], [46], [47] [48]

	CNG	Petrol	Diesel
Fuel consumption (kg/100 km, l/100 km)	3.90	5.62	4.12
Energy consumption (MJ/km)	1.93	1.81	1.48
CO_2 emissions (g CO_2/km)	105.0	(130.5)	(107.3)
CH_4 emissions (g CH_4/km)	0.0421	-	-
N_2O emissions (g N_2O/km)	0.0015	-	-

Methane exhaust emissions

Natural Gas vehicles, both as passenger cars and heavy-duty applications, have no methane emissions[31] from the fuel system as it is completely sealed. Blow by gases are re-circulated at the intake manifold and burned inside the engine.

The only methane emissions come from unburnt exhaust gases that are taken into account in the EU emissions standards. In recent years dedicated catalysts have been developed and implemented to ensure a very high conversion efficiency of methane over the total operating range of the engine.

6.2.3. Tank-to-Wheel – Inventory Analysis: Heavy-Duty Vehicles (HDV)

Primary data was collected for HDV in long haul use for both of the previously mentioned types of Natural Gas engines, i.e., the SI and the HPDI engine. The first uses spark ignition (SI) for the combustion of a gaseous Natural Gas / air mixture. The combustion process of LNG in an HPDI is initiated through the injection of a small quantity of diesel that serves as a pilot. The share of this

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[30] For passenger vehicles with Otto engine, emission limits exist, including for total hydrocarbons (THC), non-methane hydrocarbons (NMHC) and NOx

[31] Uncontrolled and unmonitored methane losses do not occur in regular operations, and are usually only caused by failures or in accidents with consequential leakages. As they are highly exceptional, they are neglected within this study, following standard LCA modelling practice [21].

diesel pilot was assumed to be about 5 % and was validated by the vehicle manufacturers as a good average value (see ICCT [49]). The fuel properties for HDV are listed in Annex C.

The data provided by HDV manufacturers contain the relative CO_2 emission advantage and/or the relative fuel consumption performance of the Natural Gas HDV technologies mentioned in long haul use compared with a baseline diesel HDV. The mean of the reported relative performance improvements was applied to the baseline diesel HDV, for which a consumption 31.5 l/100 km is considered, resulting in the individual fuel consumptions for both Natural Gas HDV (Table 6-3).. As mentioned previously in section 6.1.2, the basis of the assessment was a 40 t tractor-trailer combination in long haul use with 75 % payload. The resulting CO_2 emissions have been calculated by using the CO_2 emission factors provided in Annex C.

For HDV using Natural Gas different emission limits exist per kWh of engine output. For CH_4 the limit is currently set to 0.5 g CH_4/kWh (Euro VI regulation) [50]. Assuming the actual CH_4 emissions to be half of this emission limit serves as an approximation for both types of Natural Gas HDV. This is a conservative estimate, since some of the HDV manufacturers achieve CH_4 emissions that are considerably below the assumed value, which can lead to corresponding reductions of the overall GHG emission (in this regard consider the high characterisation factor of methane as addressed in section 4.2). Experimental studies have confirmed the compliance of Natural Gas HDV with the methane emission limit imposed by Euro VI [51].

For the determination of the CH_4 emissions per km, based on the emission limit per kWh of engine output, the engine efficiencies are required, since they relate the fuel consumption per km driven with the engine's power output. Based on a literature research (see BMVI study [52], f3 [53]), the efficiency of the diesel HDV powertrain was determined. Based on the different fuel consumptions, individual estimates for the engine efficiencies were determined for each powertrain technology and the CH_4 emissions per km were calculated (see Table 6-3 and related footnote for additional information).

Since no specific emission limit exists for N_2O, the same approximation from the JEC-WtW study [8] that was used previously for passenger vehicles, was also applied to HDV, which is a common practice for HDV also in other studies (e.g., BMVI study [52], f3 [53]). According to this approach, the N_2O emissions were estimated to be 5 % of the NOx emission limit for the HPDI HDV, and 3 % for Natural Gas HDV with Otto engine. All mentioned shares were applied to the emission limits of the world-harmonised transient cycle (WHTC), which is the test procedure used for transient analysis besides a steady-state test cycle, both being used within the world-wide harmonised heavy-duty certification procedure adopted by Euro VI regulations.

Table 6-3 summarises the fuel consumption and emissions determined from each of the assessed powertrain technologies used in HDV. The emission estimates for diesel HDV were not relevant for the emission inventory, since their emission performance was determined with estimates from the Fuel Quality Directive (FQD), Council Directive (EU) 2015/652 [4] (see section 7). More information on the characteristics of Natural Gas HDV in comparison with conventional diesel HDV can also be found in the Well-to-Wheel analysis of section 7.3.

Table 6-3: Heavy-Duty Vehicles: fuel consumption, CO_2, CH_4, and N_2O emissions [33], based on [54], [55], [56], [47], [57]

Parameter	Natural Gas (SI)	Natural Gas (HPDI)	Diesel
Fuel consumption (kg/100 km, l/100 km)	26.7	22.5 (Natural Gas) 1.8 (diesel pilot)	31.5
Energy consumption (MJ/km)	13.2	11.7	11.3
CO_2 emissions (g CO_2/km)	728	659	(827)
CH_4 emissions[32] (g CH_4/km)	0.349	0.349	-
N_2O emissions (g N_2O/km)	0.019	0.032	-

Losses from boil-off and dynamic venting

Natural gas is directly injected into an HPDI engine at high pressure. Because it is more efficient to pump a liquid (LNG) to high pressure than to compress a gaseous medium, HPDI HDVs currently employ a high pressure cryogenic pump within the LNG tank. This is similar to the high pressure common rail pump of modern diesel engines.

LNG is also attractive for long haul HDVs (both HPDI and SI) because it offers longer range potential than CNG; given that the density of LNG is greater than CNG so more energy can be stored in the same volume. At ambient pressure, LNG remains a cryogenic liquid at about -162°C, depending on the gas composition. LNG tanks are highly insulated to prevent the LNG from warming-up, boiling and exceeding their certified pressure limit. If the pressure of the tank exceeds its certified limit, a pressure relief valve vents methane from the tank for safety reasons. All modern LNG tanks used in Natural Gas HDVs are designed and certified to hold a full tank of LNG for more than five days without venting (BMVI study [52]).

Despite the effective insulation, some heat transfer to the LNG is inevitable and will eventually cause boil-off, tank pressure rise and atmospheric venting unless the fuel is consumed and the tank re-fuelled on a regular basis. For an SI HDV, this relatively low pressure boil-off gas is consumed by the engine when it is operating but cannot be consumed by an HPDI engine. Instead, it remains in the tank.

The rate of tank pressure rise is also dependent on the initial condition of the fuel when the tank is filled. Because SI systems build pressure in the tank to push the fuel to the engine, it is preferred to fill the tank with saturated "warm" LNG. Conversely, because HPDI systems employ a tank in pump method of building pressure, it is preferred to fill the tank with colder fuel at a lower initial pressure. Tanks filled with "cold", lower pressure fuel will have a longer static hold time than tanks filled with saturated "warm", pressurised fuel.

Many studies indicate high boil-off losses result in methane venting to atmosphere to prevent an excessive pressure rise in the tank. A method of managing tank pressure is to transfer the boil-off gas to a refuelling station when the vehicle is refuelled with LNG. Because an HDV is almost permanently in operation, long periods of non-usage greater than the required five day hold time are highly unlikely. This suggests current boil-off losses are relatively low in state of the art LNG powered heavy-duty vehicles.

HPDI engines may also vent small quantities of gas from the fuel system during certain engine operating conditions such as high transient load changes (often referred to as "dynamic venting") that require the fuel rail pressure to be reduced quickly. Instead of venting the gas into the atmosphere,

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[32] For the determination of CH_4 and N_2O emissions, the engine efficiency of the diesel engine was assumed to be 44.5 % based on literature sources. This results in an engine output of 1.4 kWh/km, which is assumed for all considered engine technologies. Since the diesel engine efficiency is rather high considering the transient operation of the engine, using this estimate serves as a worst-case approximation for the CH_4 and N_2O emissions from the Natural Gas HDV.

both the diesel and the Natural Gas are recaptured in modern engine architectures and returned to their respective tanks, see Westport [58]. The discussion on these types of methane emissions has a long history and is still ongoing. A recently published assessment [59] indicates high methane losses from dynamic venting of first generation HPDI engines. The comments of Westport to the study indicate that this older technology has been superseded by systems which now include the capture of dynamic venting losses [60]. Since HPDI is the proprietary and patented technology of Westport Fuel Systems, this study considers that methane emissions from dynamic atmospheric venting of HPDI engines do not occur.

6.2.4. Tank-to-Wake – Inventory Analysis: Ships

This study assessed and compared ships with four different types of fuel use. The fuel properties of the ship engines assessed are presented in Annex C.

The reported emissions from the different types of ships per kWh output at the wake are summarised in Table 6-4 (see also Annex E). Due to this chosen functional unit, the engine size can be adjusted flexibly depending on the type of ship used. The CO_2 emissions for HFO, MDO and the four-stroke dual-fuel engine were modelled based on primary data for 85 % engine load. The CH_4 emissions were neglected for HFO and MDO since most of the unburnt emissions are non-methane hydrocarbons. Similarly, the N_2O emissions were considered to be insignificant with respect to the overall GHG emissions for all engine types. The CH_4 emissions of the four-stroke dual-fuel engine were modelled according to primary data. For the two-stroke engine with high pressure injection, all properties were chosen as for the four-stroke engine, but a reduced fuel consumption and smaller methane emissions were modelled based on estimates provided by MAN Diesel & Turbo [40]. The Tank-to-Wake emissions of the two-stroke engine with high pressure injection are below that of the four-stroke engine due to the lower CH_4 emissions and a higher efficiency. It must be noted that the assessment of this study neglects the effect of implementing an additional exhaust gas after-treatment, e.g. by a scrubber.

Table 6-4: Ships: Fuel Consumption (LHV), CO_2 and CH_4 emission at 85 % load [33]

	HFO	MDO	Dual-fuel (4-stroke)	Dual-fuel (2-stroke, high pressure)
Fuel consumption (MJ/kWh)	7.5	7.9	7.9	7.7
CO_2 emissions (g CO_2/kWh)	607	577	427	427
CH_4 emissions (g CH_4/kWh)	n/a	n/a	3.1	0.3
N_2O emissions (g N_2O /kWh)	n/a	n/a	n/a	n/a

6.2.5. Tank-to-Grid – Inventory Analysis: Natural Gas Power Plants

The focus of this analysis was the electricity generation in a Natural Gas power plant using the combined cycles of gas and steam turbine (CCGT). This single technology was compared with the average mix of power plant types (direct and combined heat and power plants, CHP) for Natural Gas, hard coal and lignite in Europe.

Table 6-5: Electricity Generation: Energy use (LHV), CO_2, CH_4 and N_2O emissions, taken from GaBi databases [13]

	Lignite (Tech. Mix)	Hard Coal (Tech. Mix)	Natural Gas (Tech.Mix)	Natural Gas (CCGT)
Share CHP/electricity only plants	35.9 / 64.1	41.9 / 58.1	73.2 / 26.8	- / 100.0
Efficiency electricity only	37.3%	39.3%	51.3%	58.0%
Efficiency CHP (total)	45.9%	58.4%	71.1%	-
Share of electricity in CHP plant	0.71	0.55	0.61	-
CO_2 emissions ($kg\ CO_2/TJ_{in}$)	108 491	93 783	56 342	56 342
CH_4 emissions ($g\ CH_4/\ TJ_{in}$)	0.9	0.97	4.37	4.37
N_2O emissions ($g\ N_2O/\ TJ_{in}$)	2.35	2.02	0.6	0.6

The CCGT has the highest efficiency of all power plant technologies assessed. The emissions of both Natural Gas power plants indicated in Table 6-5 are the same, since they are related to one TJ of input energy, i.e., a certain amount of natural gas used. The shares between CHP / direct and the efficiencies were derived from statistics of the International Energy Agency.

6.2.6. Background Data

No background data were used for the Tank-to-X modelling of the road vehicles and ships. The electricity generation dataset was taken from *thinkstep's* GaBi databases [13].

6.3. Tank-to-X – Inventory Comparison with other Studies

This section compares the Tank-to-X inventory that was discussed in the previous section 6.2 and compares the characteristics of Natural Gas Vehicles with the findings from other studies, distinguishing passenger vehicles, heavy-duty vehicles, and ships.

Passenger Vehicles

There are several studies assessing the GHG emissions from passenger vehicles with different powertrain technologies. For Natural Gas Vehicles, one of the most important studies is the JEC-WtW study [8]. Due to different boundary conditions of the current study and the Ricardo study [36] for passenger vehicles, the consortium agreed not to perform a comparison between these two.

The JEC-WtW study [8] considered two different states of technologies for CNG passenger vehicles. In both the Natural Gas is injected into the engine via port injection. Besides these two technologies, there are also two different scenarios reflecting the technological development at two different points in time, 2010 as well as 2020 and beyond (2010, 2020+). The resulting four vehicle specifications consider CNG vehicles with a curb weight in the range of 1 236 kg – 1 450 kg and a power in the range of 77 kW – 99 kW. The mean of the primary data that was considered within this study is at a curb weight of about 1 440 kg and a power of 85 kW.

Table 6-6 summarises the figures that are reported in the JEC-WTW study for different vehicle technologies as well as their average. The bottom line of the table summarises the consumption and emission estimates that were determined for the passenger vehicle using Natural Gas assessed in this study (see Table 6-2).

Both states of technology considered in the JEC-WtW study for 2010 have higher fuel consumption and higher related CO_2 emissions than the current study, whereas in the 2020+ scenario these two parameters are lower than the CNG consumption determined in this study. The fuel consumption and CO_2 as well as CH_4 emissions determined in this study are in line with the average of the four different CNG vehicle scenarios assessed in the JEC-WtW study, which can be used as an approximation of the state of the technology between 2010 and 2020. The CH_4 emissions determined in the present study are below the average of the CNG vehicle technologies assessed in the JEC-WtW study.

More information on the comparison with the JEC-WtW study can be found in the Well-to-Wheel Analysis of section 7.4.

Table 6-6: Tank-to-Wheel - Inventory for CNG passenger vehicles [36], [8], [33]

Study	Vehicle	Fuel cons. (kg/100 km)	Energy cons. (MJ/km)	CO_2 (g/km)	CH_4 (mg/km)	N_2O (mg/km)
JEC-WtW	PISI 2010	5.2	2.3	131	60	1.2
JEC-WtW	DISI 2010	4.7	2.1	119	60	1.2
JEC-WtW	PISI 2020+	3.4	1.5	86	45	1.8
JEC-WtW	DISI 2020+	3.2	1.5	82	45	1.8
JEC-WtW	Average	4.1	1.9	104	53	1.5
NGVA	**NEDC**	**3.9**	**1.9**	**105**	**42**	**1.5**

Heavy-Duty Vehicles (HDV)

The assessment of heavy-duty vehicles with different powertrains is less common than for passenger vehicles. The JEC-WtW study [8] did not address HDV. The Ricardo study [36] assessed the use of Natural Gas in two types of HDV but they are not comparable to the HDV assessed in this study. The first type assessed in the Ricardo study was a rigid truck carrying loads between 3.5 – 16 t and uses a SI engine. The second was an HDV with loads up to 44 t for long haul use, but using a dual-fuel engine, which uses considerably higher shares of diesel fuel than the HPDI engine assessed within this study. Both HDV assessed in the Ricardo study did not comply with the current Euro VI regulations (see the statement of the NGVA [61]), which is why they were not considered within this study. Since there is no sound basis of comparison, the Tank-to-Wheel results of this study are not compared with the results of the Ricardo study.

Ships

The emission assessment of using different fuels in ships is also less common than assessing passenger vehicles. The Ricardo study compared ships using heavy fuel oil, maritime gas oil (or maritime diesel oil) and LNG in different types of ships. For the use of LNG, two different methane slip rates are evaluated, i.e., 1.8 % and 3.5 %. Since the Ricardo study reported annual emissions for all ships in operation, only the emission advantages from one fuel technology with respect to another can be compared with the results of this present study.

For this comparison, HFO is chosen as a baseline.

The primary data used for the 4-stroke engine in this study indicates a methane exhaust emissions of below 2 % which is also illustrated by the similarity to the Tank-to-Wake emission estimate from the Ricardo study (see Table 6-7). The lower methane emission and the higher efficiency of the two-stroke engine with high-pressure direct injection leads to a higher GHG emission reduction potential.

Table 6-7: Tank-to-Wake - GHG emission inventory for ship engines at 85 % load, [36] and own calculations [33]

	GHG reduction (in CO_2-eq) compared with HFO ship
Ricardo LNG (1.8 % methane slip)	- 19 %
Ricardo LNG (3.5 % methane slip)	- 7 %
NGVA – 4 stroke LNG	- 17 %
NGVA – 2 stroke LNG (high pressure injection)	- 28 %

7. Well-to-X Analysis

7.1. Well-to-X – Scope of the Study

7.1.1. Product System

The Well-to-X analysis combines the Well-to-Tank part (section 5) and the Tank-to-X part (section 6) and assesses the overall emissions from Natural Gas supply and consumption in the assessed applications.

7.1.2. Product Functions and Functional Unit

There are no additional product functions or functional units defined for the Well-to-X assessment. Instead, the functional units defined for the application of Natural Gas (see section 6) remain valid for the overall assessment. However, the GHG results are expressed in g CO_2-eq/MJ (LHV) in addition.

7.1.3. System Boundary

The system boundaries of the Well-to-Tank and the Tank-to-X part are illustrated within Figure 7-1. The system boundary for the Well-to-X assessment is the conjunction with the system boundary mentioned previously.

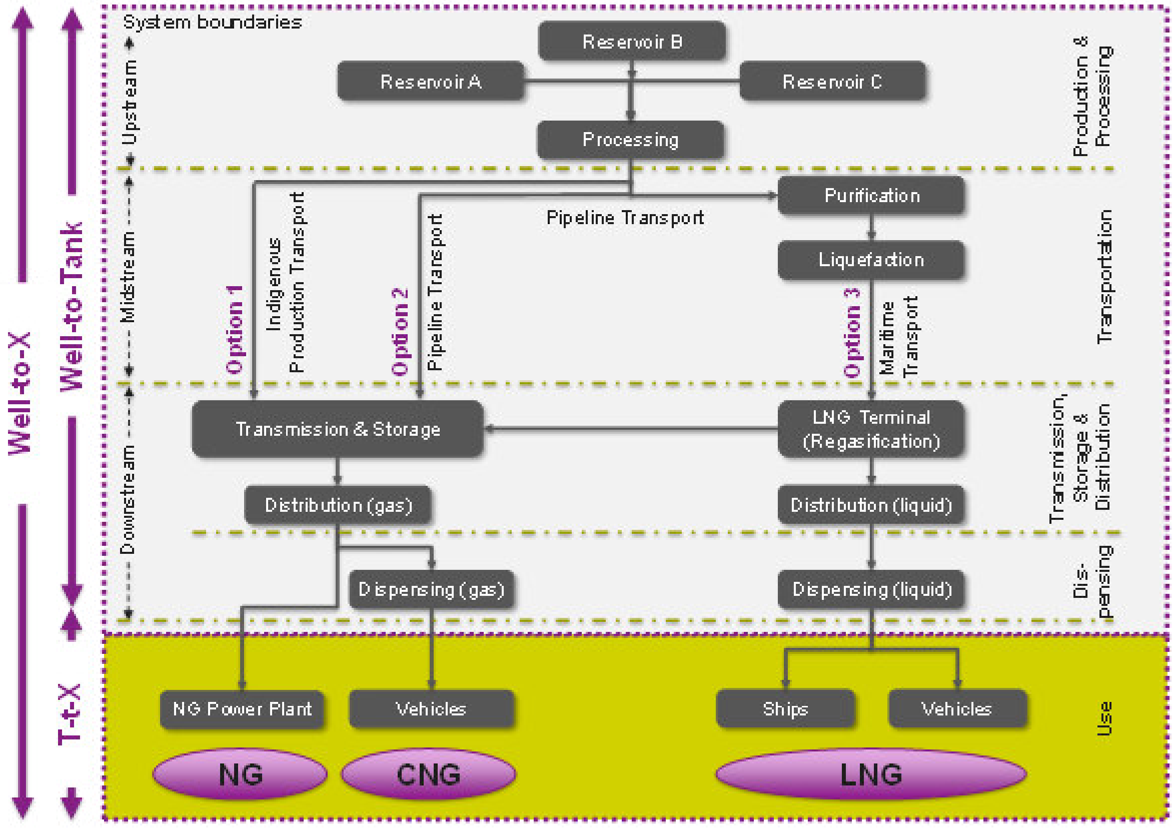

Figure 7-1: System Boundaries - Overview – Well-to- X Analysis [10]

7.2. Well-to-X – Inventory Analysis

All data are documented in the corresponding sections 5.2 and 6.2.

The complete analysis from Well-to-X refers consistently to 1 MJ (LHV) along the supply chain. However, the lower heating value (LHV) of the average Natural Gas supplied to European is assumed to be 47.5 MJ/kg (Well-to-Tank). Within the Tank-to-Wheel part, the G20 standard reference value is used (49.5 MJ/kg) to allow an efficient and standardised data collection.

This difference is not a problem since all numbers refer to MJ. However the difference needs to be kept in mind if converting the values to mass or volume.

7.3. Well-to-X – GHG Emissions (in Comparison with different Fuels)

This section provides the Well-to-X GHG emissions for the product systems assessed, i.e., CNG and LNG used in the different applications of passenger vehicles, heavy-duty vehicles, ships and in power plants. The results are displayed per functional unit and compared with the defined alternatives.

7.3.1. Well-to-Wheel – GHG Emissions: Passenger Vehicles

According to the definition of the functional unit of using Natural Gas for passenger vehicles (see section 6.1.2), the Well-to-Wheel emission results are displayed per km driven in Figure 7-2. The three relevant emissions that are assessed within this study, i.e., CO_2, CH_4 and N_2O, are aggregated to one emission indicator in CO_2-equivalents. This indicator is calculated according to the procedure explained in section 4.2 using the GWP factors of the 4th IPCC assessment report [11].

For putting the Well-to-Wheel GHG emissions determined for the CNG passenger vehicle into the broader context of the fuel and powertrain discussion, they are considered besides emissions provided by external sources for passenger vehicles using petrol and diesel. One of the most important sources in this regard is the JEC-WtW study, which assessed a number of different fuel supply pathways and vehicle technologies [8]. It is important to note that the JEC-WtW study assesses vehicle technologies related to two different points of time, i.e. for the year 2010 and for the year 2020 and beyond (2020+). For petrol vehicles, which use a spark ignited engine, two different technologies are analysed, i.e. port injection (PISI) and direct injection (DISI). The results indicated for the petrol vehicles in Figure 7-2 represent the latter technology.

Another highly relevant source for Well-to-Wheel emission factors of using petrol and diesel as well as other fuels is a document related to the Fuel Quality Directive (FQD), the Council Directive (EU) 2015/652 [4]. In this, life cycle GHG intensity default values are provided as amount of CO_2-eq per energy used. For instance, the value for diesel is 95.1 g CO_2-eq/MJ and for petrol is 93.3 g CO_2-eq/MJ. For using these energy related emission factors, they are multiplied with the fuel and energy consumption for petrol and diesel that is determined from the primary data collected within this project (see Annex F and Table 6-2). These values, which combine the Well-to-Wheel GHG emissions in g CO_2-eq/MJ provided in the mentioned regulative source with the fuel consumption data collected in this project, are indicated by the marking “FQD” in Figure 7-2 and the following illustrations.

It must be noted that the assessment methodology for the values provided in the Fuel Qualitative Directive (FQD) [1] and the related documents is not fully transparent, since the shares of Well-to-Tank and Tank-to-Wheel as well as the contribution of the different GHG emissions is not provided [4]. For this reason, there may be differences in the scope of the FQD assessment and this report, which may reduce the direct comparability of the figures. Similarly, the JEC-WtW study uses a different assessment approach, which is called incremental or marginal approach highlighting future developments, compared with the approach of this study, which is assessing the current overall situation. Despite these differences, the mentioned values from external sources are summarised together with the results for Natural Gas Vehicles in this study, for providing an overall impression about the existing landscape of Well-to-Wheel emission results.

As shown in Figure 7-2, the Well-to-Wheel emissions results from a CNG vehicle in this study are about 23 % below those determined for a passenger vehicle using petrol based on the default value of the FQD, and 27 % below the petrol vehicle assessed in the JEC-WtW study for 2010. Assuming the technology for 2020 and beyond, the future petrol vehicle assessed in the JEC-WtW study causes GHG emissions that are below those of the current Natural Gas Vehicle assessed in this study. Further, the determined GHG emissions of the CNG vehicle are 7 % below those calculated for a diesel vehicle based on the default value from the FQD and 10 % below the GHG emissions from a diesel vehicle assumed in the JEC-WtW study for 2010. For a diesel vehicle equipped with future technology (2020+) the JEC-WtW study determines GHG emissions that are below those of the current Natural Gas Vehicle assessed in this study.

The WtW emissions that are determined by using the GHG intensity default values from the Council Directive (EU) 2015/652 [4] are in between the two estimates of the JEC-WtW study (for 2010 and for 2020+) for both petrol and diesel vehicles.

Since the assessments in the JEC-WtW study considers two different points in time that do not coincide with the assessment conducted in this study since, the emissions determined based on the Council Directive (EU) 2015/652 [4] are within those reported by the JEC-WtW study, and since most importantly the GHG intensity default values provided by the Council Directive (EU) 2015/652 [4] are part of a legally binding framework, the latter source is considered to be more relevant.

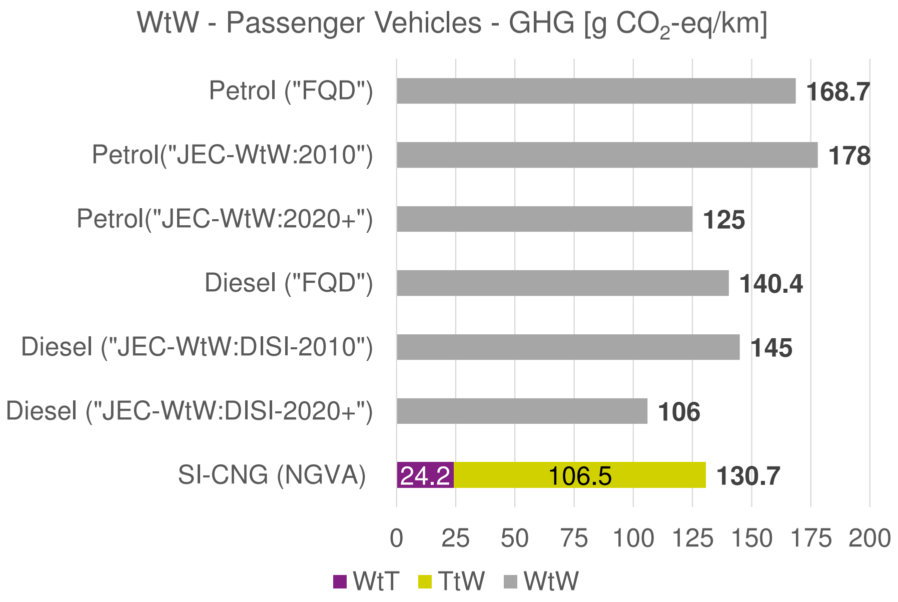

Figure 7-2: Well-to-Wheel – GHG Emissions: Passenger Vehicles using different Fuels [4], [33]

Besides analysing the emissions with respect to the functional unit, Table 7-1 provides the Well-to-Wheel emissions per amount of energy. This neglects the efficiency differences between the assessed engine technologies and the related effects on fuel consumption and emissions. Diesel vehicles show 2 % higher emissions per energy contained in the fuel compared with petrol vehicles according to the default values of the Fuel Quality Directive (FQD), Council Directive (EU) 2015/652 [4]. CNG vehicles have the lowest Well-to-Wheel emissions per energy contained in the fuel that are 27 % below those of petrol and 29 % below those of diesel.

Table 7-1: Well-to-Wheel – GHG Emissions: Passenger Vehicle Comparison for different fuels per energy contained [g CO_2-eq/MJ (LHV)] [33]

Study	WtT	TtW	WtW
Petrol ("FQD")	-	-	93.3
Diesel ("FQD")	-	-	95.1
CNG (NGVA)	12.5	55.2	67.7

Figure 7-3 shows the contribution of the three main GHG emissions contributors, i.e., CO_2, CH_4, N_2O, for the CNG vehicle. The emission of CO_2 has the highest contribution to the aggregated GHG emissions (almost 94 %), while the emission of CH_4 contributes to 6 %. The contribution of N_2O is below 1 %. More than 86 % of the methane emissions occur during the Natural Gas supply chain (WtT), the smaller share being emitted from the CNG vehicle.

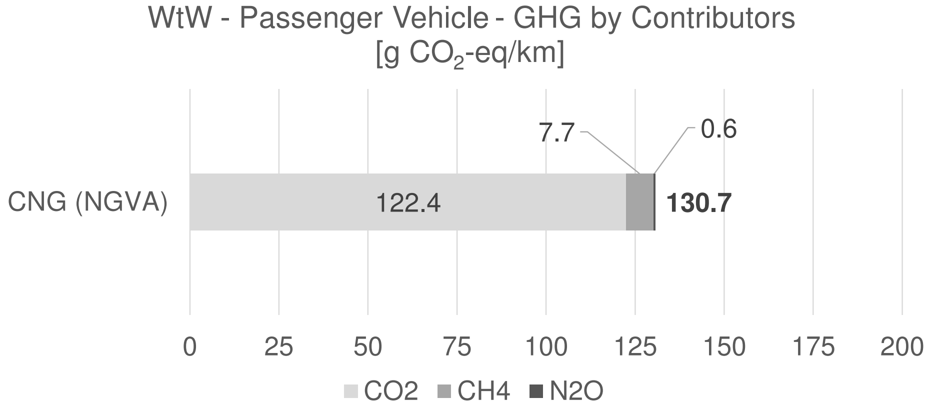

Figure 7-3: Well-to-Wheel – GHG Emissions: CNG Passenger Vehicles – breakdown by main individual emissions [33]

Besides the previous assessment, a comparative screening with electric vehicles was conducted addressing life cycle GHG emissions and emission abatement costs. This assessment, which can be found in Annex G, is not part of this LCA study as it does not comply with the ISO 14040/44 regulations.

7.3.2. Well-to Wheel – GHG Emission: Heavy-Duty Vehicles (HDV)

The Well-to-Wheel GHG emissions of the different HDV in long haul use assessed in this study are shown in Figure 7-4. The CO_2, CH_4 and N_2O emissions are combined within the aggregated GHG emission figures in CO_2-equivalents. The GHG emissions from the diesel vehicle, reflect the chosen baseline consumption of 31.5 l/100 km and the value for the Well-to-Wheel GHG emissions reported in the documents related to the Fuel Quality Directive (FQD), Council Directive (EU) 2015/652 [4]. Since the Well-to-Wheel emissions determined combine the values provided by the FQD in g CO_2-eq/MJ for diesel and the diesel consumption determined within this study, the marking in Figure 7-4 uses the term "FQD" in quotation marks.

The result provided in Figure 7-4 show that all assessed Natural Gas HDV in long haul use lead to a reduction of the Well-to-Wheel GHG compared with the conventional diesel HDV. The HDV with SI engine using CNG as fuel, achieves a reduction of the Well-to-Wheel GHG emissions of almost -16 %.

If the same vehicle uses LNG for its propulsion, the Tank-to-Wheel emissions remain the same, but the emissions from the supply of LNG are higher compared with the supply of CNG (see section 5.3).

This leads to increased GHG emissions, which reduces the emission advantage compared with the diesel HDV to slightly more than -6 %.

An HPDI[33] also requires LNG (see section 6.1.3) but due to the higher thermodynamic efficiency of this engine type, less LNG is consumed along with the small quantity of diesel used as a pilot. This leads to beneficial Well-to-Tank and Tank-to-Wheel emission reductions, and results in an emission advantage of -15 % compared with the diesel HDV in long haul use. While the emissions related to the CNG supply contribute to about 18 % of the Well-to-Wheel emissions, the supply of LNG contributes about 26 % of the Well-to-Wheel emissions of the two LNG HDV.

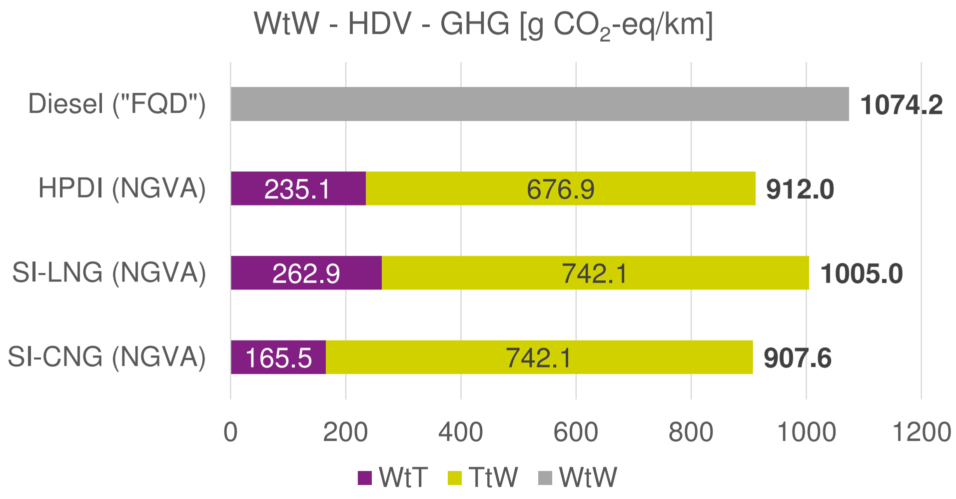

Figure 7-4: Well-to-Wheel – GHG Emissions: Heavy-Duty Vehicle Comparison (long haul use) for different Fuels [33]

Table 7-2 compares the mentioned Well-to-Wheel GHG emissions per energy contained in the fuel and neglects efficiency differences between the engine technologies and the related effects on fuel consumption. Since the HPDI engine uses a mixture of LNG and diesel, the Tank-to-Wheel emissions per energy are about 2.5 % higher compared with the two HDV using pure Natural Gas (compare fuel properties in Annex C). Nevertheless, since the share of diesel is only about 5 %, this effect is rather small. For the same reason, the GHG emissions difference per energy is also negligible for the supply of LNG used in a SI engine and the LNG-diesel mixture for a HPDI engine. The low emissions from the CNG supply lead to the lowest Well-to-Wheel GHG emissions per energy achieved by the HDV using CNG in a SI engine for long haul use.

Table 7-2: Well-to-Wheel – GHG Emissions: Heavy-Duty Vehicle Comparison for different fuels per energy contained [g CO$_2$-eq/MJ (LHV)] [33]

Study	WtT	TtW	WtW
Diesel (“FQD”)	-	-	95.1
HPDI (NGVA + “FQD”)	20.0	57.6	77.6
SI-LNG (NGVA)	19.9	56.2	76.1
SI-CNG (NGVA)	12.5	56.2	68.7

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[33] The HDV using a HPDI engine uses both LNG and diesel as pilot fuel. For assessing the contribution of the upstream emissions from the diesel supply, the direct CO$_2$ emissions from diesel combustion reported in the JEC-WtW study [10] were subtracted from the total well-to-wheel, thereby determining an approximation for the emissions from the diesel supply chain. This is a conservative approximation for the upstream GHG emissions.

The contribution of the main GHG emissions, i.e., CO_2, CH_4, N_2O, is shown in Figure 7-5. It is important to note that the approximated GHG emissions from the supply of diesel used in the HPDI engine are modelled considering CO_2 emissions only.

As for the passenger vehicles, the CO_2 emissions dominate the overall GHG emissions with a contribution of 90 % and above. The CH_4 emissions contribute 6 – 8 % of the overall emissions, of which 84 – 89 % are caused within the Natural Gas supply chain (Well-to-Tank) and the minor share being emitted from the vehicles. Between 80 – 89 % of the N_2O emissions are released from the vehicle, but the contribution of N_2O to the overall emissions is rather small (1 % and below).

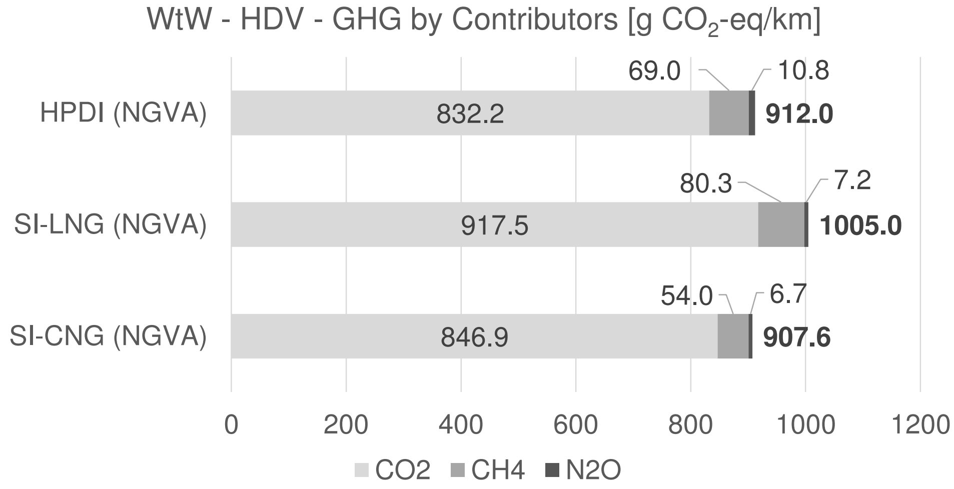

Figure 7-5: Well-to-Wheel – GHG Emissions: SI (CNG), SI (LNG) and HPDI (LNG) Heavy-Duty Vehicle – breakdown by main individual emissions [33]

Heavy-Duty Vehicle Methane Emissions

As mentioned previously, the methane emissions include vented, pneumatic, and fugitive emissions as well as other unburnt emissions. In Table 7-3 the CH_4 emissions are expressed in weight percentage related to CNG fuelled in a tank.

Table 7-3: Well-to-Wheel – GHG Emissions: SI (CNG) and HPDI (LNG) HDV in long haul use – weight percentage (wt.%) related to CNG/LNG dispensed in the tank [33]

	CNG HDV (SI) [wt.%]	LNG HDV (HPDI) [wt.%]
Vehicle	0.131 wt.%	0.155 wt.%
Fuel dispensing	0.051 wt.%	0.210 wt.%
Gas transmission, storage and distribution	0.209 wt.%	0.002 wt.%
Feedstock transportation (Pipeline, LNG carrier)	0.100 wt.%	0.021 wt.%
Gas production, processing and liquefaction	0.291 wt.%	0.840 wt.%
TOTAL	**0.782 wt.%**	**1.228 wt.%**

Well-to-Wheel methane emissions in weight percentage are 0.782 wt.% for CNG and 1.228 wt.% for LNG vehicle. The methane emissions for the European CNG supply as outlined in the Exergia study are 1.103 % [7].

7.3.3. Well-to Wheel – Greenhouse Gas Intensity Default Values from Council Directive (EU) 2015/615

In order to provide an impression of the typical value ranges for the GHG emissions that result from the use of CNG and LNG as fuel, the results of this study are put into perspective. The Council Directive (EU) 2015/615 [4] provides the following average life cycle greenhouse gas intensity default values for CNG and LNG. These are displayed together with the values calculated in the study in Table 7-4.

Table 7-4: Summary of the average Life Cycle GHG intensity default values provided in the Council Directive (EU) 2015/615 [4] and the values calculated in this study

Raw material source and process	Fuel placed on the market	Weighted life cycle GHG intensity, [4] (gCO_2-eq/MJ)	Calculated life cycle GHG intensity, NGVA [gCO_2-eq/MJ]
Crude Oil[34], EU Mix	Petrol	93.3	-
Crude Oil, EU Mix	Diesel	95.1	-
Natural Gas, EU Mix	Compressed Natural Gas in a spark ignition Passenger Vehicle engine	69.3	67.7
Natural Gas, EU Mix	Compressed Natural Gas in a spark ignition HDV engine (long haul use)	69.3	68.7
Natural Gas, EU Mix	Liquefied Natural Gas in a spark ignition HDV engine (long haul use)	74.5	76.1 (73.0)[35]

The results of this study are similar to the default values provided in the Council Directive (EU) 2015/615 [4]. In fact, the GHG intensity of using CNG is about 1 -2 % below and the GHG intensity of LNG is 2 % above the official default value. Considering the assumptions from the scenario analysis for the Algerian LNG supply (see discussions in section 5.3.2) results in a GHG intensity, would result 2 % below the default value from the Council Directive (EU) 2015/615 [4].

As mentioned earlier, it is important to note that any direct comparison of the GHG results has to be approached with caution due to different scope (including level of detail), system boundaries, modelling approaches and, in particular, different reference years.

7.3.4. Well-to-Wake – GHG Emissions: Ships

The results of the Well-to-Wake GHG emissions from ships are related to the functional unit of 1 kWh at the wake as summarised within Figure 7-6. The Well-to-Wake emissions for MDO are chosen to be the same as those reported for diesel in the documents related to the Fuel Quality Directive (FQD), Council Directive (EU) 2015/652 [4]. As for passenger vehicles and HDV, the marking in Figure 7-6

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[34] Crude oil includes: Conventional crude oil, Natural Gas-to-Liquid, Coal-to-Liquid, Natural bitumen, and oil shale.

[35] The value in brackets represents the GHG result of the scenario analysis for the Algerian LNG supply, as outlined in section 5.3.2.

uses the term “FQD” in quotation marks. For Heavy Fuel Oil, the direct CO_2 emissions from the combustion process as well as the emissions from the HFO supply are used as provided in the JEC-WtW study [8]. The Well-to-Tank emissions from the supply of MDO that is used as a pilot in both Natural Gas engines is modelled as described previously for the diesel used in a HPDI.

Both ships using LNG in their engines achieve Well-to-Wake GHG emission reductions of about -10 % and higher compared with the estimates for HFO and MDO that are based on the Council Directive (EU) 2015/652 [4] and the JEC-WtW study [8]. Of the latter two fuels, the use of MDO leads to higher emissions than HFO, due to the low emissions of the HFO supply chain according to the described modelling approach. The use of a dual-fuel four-stroke engine on a maritime ship reduces the Well-to-Wake GHG emissions by approximately -11 % compared with the use of HFO and the use of a Natural Gas two-stroke engine with high-pressure injection leads to reductions of approx. -21 %. For both Natural Gas engines, the supply of LNG contributes about 25 % of the overall Well-to-Wake GHG emissions.

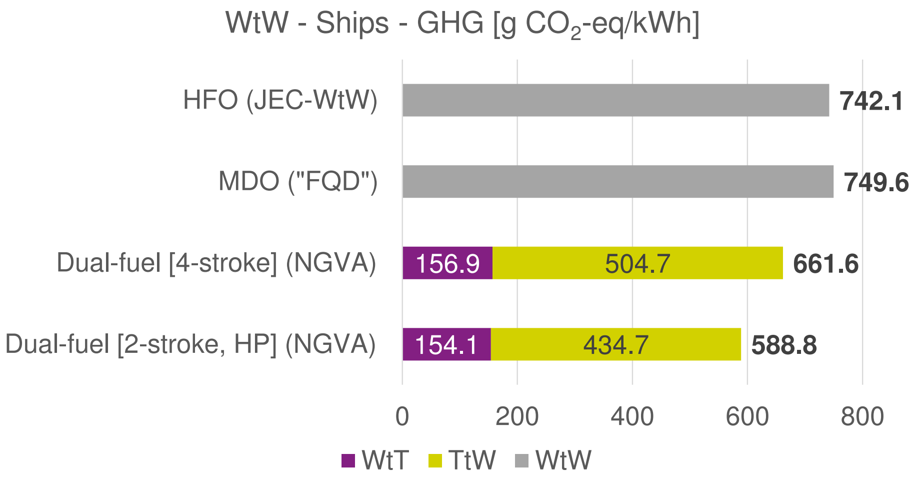

Figure 7-6: Well-to-Wake – GHG Emissions: Ships Comparison for different Fuels [33]

The Well-to-Wake GHG emissions per energy contained in the fuels used by ships is shown in Table 7-5. Since this neglects the engine efficiencies, the emissions per energy are highest for HFO and for MDO. The Well-to-Tank emissions per energy are the same for the two assessed LNG engine technologies since the shares of MDO pilot and LNG are considered to be the same. The Tank-to-Wake emissions, however, are lower for the two-stroke dual-fuel engine with high-pressure injection, due to the lower methane exhaust emissions of this engine technology.

Table 7-5: Well-to-Wake – GHG Emissions: Ships comparison for different fuels per energy contained, at wake [g CO_2-eq/MJ (LHV)] [33]

Study	WtT	TtW	WtW
HFO (JEC-WtW)	-	-	98.5
MDO (“FQD”)	-	-	95.1
Dual-fuel (4-stroke)	19.9	64.1	84.0
Dual-fuel (2-stroke, high pressure)	19.9	56.2	76.2

The contribution of the main individual GHG emissions is illustrated in Figure 7-7. For both types of LNG engines, the emission of CO_2 contributes predominantly to the overall Well-to-Wake GHG emissions with about 92 % and 82 % respectively. The contribution of the CH_4 emissions is considerably lower for the two-stroke engine with high-pressure injection due to a lower methane exhaust emissions of this engine type.

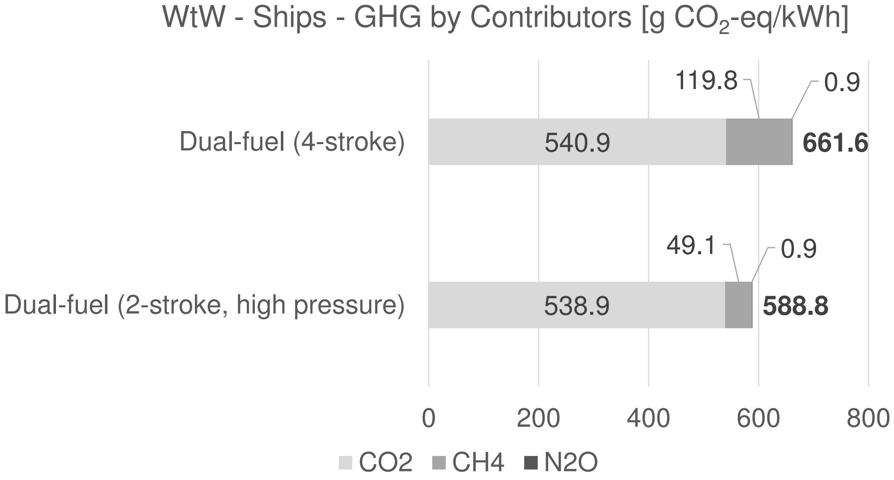

Figure 7-7: Well-to-Wake – GHG Emissions: Dual-fuel (4-stroke) and dual-fuel (2-stroke, high pressure injection) ships – breakdown by main individual emissions [33]

7.3.5. Well-to-Grid – GHG Emissions: Natural Gas Power Plants

Figure 7-8 shows the overall GHG emissions for the electricity generation based on different energy carriers and power plant technologies.

The use of lignite in a thermal power plant leads to the highest Well-to-Grid emissions across the assessed options, with emissions of more than 1 150 g CO_2-eq/kWh, net of electricity produced, at the grid connection. If hard coal is used the emission are lower but still above 1 000 g CO_2-eq/kWh (net). The EU average electricity grid mix is around 434 g CO_2-eq/kWh[36], net of electricity produced.

The use of Natural Gas is more efficient. The averaged Natural Gas power plant (technology mix), which was modelled on the shares of direct electricity and CHP power plants in Europe, emits only 475 g CO_2-eq/kWh (net) of electricity which is 53 % less than a hard coal power plant. The increased efficiency of a combined cycle Natural Gas power plant reduces the emissions to 404 g CO_2-eq/kWh which is 60 % less than the hard coal power plant.

Whereas the GHG emissions from fuel supply contribute only 3 % of the overall GHG emissions for lignite, the supply of hard coal contributes 10 % and the supply of Natural Gas contributes 13 % of the overall GHG emissions for generating 1 kWh of electricity.

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[36] With: Nuclear: 27 %, Lignite, 11 %, Hard Coal 16 %, Natural Gas 18 %, Oil 2 %, Renewables 26 % [15].

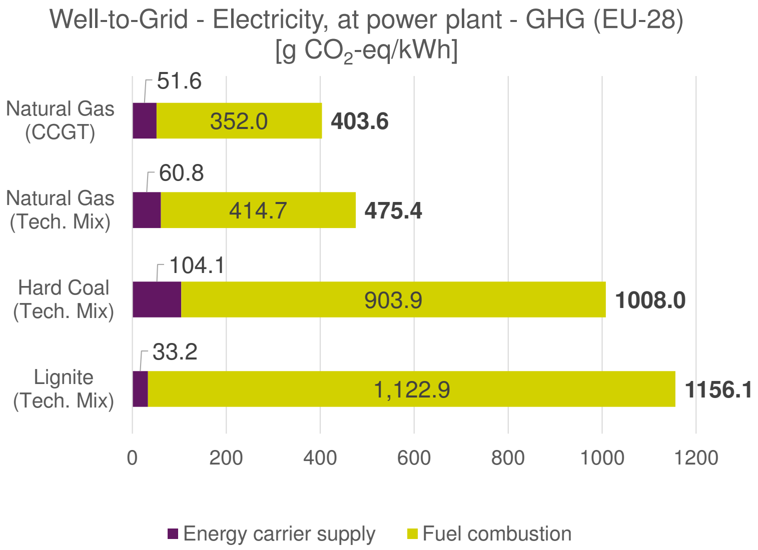

Figure 7-8: Well-to-Electricity – GHG Emissions: Electricity Production Comparison for different Energy Carriers [33]

7.4. Well-to-X – GHG Emissions in Comparison with other Studies

In this section, the Well-to-X (i.e. Well-to-Wheel, Well-to-Wake and Well-to-Grid) GHG results are compared with the estimates reported in other studies. These comparisons are conducted for the different applications of Natural Gas, i.e., passenger vehicles, heavy-duty vehicles, ships and electricity generation in the following.

Passenger Vehicles

As mentioned previously, one of the most important studies assessing the Well-to-Wheel emissions from passenger vehicles is the JEC-WtW study [8]. The Ricardo study [36] also assesses passenger vehicles, but based on the assessments of the NGVA [61] a comparison was not conducted.

The JEC-WtW study [8] provides a range of the Well-to-Wheel emissions of ± 8 g CO_2-eq/km. Figure 7-9 only considers the mean results from the JEC-WtW study. The indicated PISI and DISI scenarios reflect different petrol injection systems (Port Fuel Injection and Direct Injection respectively), see section 6.3.

As with the Tank-to-Wheel emissions (see section 6.3), the state of technology considered in the JEC-WtW study for 2010 leads to Well-to-Wheel emissions above those determined in this study and the ones considered for 2020+ are below them. The average of the assessed technologies and points of time of both parts, i.e., Well-to-Tank and Tank-to-Wheel, coincides quite well with the emissions determined within this study.

The Well-to-Wheel emissions resulting from the fuel consumption of petrol and diesel vehicles determined in this study (Annex F) combined with the Well-to-Wheel GHG default values in the documents related to the Fuel Quality Directive (FQD), Council Directive (EU) 2015/652 [4] result in higher emissions than most of the emission estimates for CNG passenger vehicles. Only the two types of CNG vehicles that were considered in the JEC-WtW study for 2010 are reported to cause higher emissions than the emissions calculated for the diesel vehicles today.

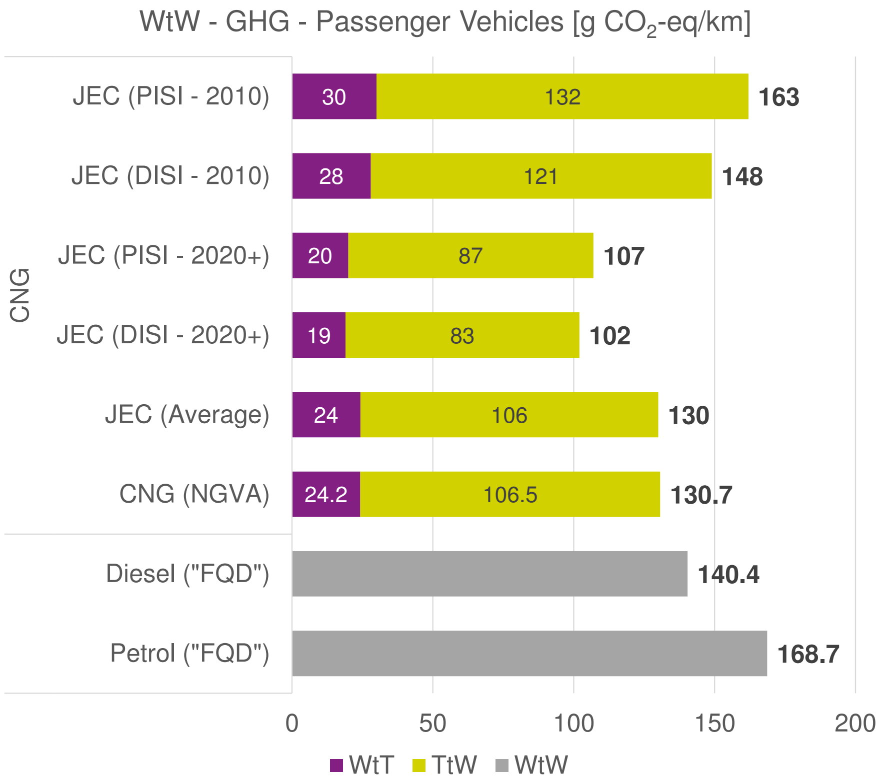

Figure 7-9: **Well-to-Wheel – GHG Emissions: Passenger Vehicles in Comparison with other Studies [33]**

Heavy-Duty Vehicles (HDV)

As mentioned previously for the comparison of the Tank-to-Wheel emissions of heavy-duty vehicles, the Ricardo study assesses different types of heavy-duty vehicles from those in this study (see section 6.3 and the statement of the NGVA [61]). The different vehicle concepts do not allow a sound comparison between the HDV of the Ricardo and the present study.

Ships

Since the Ricardo study [36] assesses the GHG emissions caused by a number of ships in one entire year, it is not possible to compare the emissions results in the Ricardo study directly with those of this study. Instead, the relative emission advantage with respect to the engine using HFO is compared.

The Ricardo study provides three different scenarios for the emissions from the fuel supply, i.e., low central, high scenario. Two different methane exhaust emissions are considered for the LNG engine, 1.8 % and 3.5 %. The resulting Well-to-Wake emission advantages are summarised in Figure 7-10, which range from a disadvantage of +1.5 % to an advantage of -10.4 % of LNG fuelled ships compared with the use of HFO.

Since the methane exhaust emissions of the four-stroke engine determined in this study is less than 2 %, the Well-to-Wake emissions are very similar to the emission advantage reported in the Ricardo study assuming 1.8 % methane exhaust emission (-10.9 % vs. -10.4 % reduction in the central scenario), see Figure 7-10.

The two-stroke LNG engine with high-pressure injection achieves even higher emission reductions (-21 %) compared with the use of HFO.

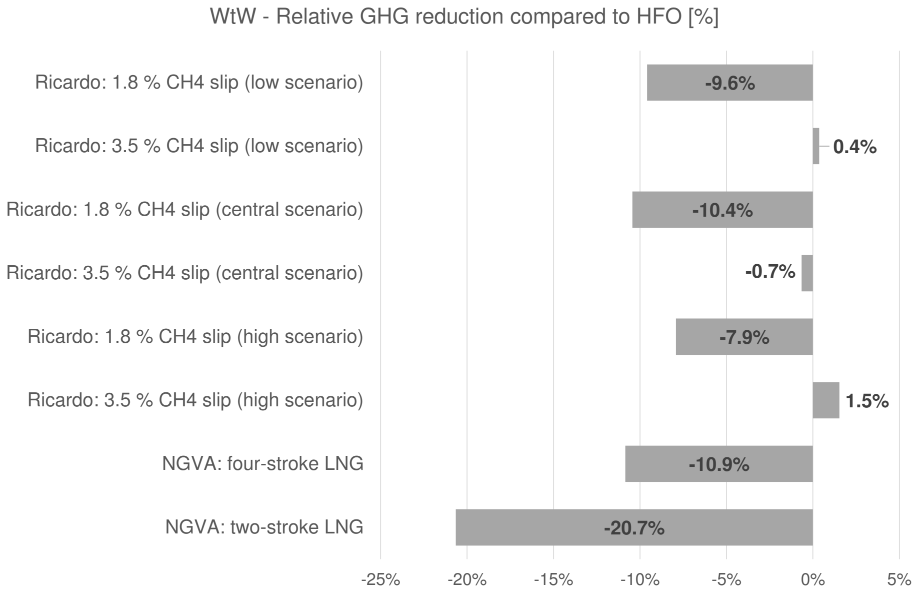

Figure 7-10: Well-to-Wake – GHG emissions: Relative GHG improvement of Ships using LNG compared with the use of HFO [33]

Electricity Generation

The JEC-WtW study [8] analyses electricity generation from Natural Gas and from hard coal values.

For hard coal the value in JEC-WtW is 1 053 g CO_2-eq/kWh (present study 1 008 g CO_2-eq/kWh). For Natural Gas between 477-522 g CO_2-eq/kWh (for a 400 km resp. 7000 km Natural Gas supply distance). The present study calculates a value for the technology mix of 475 g CO_2-eq/kWh, and for CCGT 404 g CO_2-eq/kWh.

7.5. Well-to-Wheel – Sensitivity Analysis

7.5.1. Well-to-Wheel – Sensitivity Analysis on Impact Categories

As described in section 4.2, all GHG results presented so far refer to the IPCC characterisation factors taken from the 4th Assessment Report (AR4) for a 100-year timeframe (GWP100). E.g. in AR5 the methane emission factor is a little bit higher than in AR4 (28 vs. 25).

In order to analyse the sensitivity on the chosen metrics, a sensitivity analysis on the environmental impact category used was performed. The AR4 GHG results are compared with the most current factors from the 5th Assessment Report (AR5) for a 100 year timeframe (GWP100) and the sensitivity analysis also involved calculating the global temperature approach for a 100-year timeframe (GTP100). The results are presented in Figure 7-11 and Figure 7-12.

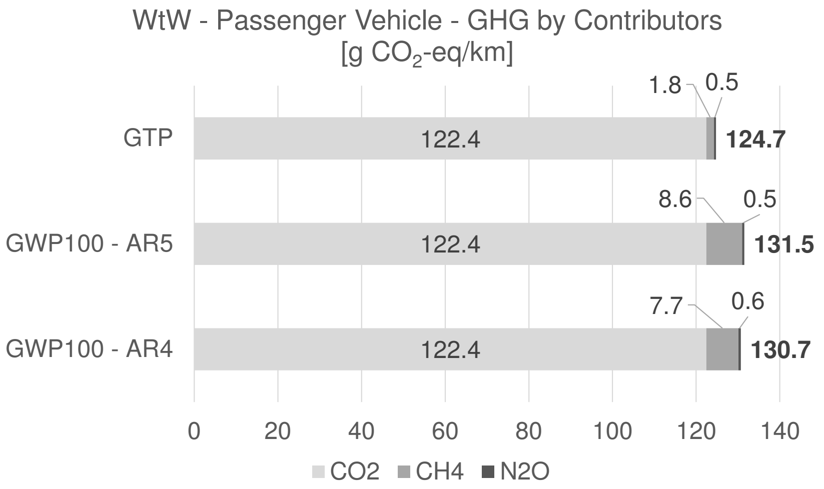

Figure 7-11: Well-to-Wheel – Passenger Vehicles: Sensitivity analysis on impact categories – breakdown by main individual emissions [33]

The Global Warming Potential GWP_{100} (AR5) shows slightly higher results (+1 %) compared with the GWP_{100} (AR4). The GTP shows -5 % lower GHG intensity, compared with the AR4 results.

A similar picture is presented for the heavy-duty vehicles.

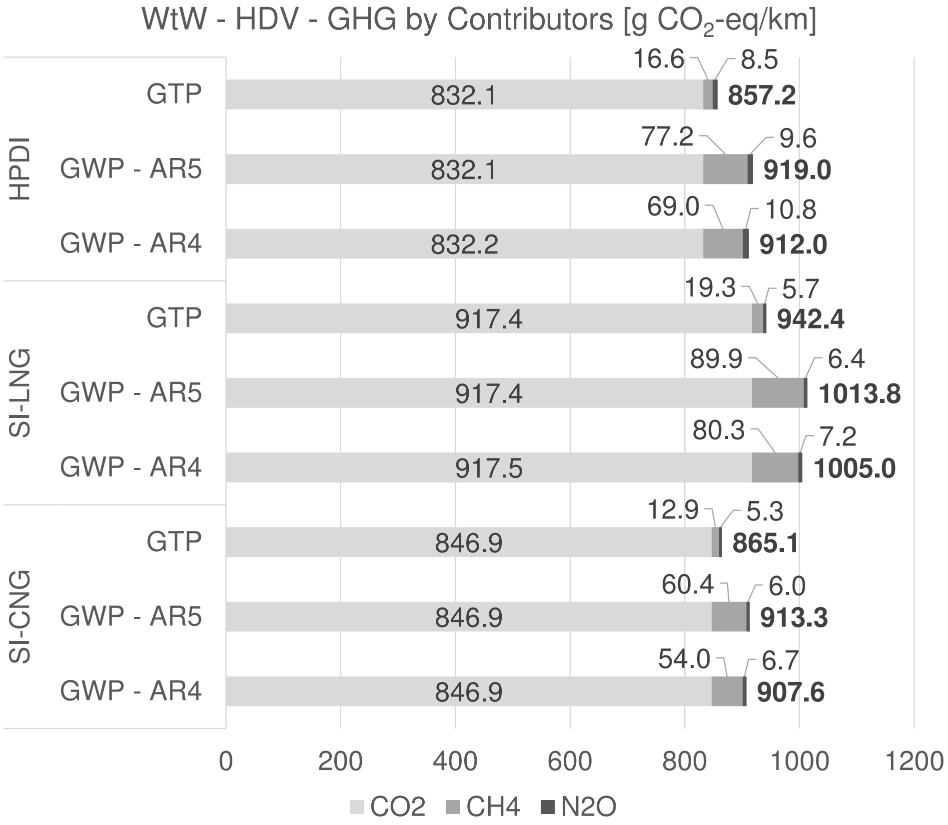

Figure 7-12: Well-to-Wheel – Heavy-Duty Vehicles: Sensitivity analysis on impact categories – breakdown by main individual emissions [33]

7.5.2. Well-to-Wheel – Sensitivity Analysis on Technical Parameters

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

- Passenger vehicles – CNG,
- Heavy-Duty vehicles – SI-CNG,
- Heavy-Duty vehicles – SI-LNG,
- Heavy-Duty vehicles – HPDI-LNG.

Since the sensitivity analysis showed quite similar results for the different vehicles considered, the "heavy-duty vehicle – SI-CNG" and heavy-duty vehicle – HPDI-LNG" results are presented in this section. The results of the other vehicles are in Annex H.

For the CNG fuelled vehicles, the following parameters are checked as outlined in Table 7-6.

Table 7-6: Sensitivity Analysis - Selected parameters for the CNG fuelled vehicles

Life cycle phase / Process step	Parameter
Pipeline transport	Energy consumption
	Methane losses
Transmission	Methane losses
	Natural gas consumption
Distribution	Gas losses
Dispensing	Electricity consumption
	Gas losses
Fuel use	Vehicle fuel consumption

The sensitivity on the overall GHG results for the LNG fuelled vehicles are analysed on the basis for the following parameters.

Table 7-7: Sensitivity Analysis - Selected parameters for the LNG fuelled vehicles

Life cycle phase / Process step	Parameter
Liquefaction	Efficiency
LNG transport	Utilisation rate
Dispensing	Electricity consumption
	Gas losses
Fuel use	Vehicle fuel consumption

Assessing the sensitivity of the methane emissions for production and processing is only possible in a limited way due to the fact that for literature values (expressed in CO_2-eq.), a sensitivity analysis can't be performed. However, varying the gas losses and energy consumption values for the countries not based on literature by ±50 %, show a deviations smaller than 1 % to the overall GHG results. However, it is important to bear in mind that the possible variance of especially gas losses could be much higher than 50 %.

The following two graphs display the overall effect of the respective GHG result for a parameter variation of ± 50 %, first for HDV with SI-CNG engines, second for HDV with HPDI-LNG engines.

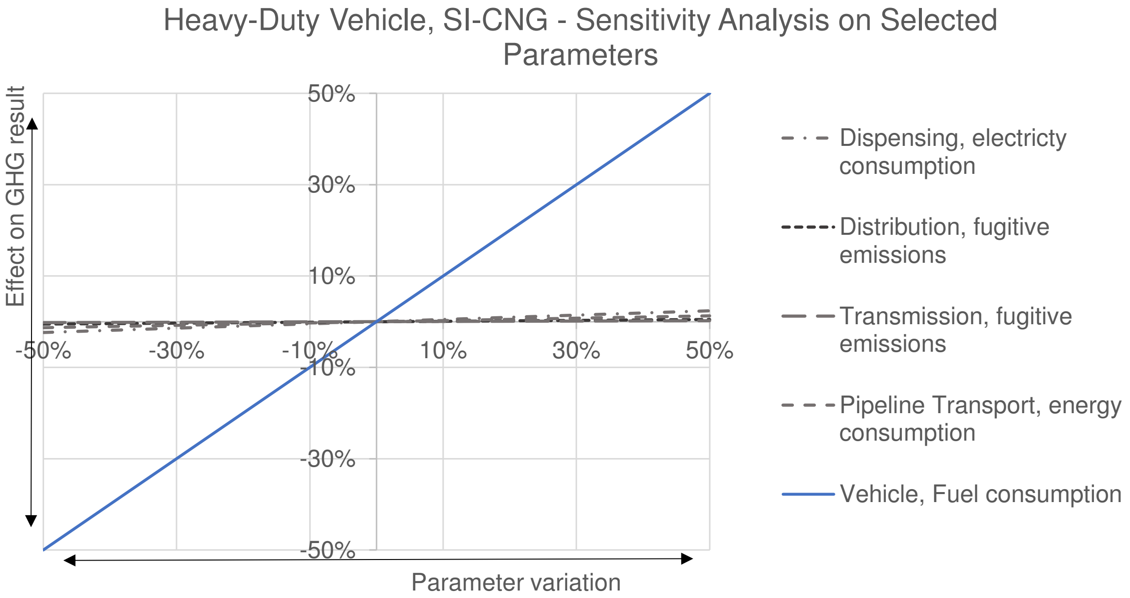

Figure 7-13: Sensitivity Analysis on various parameters from the Well-to-Wheel GHG model of Heavy-Duty Vehicle SI-CNG in long haul use [33]

Findings: Heavy-Duty Vehicle SI-CNG

- **Fuel use – Vehicle fuel consumption**
    - Effect: very high impact on Well-to-Wheel GHG result → 50 % per 50 % parameter variation). Both, GHG emissions of use phase and upstream GHG emissions are directly linked to fuel consumption (linear relation).
- **Dispensing – Electricity consumption**
    - Effect: low impact on Well-to-Wheel GHG result. Below 5 % per 50 % parameter variation → 2.38 %
- **Dispensing – Gas losses**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.08 % (not displayed in figure above)
- **Distribution – Gas losses**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.50 %
- **Transmission – Methane losses**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.21 %
- **Transmission – Natural Gas consumption**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.20 % (not displayed in figure above)
- **Pipeline transport – Energy consumption**
    - Effect: low impact on Well-to-Wheel GHG result. Below 5 % per 50 % parameter variation → 1.30 %
- **Pipeline transport – Methane losses**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.34 % (not displayed in figure above)

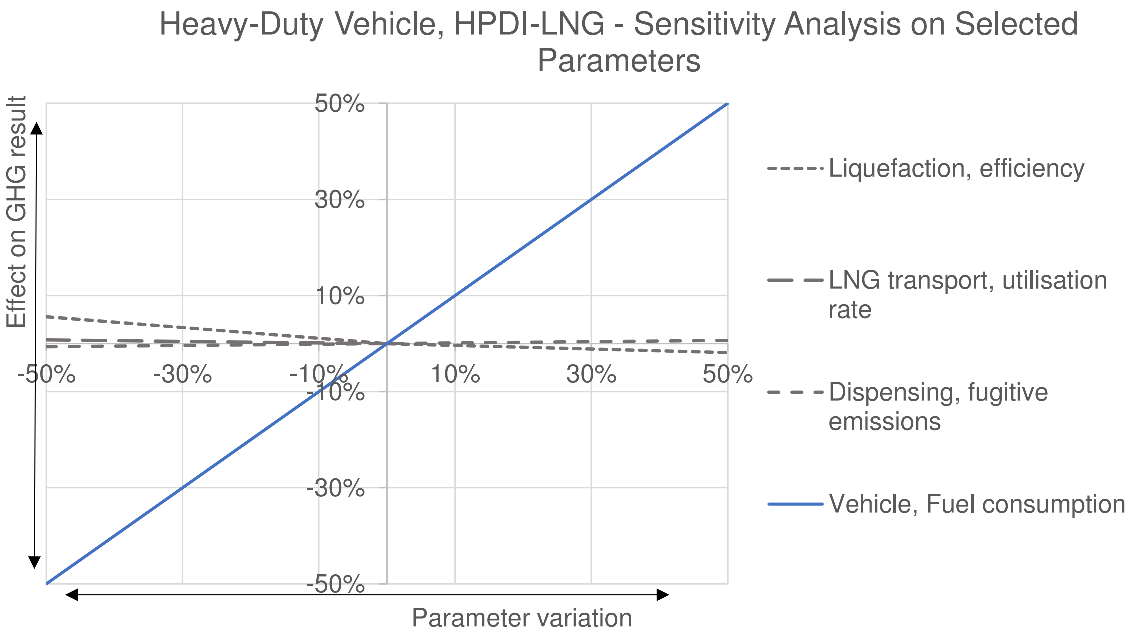

Figure 7-14: Sensitivity Analysis on various parameters from the Well-to-Wheel GHG model of Heavy-Duty Vehicle HPDI-LNG in long haul use [33]

Findings: Heavy-Duty Vehicle HPDI-LNG

- **Fuel Use – Vehicle fuel consumption**
    - Effect: very high impact on Well-to-Wheel GHG result → 50 % per 50 % parameter variation). Both, GHG emissions of use phase and upstream GHG emissions are directly linked to fuel consumption.
- **Dispensing – Electricity consumption**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.10 % (not displayed in figure above)
- **Dispensing – Gas losses (from LNG terminal to tank)**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.67 %.
- **LNG transport – Utilisation rate**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.76 %. Since the utilisation rate is defined as 100 %, a sensitivity check only for values below 100 % were performed.
- **Liquefaction – Efficiency**
    - Non-linear relation between parameter variation and GHG results – higher effect for decreasing efficiencies, lower effect for increasing efficiencies.
    - Effect for decreasing efficiencies: medium impact on Well-to-Wheel GHG result. Below +10 % per -50 % parameter variation → +5.57 %
    - Effect for increasing efficiencies: low impact on Well-to-Wheel GHG result. Below -5 % per +50 % parameter variation → -1.86 %

As the vehicle fuel consumption is the dominating parameter of the Well-to-Wheel GHG results, for CNG and LNG vehicles, a separate sensitivity analysis is displayed for the CNG and LNG upstream part (Well-to-Tank).

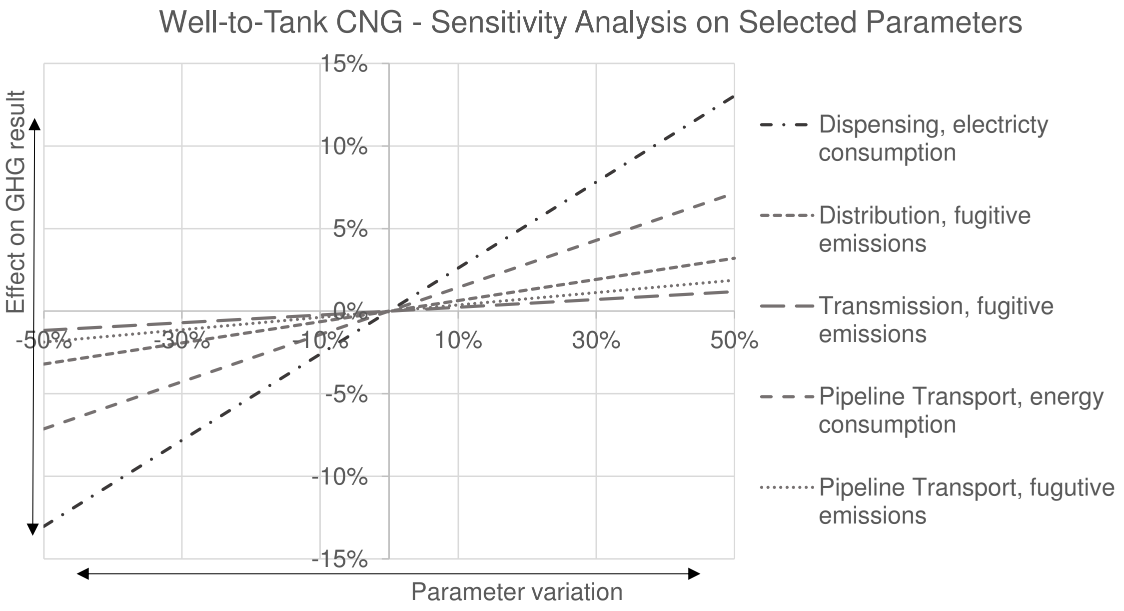

Figure 7-15: Sensitivity Analysis on various parameters from the Well-to-Tank GHG model of CNG [33]

The effects on the GHG emissions are relative to each other, as is the case for the analysis based on the Well-to-Wheel model. However, as the sensitivity analysis based on MJ produced CNG ignores the vehicle itself, it is "zooming into" the CNG related parameters to better visualise the effects on the GHG emissions.

Findings: Well-to-Tank – CNG Supply

- **Dispensing – Electricity consumption**
    - Effect: high impact on Well-to-Tank GHG result. Above 10 % per 50 % parameter variation → 13.03 %
- **Dispensing – Gas losses**
    - Effect: very low impact on Well-to-Tank GHG result. Below 1 % per 50 % parameter variation → 0.45 % (not displayed in figure above)
- **Distribution – Gas losses**
    - Effect: low impact on Well-to-Tank GHG result. Below 5 % per 50 % parameter variation → 3.20 %
- **Transmission – Methane losses**
    - Effect: low impact on Well-to-Tank GHG result. Below 5 % per 50 % parameter variation → 1.17 %
- **Transmission – Natural Gas consumption**
    - Effect: low impact on Well-to-Tank GHG result. Below 5 % per 50 % parameter variation → 1.09 % (not displayed in figure above)
- **Pipeline transport – Energy consumption**
    - Effect: medium impact on Well-to-Tank GHG result. Below 10 % per 50 % parameter variation → 7.13 %
- **Pipeline transport – Methane losses**
    - Effect: low impact on Well-to-Wheel GHG result. Below 5 % per 50 % parameter variation → 1.87 % (not displayed in figure above)

The sensitivity check for the LNG supply chain (Well-to-Tank) was performed similarly to the CNG supply.

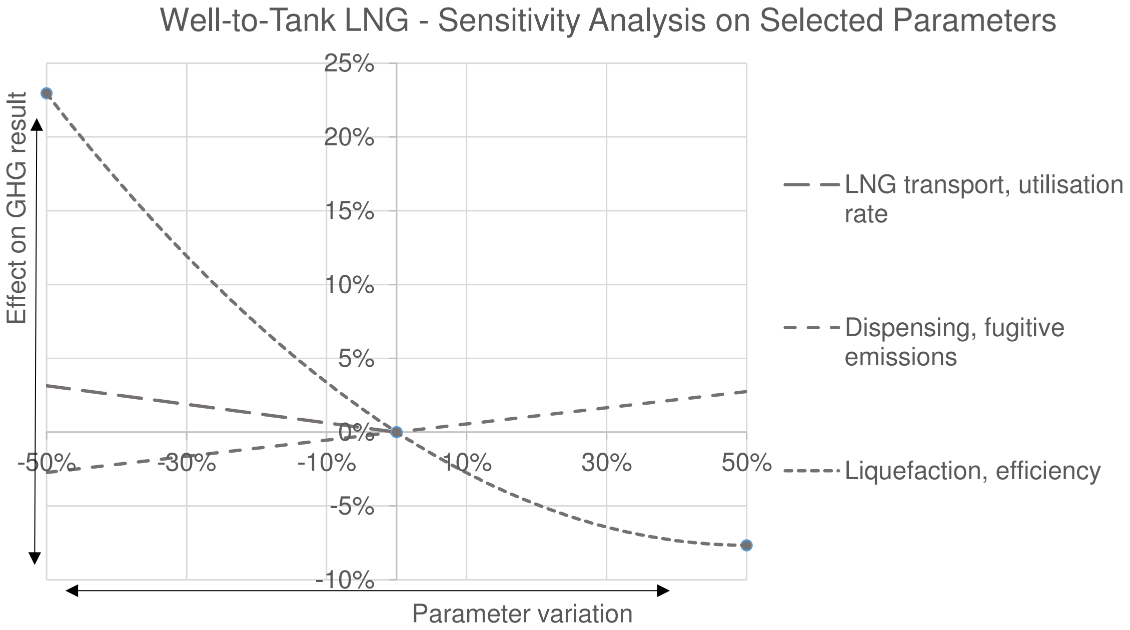

Figure 7-16: Sensitivity Analysis on various parameters from the Well-to-Tank GHG model of LNG [33]

Findings: Well-to-Tank - LNG Supply

- **Dispensing – Electricity consumption**
  - Effect: very low impact on Well-to-Tank GHG result. Below 1 % per 50 % parameter variation → 0.39 % (not displayed in figure above)
- **Dispensing – Gas losses (from LNG terminal to tank)**
  - Effect: low impact on Well-to-Tank GHG result. Below 5 % per 50 % parameter variation → 2.47 %
- **LNG transport – Utilisation rate**
  - Effect: low impact on Well-to-Tank GHG result. Below 5 % per 50 % parameter variation → 3.14 %. Since the utilisation rate is defined as 100 %, a sensitivity check only for values below 100 % were performed.
- **Liquefaction – Efficiency**
  - Non-linear relation between parameter variation and GHG results – higher effect for decreasing efficiencies, lower effect for increasing efficiencies.
  - Effect for decreasing efficiencies: very high impact on Well-to-Tank GHG result. Above +15 % per -50 % parameter variation → +22.96 %
  - Effect for increasing efficiencies: medium impact on Well-to-Tank GHG result. Below -10 % per +50 % parameter variation → -7.67 %

In summary, the fuel consumption is the dominant parameter for both vehicle types: CNG and LNG. While for the CNG supply chain, the electricity consumption of dispensing, and the energy use for the pipeline transport are decisive, the liquefaction efficiency is most relevant in the LNG supply chain.

7.6. Well-to-Wheel – 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.

Uncertainty analysis is performed using Monte-Carlo simulation, which draws random numbers 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. The results for a SI-CNG heavy-duty vehicle are shown here as an exemplary picture of the Monte-Carlo simulations performed.

In the following table, uncertainty intervals are defined for relevant parameters, which are independent from each other, called variance 1 and variance 2. In total, 10 000 simulations are run and every simulation is generating a GHG result for the product system based on a random combination of parameter values.

Table 7-8: Uncertainty Analysis - Monte-Carlo simulation for SI-CNG Heavy-Duty Vehicle - defined variances [33]

Process step	Parameter	Base case	Variance 1	Variance 2
Fuel use	Vehicle fuel consumption	26.7 kg/100km	-15%	+5%
Dispensing	Electricity consumption	0.32 kWh/kg	-100%	+50%
Dispensing	Gas losses	0.022 wt.%	-100%	+350%
Distribution	Gas losses	0.15 wt.%	-100%	+200%
Pipeline transport	Natural Gas consumption			
	Russia, Ukrainian Corridor	2.39E-5 J/(J*km)	-30%	+30%
	Russia, Belarussian Corridor	2.39E-5 J/(J*km)	-30%	+30%
	Russia, Northern Corridor	1.58E-5 J/(J*km)	-30%	+30%
	Norway	4.42E-6 J/(J*km)	-30%	+30%
Pipeline transport	Electrical energy consumption			
	Norway	3.26E-6 J/(J*km)	-30%	+30%

The intervals per parameter are defined with the following premises:

- Vehicle fuel consumption is the dominant parameter for the GHG system and thus most relevant for the uncertainty analysis. The variances represent an estimated best/worst case range taking technical improvements in the near future into account, see -15 % to +5 %.
- The parameters for dispensing, distribution and pipeline transport represent best/worst case ranges from literature (e.g., distribution from Marcogaz [24]) and primary data collection. Pipeline transports for Russia and Norway have been used since together they are supplying >50 % of the Natural Gas to the EU.

The results for the Monte-Carlo simulation are shown in the following Table 7-9. The simulations showed that the results based on the GHG model with the parameter settings for heavy-duty vehicle SI-CNG are very stable and robust. The standard deviation of 12.4 % is very low. This low standard deviation is visible in Figure 7-17 as the results create a high Gaussian bell curve. The higher the bell curve, the more stable the results. The median is 8.1 % lower than the base case result, so the base case result is within the distribution of the 10 000 simulation runs.

Table 7-9: Uncertainty Analysis - Monte-Carlo simulation for SI-CNG Heavy-Duty Vehicle - Results [33]

Parameter		Value
Base case, GHG result	907.6	g CO_2-eq/km
Monte-Carlo simulation		
Median, GHG result	834.1	g CO_2-eq/km
Standard deviation		12.4 %
10 % Percentile, GHG result	694.9	g CO_2-eq/km
25 % Percentile, GHG result	768.5	g CO_2-eq/km
75 % Percentile, GHG result	908.7	g CO_2-eq/km
90 % Percentile, GHG result	958.9	g CO_2-eq/km

The percentile values show the distribution of the simulation results: for example, 90 % of all simulation GHG results are below 958.9 g CO_2-eq/km and 10 % of all simulation results are below 694.9 g CO_2-eq/km.

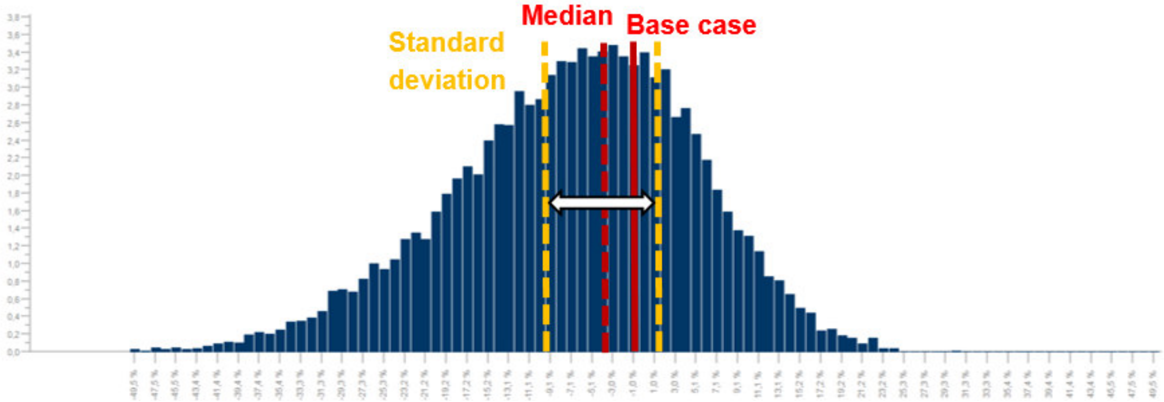

Figure 7-17: Uncertainty Analysis - Monte-Carlo simulation for Heavy-Duty Vehicle SI-CNG – distribution of results, calculated with GaBi software system [33]

Summarised, the uncertainty analysis demonstrates robustness of the calculated GHG results. Conclusion is high confidence in base case results.

7.7. Well-to-Wheel – Renewable Supply Sources of Natural Gas

Biomethane, also known as bioCNG, from renewable resources can be obtained from various pathways and feedstocks as illustrated in Figure 7-18. If bioLNG is produced, a micro or small-scale liquefaction plant has to be added to each production pathway.

Biogas, a mixture of methane and carbon dioxide, from anaerobic digestion, landfill or sewage sludge treatment can be upgraded to Natural Gas quality and fed into the Natural Gas grid. Within the last couple of years the installation of upgrading units has grown, with a concentration on Germany, United Kingdom, Sweden, Switzerland, Netherlands and France [62]. 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 gained by via electrolysis and methanation has different names, such as Power-to-Gas (PtG), Synthetic Natural Gas (SNG), e-gas, or windgas etc.

An important advantage of bioCNG and bioLNG as well as SNG compared to other renewable liquid fuels, is that Natural Gas vehicles are capable of using any share of bioCNG, bioLNG or SNG in their fuel (even up to 100 %) without the need of any technical changes.

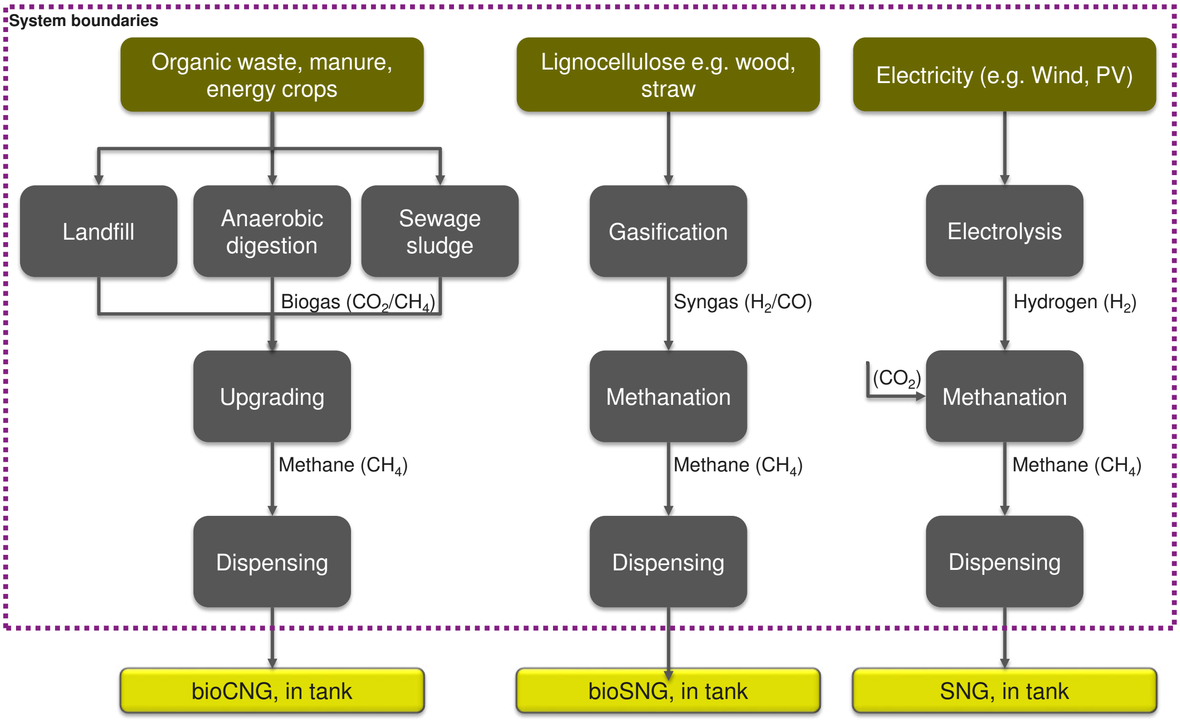

Figure 7-18: Schematic overview of bioCNG, bioSNG and SNG production pathways from renewable resources [10]

In the following, the WtW performance of bioCNG and bioSNG from anaerobic digestion of organic waste and manure as well as Synthetic Natural Gas (SNG) from power-to-gas is summarised based on the typical values derived from the Renewable Energy Directive (RED) [3], mainly the Fuel Quality Directive (FQD) [1], and its related Council Directive (EU) 2015/652 [4]. In addition, the reduction potential of possible blends composed of CNG and bioCNG / SNG was analysed[37].

Figure 7-19 illustrates the WtW GHG emissions of different bioCNG and SNG pathways as well as CNG blends are put in context with the GHG emissions of pure Natural Gas. For better understanding the WtW GHG emissions for bioCNG and SNG, the results are referenced to energy and later in Figure 7-20 per km driven. The TtW emissions per unit of energy are calculated based on the consumption values and GHG emissions of the defined passenger vehicles in section 6.2. The clear advantage of bioCNG and SNG is that the carbon dioxide emitted is effectively carbon neutral[38], i.e.,

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[37] Since this study assesses the use of Natural Gas in detail, unlike the modelling of bioCNG and SNG, it is not a comparative assertion with regard to renewable supply sources of natural gas following ISO 14040/44 standard

[38] The combusted carbon in the Biomethane has already been incorporated into the biomass using CO_2 from air. For PtG, carbon dioxide is assumed to be separated from flue gas of a power plant, see RED/FQD.

no additional CO_2 is released) and therefore not accounted in the WtW analysis. Only the CH_4 and N_2O emissions of the CNG vehicle using bioCNG/SNG are considered in the TtW GHG emissions.

Compared with fossil CNG (analysed in this study) the use of bioCNG from organic waste can reduce the WtW GHG emissions by -74 % (residues) resp. -80 % (wet manure) using the typical values in the RED for the Biomethane supply. For SNG the default value is of 3.3[39] g/MJ [4], which does not include any infrastructure for the electricity generation (e.g., wind power plant, photovoltaic panels), resulting in a reduction compared with Natural Gas based CNG of -94 %.

A share of 20 % bioCNG and 80 % fossil CNG is currently dispensed in Germany at CNG stations [63] and higher shares are dispensed in the Netherlands [64] and Sweden [65]. To better understand the impact of a possible blending of Natural Gas and bioCNG/SNG for NGV in Europe the analysis focusses on a blend composed of 80 % Natural Gas and 20 % bioCNG or SNG. Using RED/FQD values for the bioCNG/SNG supply, such a blend of 80 % CNG and 20 % bioCNG (of which 50 % wet manure, and 50 % residues) would reduce the WTW GHG emissions by 15 % compared with pure CNG. A blend including 20 % SNG would result in a reduction of 19 % compared with pure CNG.

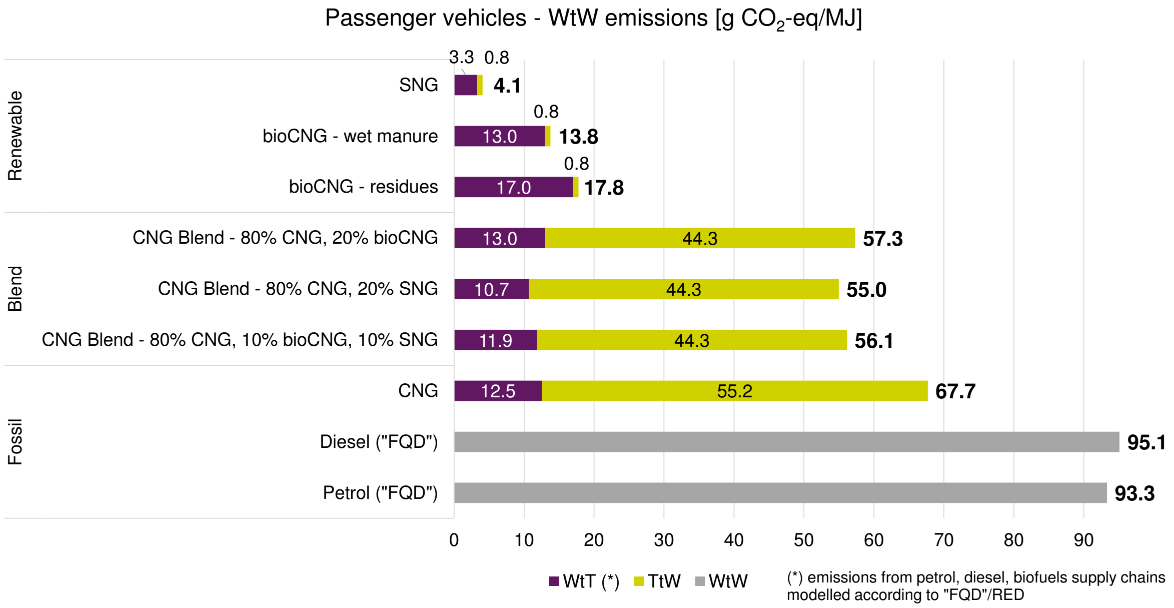

Figure 7-19: Well-to-Wheel – GHG Emissions: Passenger Vehicles [g CO_2-eq/MJ] [33]

Figure 7-20 includes the different fuel consumptions of the diesel, petrol and CNG passenger vehicle, as presented in section 6.2, illustrating the WtW GHG emissions per km. The usage of a CNG blend with 20 % bioCNG instead of pure CNG would increase the reduction compared with petrol from -23 % to -36 % and compared with diesel from -7 % to -21 %. The GHG reduction for the CNG blend using 20 % bioCNG or SNG compared with 100 % pure CNG remains at -15 % for the blend with bioCNG and -19 % for the blend with SNG.

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[39] The inclusion of the manufacturing and installation of wind power plants with data from the GaBi database would increase the impact from 3.3 g/MJ to 8.0 g/MJ.

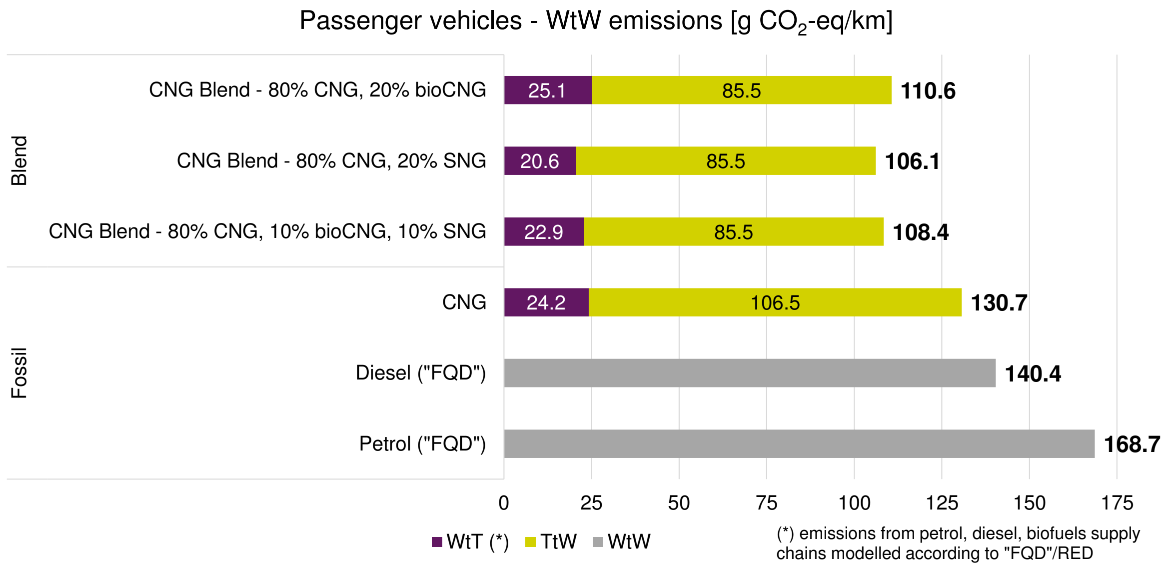

Figure 7-20: Well-to-Wheel – GHG Emissions: Passenger Vehicles [g CO_2-eq /km] [33]

Finally, the use of a Natural Gas blend composed of 80 % Natural Gas and 20 % bioCNG or SNG is analysed for heavy-duty vehicles. Figure 7-21 includes the different fuel consumptions of the different heavy-duty vehicles, using the consumption and emission values presented in Table 6-3 per MJ and Figure 7-22 per km driven.

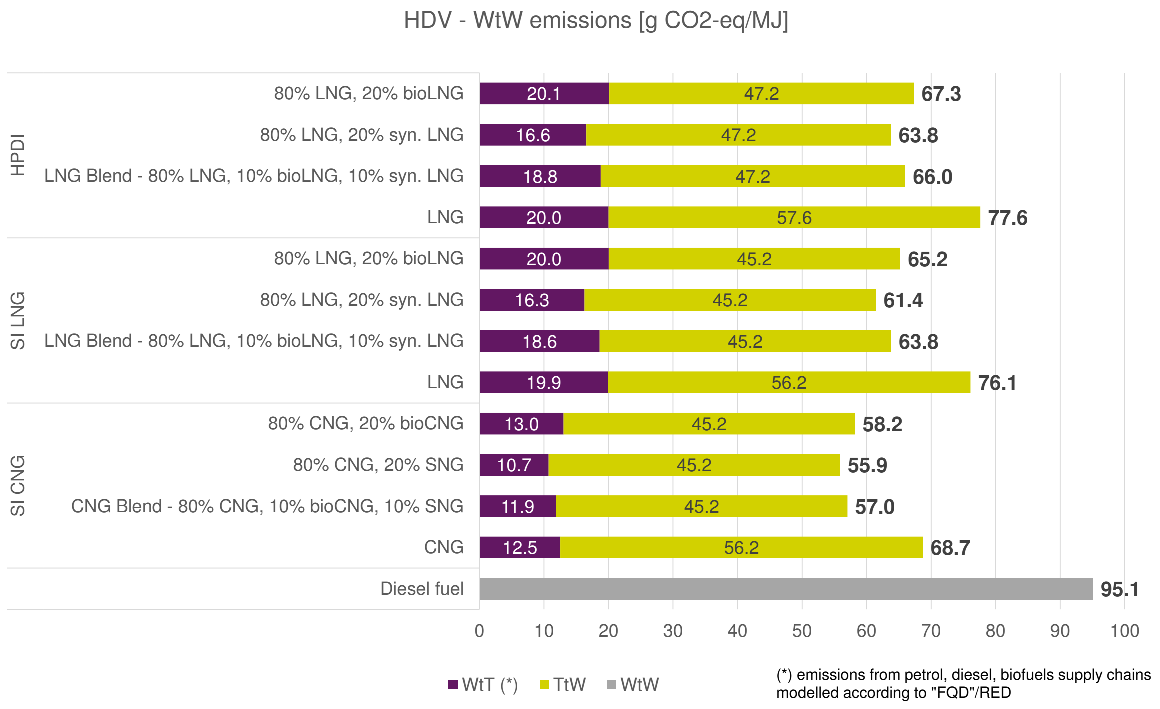

Figure 7-21: Well-to-Wheel – GHG Emissions: Heavy-Duty Vehicles in long haul use [g CO_2-eq/MJ] [33]

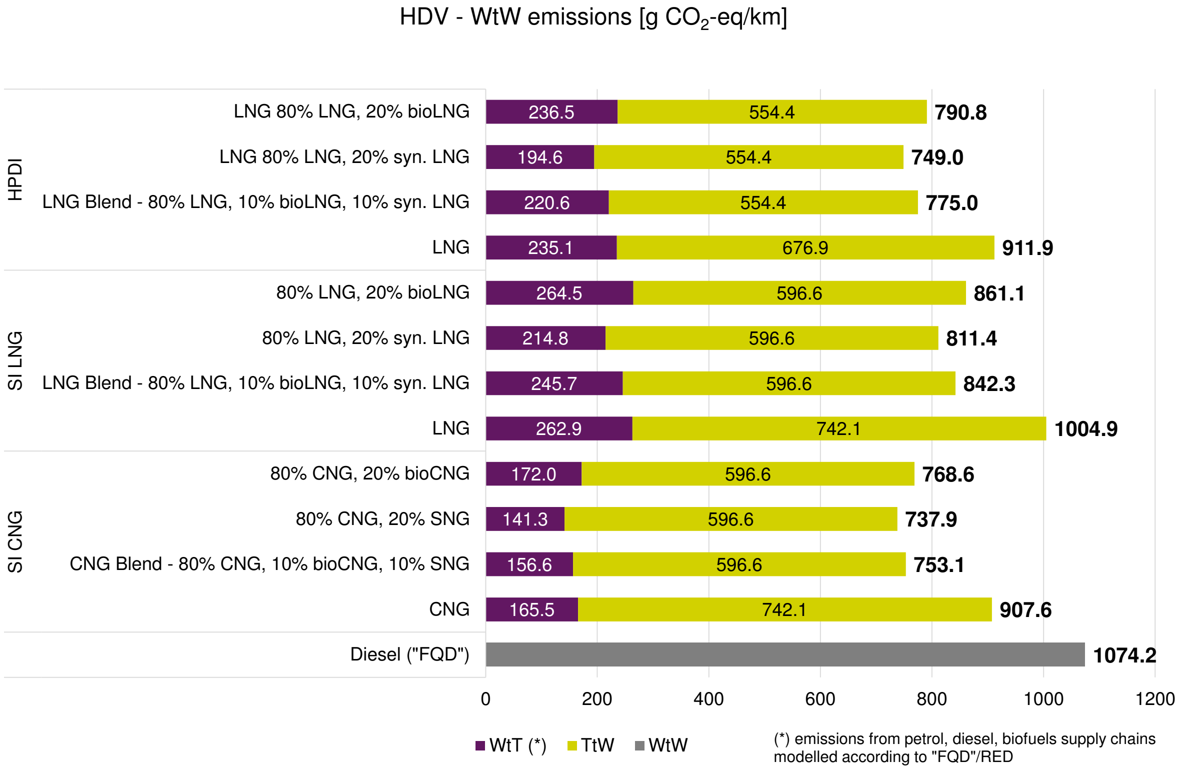

Figure 7-22: Well-to-Wheel – GHG Emissions: Heavy-Duty Vehicles [g CO_2-eq /km] [33]

The RED/FQD does not contain data for liquefied Biomethane or liquefied SNG. For the analysis, RED/FQD values for the supply of Biomethane from residues and manure or SNG have been used. However, for the micro scale liquefaction, literature data[40] were used and for the LNG distribution and dispensing the same data as for the fossil LNG.

Similar to the CNG passenger vehicle, the use of a 20 % share of bioCNG or SNG in the dispensed CNG would reduce the WtW GHG emissions for the SI engines by approximately -15 % (-19 % for the blend with SNG). For the HPDI engine, the reduction is less as the diesel fuel share used stays constant. Using RED/"FQD" values for the comparison of diesel with Natural Gas, the usage of a CNG blend that contains 20 % bio would increase the advantage for Natural Gas powered SI-CNG HDV in long haul use compared with diesel trucks from -16 % to approximately -28 %.

7.8. Well-to-Wheel Prospective Outlook – Technical Improvements in Natural Gas Supply and Natural Gas Vehicles and Ships

7.8.1. Development and Technical Improvements in Natural Gas Supply

Production, Processing, Liquefaction (if any) and Transport

Flaring, venting and fugitive emissions have reduced greatly over the last decades, and reached high standards in many countries providing gas to the EU. However, there are still some countries with improvement potentials in this area.

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[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 [64]. 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.

Algeria appears to be one of these. Results in this study suggest that installation of new, energy efficient production could reduce overall emissions by up to 50 % at full utilisation. However, it should be noted that while the data used in this study for Algeria are the best available, they might be outdated.

LNG production plants built in the 1970s are at the age where economic replacement by new, energy efficient liquefaction plants could be considered. New and energy efficient production will reduce the overall emission up to 50 % if running fully utilised, as the scenario analysis of the Algerian LNG production demonstrated in this study, see section 5.3.2.

Transmission, Storage and Distribution

Transmission, underground gas storage and LNG terminal operators have started to develop, design and implement accurate methane detection and measurement technologies and best practices to reduce GHG emissions. Some measures already in place show additional potential:

- Flaring the Natural Gas instead of venting it, and in addition the next step is the installation of compressors at the LNG terminals to reinject the boil-off gas instead of flaring this gas,
- Replacement of gas pneumatic controls by instrument air or electric actuators,
- The installation of electric motor starters in compressors, and
- Leak Detection and Repair campaigns to reduce fugitive emissions.

Though not the main GHG intensive process step, there is room for improvement in this part of the Natural Gas chain, and the gas companies are working on filling the existing technology gaps by means of new abatement opportunities and technologies in the future.

Refuelling Stations and Dispensing

As part of their efforts to reduce GHG emissions of Natural Gas, members of the NGVA have formally adopted a 'ZERO venting' target for routine operations for all new built CNG and LNG filling stations. In order to meet this commitment new CNG and LNG retail station infrastructure and operations are designed to prevent methane leaks ('fugitive emissions'), including modified components, such as connectors, receptacles, compressors etc., as well as boil-off management and vent recovery at LNG filling stations.

Since CNG filling stations in particular consume considerable amounts of electricity, the carbon footprint change associated with dispensing will drop due to the lower carbon intensive electricity grid mix 2030 (in 2030, the electricity mix has a 37 % lower carbon intensity compared with the 2014 mix), see Annex C. The EU-28 2030 electricity mix is based on the "EU Energy Trends to 2050" [66] of the European Commission.

In general, other sources of Natural Gas, like LNG from Australia (expected to be the largest LNG producer, worldwide) or US liquefied gas from unconventional sources were out of scope of this study.

7.8.2. Development and Technical Improvements in Natural Gas Vehicles and Ships

It is important to keep in mind that gas engine technologies are at a relatively early stage of development compared with diesel and petrol engines, and that the potential for improvement is quite large for Natural Gas engines.

SI Gas Engines

An important future development step for SI gas engines is the direct injection of Natural Gas into the cylinder, similar to today's practice in petrol engines, instead of the currently used port injection of Natural Gas. This development has a potential market entry within the next 10 years and provides more flexibility for the combustion process, and helps to increase the efficiency and reduce methane emissions.

More potential for efficiency increases is related to higher compression ratios that can be utilised in dedicated Natural Gas engines compared with petrol engines, due to the higher anti-knock index of methane (octane number of >120). A dedicated Natural Gas engine may use higher compression ratios than petrol engines that are often converted into bi-fuel engines today, which would lead to efficiency gains.

The application of advanced ignition systems offers the potential for improved combustion stability, higher exhaust gas recirculation tolerance and reduced unburned methane. If these enhancements can be realised there is the potential for overall increased combustion efficiency, combustion phasing and higher thermal efficiency.

Another relevant source of efficiency improvement is waste heat recovery. Spark ignited gas engines have higher exhaust temperatures than diesel engines, which means there is more energy available for recovery.

These advantages apply to SI engines in both passenger vehicles and HDV. In general, it is assumed that Natural Gas combustion engines will narrow the efficiency gap with respect to compression ignition engines.

HPDI Gas Engines

HPDI Natural Gas engines can already match or exceed the efficiency of diesel engines at similar NO_X levels. Further efficiency improvements can be found by tuning the combustion system to better match the HPDI characteristics (matching piston design to the HPDI injector, better matching of air handling, increased injection pressures). At a system level, further improvements include reducing the parasitic losses for driving the LNG pump. In general, the similar combustion approach means that HPDI engines tend to benefit from the same improvements that are made to diesel engines.

When LNG is used in a SI or HPDI engine, improvements of the thermal insulation of LNG containing components can extend the time during which no boil-off gas has to be released into the environment.

Additional measures exist, such as improved aerodynamics, low resistant running tires (LRR), friction reduction in other parts of the powertrain, the electrification of accessories, etc. to improve the fuel economy and therefore enhance emission reduction of vehicles in general. This section, however, has deliberately focused on gas-technology specific measures.

The existing efficiency gap of Natural Gas versus diesel engines will disappear, when the gas engine is predicted to have similar efficiency increase and CO_2-saving as the diesel engine. The developments for cars and trucks are to a certain extent comparable. The big advantage of Natural Gas as a vehicle fuel lies in its properties, e.g., composition, heating value and a very high octane number up to 120 (for pure methane). Energy efficiency is also improving for dedicated gas engines without a petrol reserve tank as in bi-fuel cars.

Looking to post 2020 development, the future generation of Natural Gas vehicles will provide a 20 % CO_2 emissions reduction (www.gason.eu) compared with the best state of the art technology thanks to the combination of engine technologies (downsizing, high compression ratio, Miller/Atkinson cycles, variable displacement through cylinder deactivation, direct injection systems, down speeding) that perfectly match with the Natural Gas properties, especially with regard to the high knocking resistance.

While 2-stroke high-pressure vessel engines show already reduced methane emissions, there is a potential for 4-stroke dual-fuel engines in this regard (e.g., e.g., closed crankcase ventilation systems, skip firing, variable valve timing or dedicated after treatment systems). Introducing current and upcoming technology in the maritime sector will have an impact on the overall GHG performance.

7.8.3. Prospective Outlook 2030 – Well-to-Tank and Well-to-Wheel GHG emissions

Well-to-Tank

The following changes were made in the model to get an indication of the potential 2030 Well-to-Tank performance for the CNG and LNG supplied in the EU Total.

- EU-28 Electricity grid mix 2030, instead of today's grid mix for "Transmission and Storage" as well as "Dispensing".
- Only new or refurbished LNG plants are in operation Algeria and have improved production as described in section 5.3.2.
- Higher efficiencies for the LNG production in Qatar, assuming old plants will be refurbished.

This changes lead to a GHG intensity of:

- 11.8 g CO2-eq/MJ (2015: 12.5 g CO2-eq/MJ) for the CNG supply mix, and
- 16.2 g CO2-eq/MJ, instead of 19.9 g CO2-eq/MJ for LNG supply mix.

These three changes alone led to a reduction of -6 % for CNG, and -19 % for LNG in the GHG intensity. Other sources of Natural Gas, like such as LNG from Australia or liquefied unconventional gas from US are out of the scope of this study.

Well-to-Wheel

An indication of the future Natural Gas Vehicle performance is outlined in Figure 7-23 (passenger vehicles) and Figure 7-24 (heavy-duty vehicles). BioCNG and SNG shares are also integrated into the analysis. In addition to the Well-to-Tank analysis, the following change is made:

- 10 % bioCNG and 10 % SNG in the Natural Gas fuel mix for 2030

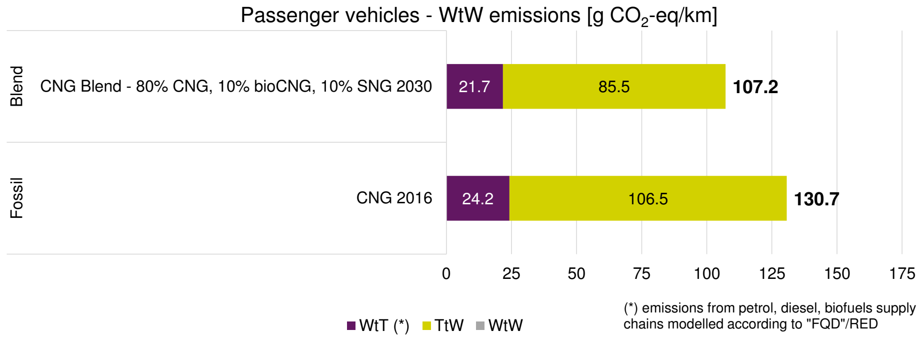

Figure 7-23: Well-to-Wheel – GHG Emissions: Passenger Vehicles, 2016 and 2030 [33]

These four assumed developments, lead to a GHG intensity improvement for the passenger vehicles of -18 % in 2030, compared with Natural Gas passenger vehicles in 2015, mainly driven through the share of bio and synthetic shares.

Other changes in the supply chain or related to the vehicle technologies, such as fuel improvements, unconventional natural gas sources, powertrain improvements, have not been considered beyond the ones mentioned previously.

Based on current technology development on CNG dedicated engines (EU projects GasON and HDgas) it is expected there will be further CO_2 reduction. GasON project is aiming to reduce CO_2

by -20 % with respect to 2015 CNG vehicle technologies, while HDgas is aiming to reduce CO_2 by -10 % on the HD SI engines compared with 2015 figures.

The following graph shows the indicative GHG results for HDVs in long haul use.

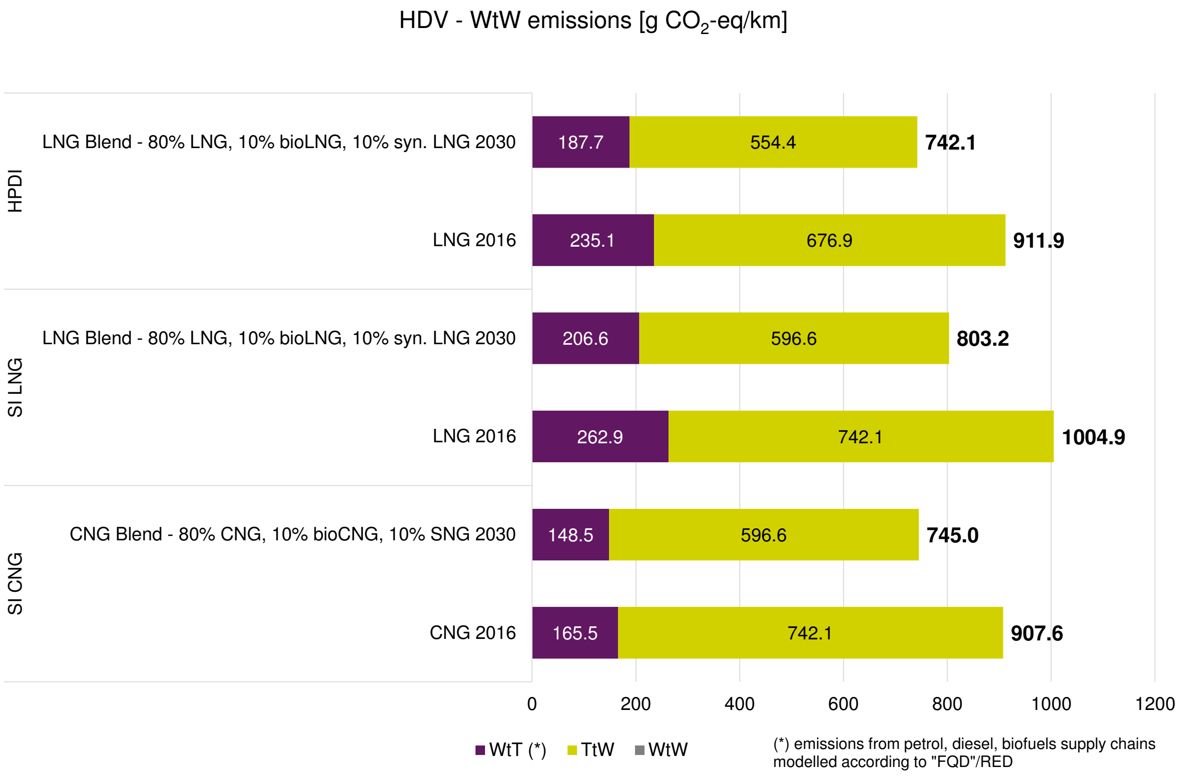

Figure 7-24: Well-to-Wheel – GHG Emissions: Heavy-Duty Vehicles, 2016 and 2030 [33]

The reduction of the GHG emissions for the SI-CNG HDV is also about -18 %, for the SI-LNG -20 % and for the HPDI engine -19 % compared with Natural Gas HDVs in 2015.

As with the passenger cars, vehicle efficiency or any other improvement in the supply chain, except the ones mentioned, have not been considered.

8. Interpretation

8.1. Identification of relevant Findings

Natural Gas and LNG Supply

The European Natural Gas consumption mix is mainly limited to a few major countries of origin. Eight countries: Russia, Norway, the Netherlands, UK, Algeria, Qatar, Germany and Nigeria are providing 90.3 % of the consumed Natural Gas in the EU. Hence, the Natural Gas market is less diverse than, for instance, the crude oil supply.

The study considers the total supply chain for Natural Gas and LNG as it exists today. From the production and processing (incl. well drilling and well installation) of Natural Gas, the pipeline transport, the purification, liquefaction, LNG transport, and regasification (if any), the transmission and storage, distribution and the dispensing. The CNG and LNG supply chains have some differences. In the CNG supply chain, Natural Gas is produced, transported, and mainly distributed directly by pipelines to the filling stations in Europe (roughly ~10 % are imported by LNG carriers and mainly regasified). In the LNG supply chain, the Natural Gas is purified, after production and processing, and is liquefied for long distance transportation before being distributed by truck or train from the LNG import terminal to the filling station.

The relevant key findings regarding the Well-to-Tank analysis:

- For EU Total, the GHG intensity of the CNG supply chain is **12.5 g CO_2-eq/MJ** (LHV), in tank.
- For EU Total, the GHG intensity of the LNG supply chain is **19.9 g CO_2-eq/MJ** (LHV), in tank.
- The EU LNG imports from Algeria only account for 22.1 %, but the associated GHG emission data have a large impact on the overall GHG result in the LNG supply chain. However, this may be the result of old data, and a sensitivity analysis based on only having current state of the art LNG plants in Algeria and improvements in the upstream operations to a comparable international level, reduced the EU Total LNG supply GHG intensity by -16 % to **16.8 g CO_2-eq/MJ** (LHV) from the base case (19.9 g CO2-eq/MJ). More details below in the data quality section (see section 8.3).
- Main contributors in terms of life cycle phases (“hot spots”) for the average CNG supply are:
  - Production, processing and liquefaction (if any), defined by energy demand and methane emissions.
  - Dispensing (i.e., compression at the filling station) defined by the electricity demand,
  - Transport if Natural Gas is transported over long distance, defined by energy demand and methane emissions,
  - Transmission, storage and distribution have a minor influence on the GHG intensity.
- Main contributors in terms of life cycle phases (“hot spots”) of the average LNG supply chain:
  - Purification and Liquefaction defined by its energy demand.
  - LNG Transport, defined by the distance travelled and the utilisation (in terms of time) of the LNG carrier
  - Distribution and dispensing are less important in terms of GHG intensity.
- Carbon dioxide is the main GHG contributor, followed by methane. Nitrous oxides are emitted only in small quantities. Other GHG emissions can be neglected.
- Well-to-Tank methane emissions for the CNG supply are 0.651 wt.%
- Well-to-Tank methane emissions for the LNG supply are 1.228 wt.%

- For the CNG and LNG supply chains, large variations (± 30 %) were identified for the four defined regions (North, Central, South East, South West) compared with the European average. Reasons are:
    - Different electricity grid mixes in regions (e.g., especially relevant for dispensing, less for transmission)
    - Differences in transmission energy intensity, and related methane emissions,
    - Different Natural Gas countries of origin, with associated different supply routes and technologies used (i.e., pipeline, LNG Transport), and hence GHG intensities.
    - Different GHG intensity of production and processing.
    - Different availability of up-to-date primary data.
- Technology consideration as well as a country-by-country analysis is key for the assessment of the supply chains due to remarkable differences.
- Comparison with other studies:
    - The GHG results compared with the Exergia study [7], are considerably lower for CNG (-35 %), and -19 % lower for LNG due to the improvements in data quality, e.g., data for Natural Gas coming from Russian or the observed new LNG technologies in Algeria. While the Exergia study outlines methane emissions in the order of 1.56 wt.%[41], this study calculates a value of 0,65 %.
    - The JEC-WtW study [8] showed a similar GHG performance.
    - The comparison of the GHG emissions for Natural Gas consumed in EU Central calculated by DBI are slightly higher compared with the values calculated in this study. 7.9 g CO_2-eq/MJ vs. 7.0 g CO_2-eq/MJ, both without dispensing. The main differences can be explained as follows: a) the present study refers to 2015, the DBI study to 2014, i.e. different Natural Gas consumption mixes. b) 2015 data are used for this study for the Natural Gas supply from Russia and more up-to-date primary data were collected for Norway. Smaller differences are due to different model assumptions and background data information.

Both, the CNG and LNG supply chains are solid and reliable technologies in daily operation allowing a secure Natural Gas supply for the European Union. Both products need to be analysed in the context of the respective application case and the related system. This matter is explained in the next section.

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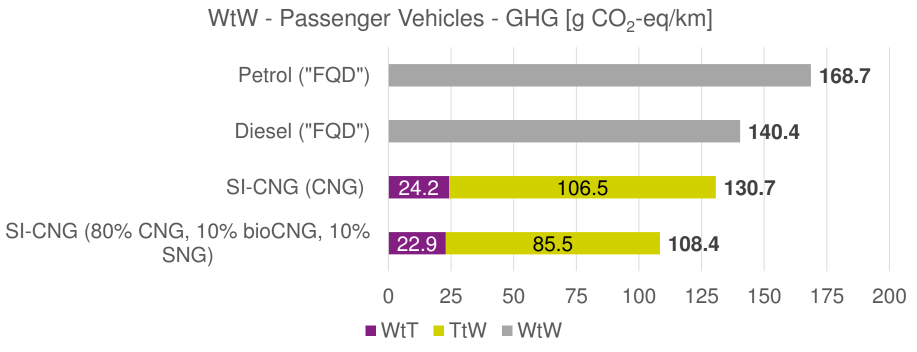
[41] Since the Methane losses as outlined in the Exergia study (table 5-21) [16], do not take distribution and transmission losses into account for the region EU Total, but for the other EU regions and since for all EU regions the distribution and transmission losses for the 2030 scenario are the same as for 2012, the EU Total distribution and transmission losses from 2030 are added to the 2012 losses (1.103 % + 0.401 % + 0.057 %, resulting in 1.561 %).

Natural Gas usage in Vehicles, Ships and NG Power Plants

The overall GHG intensity of the different Natural Gas Vehicles, i.e., Natural Gas supply including combustion is displayed in Figure 8-1 together with the values for petrol and diesel derived from the default values from the Council Directive (EU) 2015/652 [4]. It must be noted that this assessment is not a comparative assertion, since the results for natural gas were determined in a detailed LCA assessment, whereas the values for petrol and diesel are based on external sources.



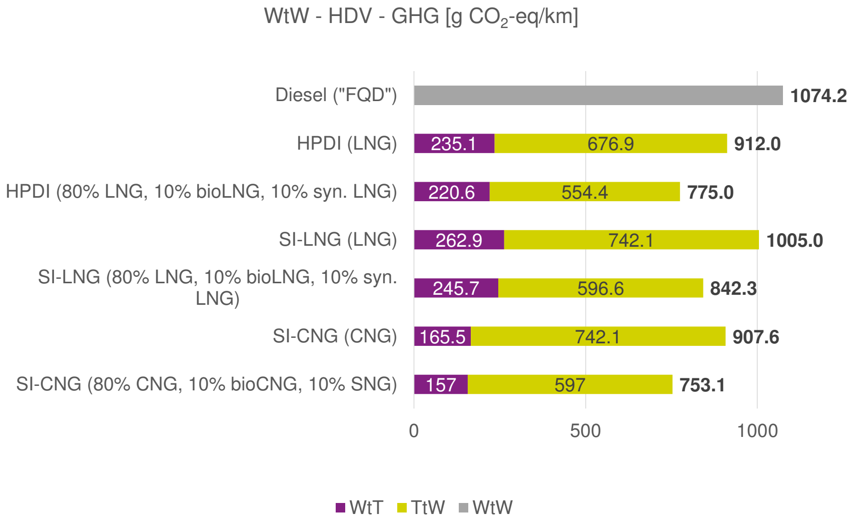


Figure 8-1: Well-to-Wheel – GHG Emissions: Passenger and Heavy-Duty Vehicles (long haul use) for different Fuels [33]

The relevant findings for the Well-to-X analysis are:

- All CNG and LNG vehicles show lower GHG results compared with the diesel and petrol vehicles related to the Council Directive (EU) 2015/652 [4].
- Passenger vehicles fuelled with CNG show GHG emission reductions of -7 %, compared with diesel and -23 % with petrol cars. Using a 10 % bioCNG and a 10 % SNG share increases the emission reduction to -23 % with respect to diesel and -36 % with respect to petrol.
- Heavy-Duty vehicles in long haul use show -6 % to -16 % lower GHG emissions, compared with diesel. SI-CNG engines -16 %, SI-LNG engines -6 %, and HPDI engines -15 %. Using a 10 % bioCNG and a 10 % SNG share increases the emission reduction with respect to diesel to -30 % for the SI-CNG HDV, -22 % for SI-LNG HDV, and -28 % for the HPDI engine.
- The majority of GHG emissions are released due to the combustion of the fuel in the vehicle, while the upstream fuel supply contributes around 18 - 26 %.
- Carbon dioxide is the main GHG contributor, followed by methane. Nitrous oxides are emitted only in small quantities. Other GHG emissions can be neglected.

- Well-to-wheel methane emissions show that ~80-90 % are associated with the Natural Gas supply.
- For the comparison of the NGV GHG intensity with diesel and petrol vehicles, the default values as outlined in the Council Directive (EU) 2015/652 [4] are used. The Directive is related to the Fuel Quality Directive (FQD). It must be noted that the reference baseline is important when making comparative statements.
- Beyond the passenger and heavy-duty vehicles,
  - LNG used in maritime ships also shows advantages in the GHG performance compared with oil based propulsion systems in the order of -11 to -21 %.
  - Usage of Natural Gas in power plants shows clear advantages compared with hard coal and lignite.

Sensitivity and Uncertainty Analysis

Sensitivity analyses were performed to test the sensitivity of the GHG results towards changes in parameter values that are relevant for the overall GHG result. The sensitivity analysis on the environmental impact category GWP_{100} (AR5) compared with GWP_{100} (AR4), demonstrates a slightly increased GHG intensity +1 % (higher characterisation factors for methane in AR5 compared with AR4). Hence, the choice of characterisation factors is of minor relevance to the overall GHG results. The sensitivity evaluation of the Global Temperature Potential GTP_{100} showed around 8 % lower results for passenger vehicles compared with the base case of GWP_{100} (AR4).

The sensitivity analyses on the technical parameters underpinned the strong dependency of the GHG intensity on fuel consumption. For the CNG supply chain, the analysis showed a high sensitivity in regard to the electricity demand of dispensing and the energy demand of pipeline transport. Within the LNG supply chain, variations in energy demand of liquefaction has the highest effect on the results.

An uncertainty analysis was performed to test the robustness of the Well-to-Wheel GHG results towards the combined parameter variations. A SI-CNG heavy-duty vehicle was used as the test case, with 10 000 Monte-Carlo simulations for a set of nine parameters with defined intervals. The overall GHG results are deemed to be robust based on the simulation results with a very low standard deviation of 12.4 %, even some parameters are varied in a ±100 % range.

Prospective outlook to 2030

The prospective Outlook to 2030 demonstrates promising GHG emissions result, for both: passenger and Heavy-Duty Vehicles.

Blends of Biomethane (bioCNG) or Synthetic Natural Gas (SNG) with fossil Natural Gas show a big potential to reduce the carbon footprint. The main blend considered consists of 10 % bioCNG, 10 % SNG and 80 % Natural Gas. For the adapted fuel share and three defined single improvements in the upstream supply chain, the GHG intensity of passenger vehicles is about -18 %, compared with Natural Gas passenger vehicles in 2015.

For Heavy-Duty Vehicles in long haul use, the reduction of the GHG emissions for the SI-CNG HDV is about -18 %, for the SI-LNG -20 % and for the HPDI engine -19 % compared with Natural Gas HDVs in 2015.

Further improvements in the supply chain and the vehicles will further increase the GHG performance. Based on current technology development on CNG dedicated engines (EU projects GasON [67]and HDgas [68]) it is expected there will be an additional CO_2 reduction; GasON project is aiming to reduce CO_2 by -20 % with respect to 2015 CNG vehicle technologies, while HDgas is aiming to reduce CO_2 by -10 % on the HD SI engines based on comparison with 2015 figures.

However, to make a complete and reliable outlook, other sources of Natural Gas, such as LNG from Australia (expected to be the largest LNG producer in the near future) or liquefied unconventional gas from US would have to be taken into consideration. It is relevant to note that the diesel and petrol reference baseline will also change over time. Hence, this outlook is only a rough prospective indication.

8.2. Assumptions and Limitations

It must be noted that this assessment is not a comparative LCA study (comparative assertion following ISO 14040/44), since it does not compare different product systems, i.e. vehicles with different powertrains using the respective fuels, in the same level of detail and within the same boundary systems. Instead, the study assesses the CNG and LNG supply and their use in different applications (see section 6.1) according to ISO 14040/44 and compares the determined GHG results with values for petrol and diesel provided in external sources, especially the Council Directive (EU) 2015/652 [4], which is related to the Fuel Quality Directive (FQD) [1].

Due to the focus of the study, diesel and petrol are not addressed in the same level of detail as Natural Gas.

The assumptions made and limitations identified within the assessment of Natural Gas are the following:

- Only 98.6 % of the countries of the European Natural Gas consumption mix were included but this can't be considered a "real" limitation.
- Primary data were collected for the majority of Natural Gas supplied to Europe. However, literature data (mainly from the Exergia Study [7]) were used for several Natural Gas supplying countries, e.g., Denmark, Hungary, Italy, Libya, Poland and Romania (all together 8.4 % of total CNG supply to Europe).
- Comprehensive primary data were collected for the fuel consumption in vehicles and LNG fuelled 4-stroke ships, while the combustion in LNG fuelled 2-stroke ships was based on literature as the power plant data for electricity generation.
- While nearly all primary data refer to 2014-2016, literature data covers a reference time period of 2011-2016. In particular, the data taken from the Exergia study [7] refer to 2012, but also uses older data.
- The contribution of literature data (i.e., data taken from the Exergia study [7]) applied in the present GHG models to the overall GHG results is shown in the following table.

Table 8-1: Contribution of literature data in GHG models to the overall GHG results for EU Total [33]

System	Upstream – LNG or CNG	Contribution
Well-to-Wheel	LNG based GHG models	5.5 to 5.9%
	CNG based GHG models	3.6 to 3.7%
Well-to-Tank	GHG model for LNG	22.6%
	GHG model for CNG	19.7%

Note: The contribution bandwidth is due to different vehicles.

Further:

- The literature contribution to the GHG results for the Well-to-Wheel analysis is small (below 4 % for CNG and below 6 % for LNG). The contribution of literature data to the overall GHG results for the Well-to-Tank component is important (~20 %), for both LNG and CNG.

- Broader primary data on dispensing operations is preferable, i.e., more detailed information on pipeline outlet pressure, electricity demand and methane emissions.
- More detailed information on methane emissions for Natural Gas distribution for all EU regions is preferable, with current data based on a representative European average value provided by Marcogaz [34].
- Within transmission and storage, some companies provided measured, while some other estimated and some calculated methane emission data due to the lack of a commonly agreed industry standard. In future, preferably all information would be based on the same method.
- Data gaps in country-specific transmission and storage information were filled by data from the Exergia study [7]. In particular, for the regions EU Total and EU South East less primary data were available. As outlined in the key findings, the data quality of the LNG supply chain in Algeria is quite limited, and due to the fact that new LNG plants came on-stream recently, the new technologies were estimated based on common average technical parameters.
- Some pipeline distances were “qualified” estimations. For instance, if several gas fields feed an export pipeline, an average pipeline length was assumed. It should be noted, that the sensitivity of the overall GHG results varying the pipeline distance by ±100 km was of minor relevance.
- Infrastructure does not contribute largely to the GHG intensity. E.g., Liquefaction plants contribute ~0.1 %, LNG carriers ~1 % and pipelines 3 - 5 % to the GHG to the Well-to-Tank emissions. For Well-to-Wheel, it is ~below 1 %.
- The influence of the Algerian GHG performance on the total LNG import mix to Europe is remarkable, and needs to be kept in mind for the interpretation of the GHG results.
- The manufacturing of the vehicles themselves was not considered, since it was assumed that gas, petrol and diesel fuel vehicle manufacturing and its related GHG emissions are similar to each other.
- The possibility of comparing and benchmarking the GHG results among different studies was limited due to different scope, system boundaries, reference year, etc.
- The comparison of the Well-to-Wheel GHG emissions calculated for NGVs with the diesel and petrol vehicles depends on the reference chosen. It was commonly agreed by the NGVA members to benchmark against the default values as outlined in the Council Directive (EU 2015/652 [4]). This Directive is related to the Fuel Quality Directive (FQD)[42]. However, the CNG and LNG GHG emissions of the Well-to-Wheel analysis were not affected directly and hence not addressed in further steps, by a sensitivity analysis.
- The goal and scope of the study was limited to the analysis of the GHG intensity only. No further environmental aspects, like local pollutants, were taken into consideration.
- No new sources of Natural Gas, like LNG from Australia or LNG from unconventional sources in the US were taken into account, since they are not relevant today.
- The assumptions for the prospective outlook to 2030 are only indicative and do not reflect the most probable future trends. Instead, they are intended to demonstrate the effect of potential developments.

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[42] JEC-WtW refinery data are based on the marginal approach. It considers energy and GHG emissions for the diesel/petrol production for a marginal reduction/increase in demand, compared with 2010. A discussion if this modelling approach is suitable for the average diesel and petrol default for the Council Directive (EU 2015/652 is not part of this study and not discussed further.

8.3. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated, literature, 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 collected are primarily used. Background information data are consistently used from the GaBi databases 2016. The LCI datasets from the GaBi databases 2016 are widely distributed and used with the GaBi 7 software system. The datasets have been used in GHG 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 other databases and values from industry and science.

The GHG intensity for the LNG supply chain from Qatar, Nigeria and Algeria (new technology) to Europe was calculated using *thinkstep's* own GaBi LNG model (the model was updated early 2016 and the results calculated in the present study are crosschecked with industry).

Main literature source for upstream information (not collected in this study), are derived from the Exergia study [7].

8.3.1. Precision and Completeness

- ✓ **Precision:** As the majority of the relevant foreground data are primary data or calculated based on primary information sources of the owner of the technology, precision is considered to be high for the Tank-to-Wheel part. Variations across different manufacturers were balanced out by using averages. For the Well-to-Tank chapter, partly good primary data were available, e.g., the production data for Norway, Russia, Nigeria, respectively for dispensing, and partly acceptable data were available, e.g., methane emissions from distribution. However, production and processing data from Algeria (Exergia study [7]) and Qatar (Sustainable Reports, [69] and [70]) are taken from literature. For the LNG supply from Qatar, Nigeria and Algeria (new technologies), *thinkstep's* own GaBi LNG model was utilised, and the results crosschecked with other literature sources and gas producers. All background data, e.g., electricity grid mixes are sourced from GaBi databases 2016 with the documented precision. 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 GaBi databases 2016 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 GaBi databases or literature, see also section 8.2.
- ✓ **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 year 2015. Some are from 2014, some are from 2016. All secondary data come from the GaBi 2016 databases and are representative of the years 2011-2014. 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, proxy data were used. Geographical representativeness is considered to be high due to the coverage of about 90.3 % of the EU Natural Gas supply, and the collaboration of all major vehicles manufacturers (OEMs) in Europe for the Well-to-Wheel part.
- ✓ **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, proxy data were used. Technological representativeness is considered to be very 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 two draft versions of the study report hence improving the quality of the assessment.

This study is ISO 14040/44 conform [5], [6] and a review in accordance with ISO/TS 14071 [14] was performed.

Considering the data quality assessment, *thinkstep* considers the assessment to be sound. Parts where the data quality may be low, are discussed in detail in this report. Main data quality issues are addressed in the reports, like the lack of primary data for the Algerian upstream operations incl. liquefaction.

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

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 predominantly using LCI data from the GaBi databases 2016. System boundaries, allocation rules, and the impact assessment method have been applied consistently throughout the study.

9. Conclusions, Recommendations

9.1. Conclusions

This study is based on high quality, reliable, and up-to-date industry-based life cycle data for CNG and LNG, 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 review panel.

The study reaffirms the importance of Natural Gas in the EU energy mix for road and ship transport, and for electrical energy generation. The study also demonstrates unequivocally the benefit from reduced GHG emissions that comes from powering passenger and heavy-duty vehicles from CNG or LNG, compared with the estimates based on the Council Directive (EU) 2015/652 [4] for petrol or diesel. Similar benefits are evident from powering ships with LNG.

These findings are extremely important for the EU major policy objectives. Over the past several decades the EU has committed to a number of relevant actions to reduce the extent and impact of, for example, climate change, and to improve air quality. The increased use of NG in vehicles can play a decisive role in achieving these objectives.

The study has also highlighted the important role bioCNG and bioLNG can and should play in the future fuel mix. Adding even a relatively small proportion (20 %) of these fuels to the NG mix reduces the emissions even further, and greatly increases the GHG benefits. Most importantly this initiative has the potential to have local economic benefits. Locally produced bio-fuels will contribute to local economic development in cities and regions across the EU, as well as providing increased security of energy supply to that region.

Similar benefits can be realised from the use of NG in preference to coal in electrical power generation.

These benefits can be realised as part of a comprehensive EU transport and stationary energy ‘menu’ of options. Future fuel supplies are likely to be highly diverse with a range of options that suit the particular vehicle, its duty cycle, and the locality. The range of options will likely not be dominated by a single liquid fuel as has been the case in the past. NG in both gaseous and liquid forms will have an important role to play in that menu of options.

These findings demonstrate the benefits over the full life cycle of NG, from production and processing, to supply and use. This is an important point as considering only some components of the life cycle of fuel and drive train options can lead to partial, if not misleading, findings, and inappropriate policy decisions.

An important finding of the study was that the GHG intensity of Natural Gas used within the EU was not as high as previously thought from some previous estimates (e.g. in the Exergia study [7]). This has been an important point of controversy, which was often not supported by hard data. The study has assessed the impact of the methane emissions from the NG sector that will be mitigated in the future by the progressive renewal of the production plants and the introduction of new technologies aiming at reducing methane losses in the atmosphere.

Future developments in the NG industry, including simply updating existing technology to current state of the art, are likely to play a fundamental role in further improving the benefits from the use of

NG in vehicles and electrical energy production. Data suggest that the Algerian production and supply route could be improved by various initiatives, including up-dating infrastructure and local operating systems.

Improvements in vehicle engine technology for Natural Gas and Biomethane are also likely to be substantial, particularly for dedicated NG engines. Efficiency improvements are steadily reducing NG consumption and emissions. The dynamic developments that are expected in the energy sector, in particular for the electricity production technologies from renewable energies, will have an effect on the developments for several propulsion technologies. Among them, the production of Synthetic Natural Gas from renewables will further support the development of Natural Gas Vehicles..

9.2. Recommendations

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 needed to develop appropriate policies and making sound decisions.

The potential to enlarge the actual scope of this study to a larger overview, including LCA consideration and/or introducing a wider number of powertrain configurations (including electric architectures) could be subject for further revisions to the present study.

Recommendation: The extension of the scope of this report to other aspects related to environmental impact, such as local pollutant emissions (PM/PN, NOx, NMHC, etc.), would provide a more complete evaluation of the Natural Gas potential completing the GHG impact assessment with a quantitative analysis on the air quality benefits.

Dissemination

The results of this study should be used for the dialogue with external stakeholders involved in the determination of fuel emission impacts, and development of regulations. These include relevant units of the European Commission, JEC consortium, International Energy Agency, and International Gas Union.

Recommendation: The key results of this study should be disseminated to and discussed with relevant policy and decision makers in government with the objective of promoting the harmonisation of Natural Gas related data collection, and analytical methodology.

Recommendation: The key results of this study should be disseminated to and discussed with representatives of the JEC consortium to facilitate the input of high quality, up to date information into the upcoming revision of Well-to-Wheel analyses.

Recommendation: The key results of this study should be disseminated to and discussed with relevant policy EC Directorate Generals and other local and national policy makers.

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Annex A: Literature Overview

A.1. Relevant Studies for Comparison and Benchmarking

Besides the legal framework documents "Fuel Quality Directive (FQD)" [1], [2], "Council Directive (EU) 2015/652" (2015/652) [4] and "Renewable Energy Directive (RED)" [3], four documents were identified as relevant for comparison and benchmarking purposes. These studies have a similar goal and scope as well as comparable system boundaries and modelling approach compared with the study at hand. These studies are:

1. Study on Actual GHG Data for Diesel, Petrol, Kerosene and Natural Gas, ("Exergia study") [7]
2. Well-to-Wheels Report Version 4.a ("JEC-WtW Study") [8]
3. Critical Evaluation of Default Values for the GHG Emissions of the Natural Gas Supply Chain ("DBI study") [9]
4. The Role of Natural Gas and Biomethane in the Transport Sector ("Ricardo study") [36]

Special attention is given to the DBI study. Since some companies providing data for the DBI study were also supporting this study, there was close cooperation between DBI and *thinkstep*.

The Well-to-Wheels Report Version 4.a ("JEC-WtW Study") [8] was analysed since this document describes underlying work for the FQD, in particular the calculation methods and reporting requirements relating to the quality of petrol and diesel fuels (Council Directive (EU) 2015/652) and the RED.

As these studies are current and closely related to the topic of the present study, they will be briefly described and presented in the following. The brief description highlights the underlying methodology used, scope, timeframe, and data sources used. A comparison of the GHG results is shown in sections 5.4, 6.3 and 7.4.

Study on Actual GHG Data for Diesel, Petrol, Kerosene and Natural Gas (Exergia)

The "Study on actual GHG data for diesel, petrol, kerosene and Natural Gas" published in July 2015 by the European Commission (DG ENER) was conducted by the Exergia consortium in collaboration with E3M-Lab (Economics-Energy-Environment Modelling Laboratory) of the National Technical University of Athens and COWI A/S [7]. It focuses on the GHG emissions of common fuels used for transportation in the EU-28 member states. The total supply chain from Well-to-Tank (WtT) is analysed, i.e., from the extraction of the resource up to the nozzle. Hence, gas production and processing, feedstock transportation via pipeline or via LNG carrier, and transmission, storage and distribution are considered for the Natural Gas supply of the EU-28. In addition to the direct emissions, indirect (induced land development, military involvement and emission due to accidents) are considered. However, the indirect emissions are of minor relevance.

To represent the GHG emissions for the Natural Gas supply, the Natural Gas pathways from the gas producing countries outside of the EU as well as the pathways of the gas produced by EU member countries are taken into account along with the Natural Gas supply network within the EU. However, small quantities of Natural Gas production or import are considered negligible and hence cut off.

For a better overview on the results of the study, the GHG emissions are calculated country-by country, but also aggregated to four EU regions:

- EU North i.e., Denmark, Ireland, Finland, Sweden and the United Kingdom,
- EU Central i.e., Austria, Belgium, Czech Republic, Estonia, Germany, Hungary, Latvia, Lithuania, Luxemburg, Netherlands, Poland and Slovakia,
- EU South East i.e., Bulgaria, Croatia, Cyprus, Greece, Italy, Malta, Romania and Slovenia,
- EU South West i.e., France, Portugal and Spain.

The gas production of all EU countries are analysed in detail, with exception of Malta and Cyprus, as they did not consume Natural Gas in the reference year 2012. The gas production and the transportation to the EU from the following non-EU countries are also considered: Algeria, Libya, Nigeria, Norway, Qatar and Russia. CNG and LNG are both taken into account as Natural Gas products.

While companies, associations and organisations linked to the Natural Gas supply chain of the EU were asked to provide data on single Natural Gas supply stages, most of the data were taken from literature sources. The reference year of the literature data is 2012. The GHGenius model (version 4) was used as a tool to calculate the GHG emissions [30].

GHGenius is an excel-based tool and methodology to determine GHG emissions for selected transportation fuels, including Natural Gas for Canada, USA, Mexico and India. This original version is published by the Canadian government and publicly available. The GHGenius model is generic and hence, parameters such as methane emissions, energy demand, etc. can be adapted. For the Exergia study, the GHGenius model was partly modified to represent the Natural Gas supply of the European region (e.g., countries, transportation distances, country-specific energy supply). This modified European version of the GHGenius model is intellectual property available under license from S&T² Consultants Inc., a Canadian based company [30]. The GHG emission are calculated following the IPCC 4th Assessment Report, 2007[43] [11]. A third party critical review following ISO 14040/44 was not performed for the assessment.

JEC Well-to-Wheels Report, Version 4.a, (JEC Consortium)

The “Well-to-Wheels Report Version 4.a” published by the European Commission’s Joint Research Centre (JRC) in March 2014, was conducted in collaboration with EUCAR (the European Council for Automotive R&D) and CONCAWE (the oil companies’ European association for environment, health and safety in refining and distribution) [8]. The first version of this study was published in 2003, the current version is version 4, and version 5 is in preparation.

The report combines the “Well-to-Tank Report (Version 4.a)” and the “Tank-to-Wheels Report (Version 4.0)” and focuses on the energy and GHG emissions of all representative fuel pathways and its use in different powertrains from Well-to-Wheel for road transportation in Europe. The supply chains considered in the Well-to-Tank part include the production and conditioning at source, transformation at source, transportation to EU, transformation in EU, conditioning and distribution. In the Well-to-Wheel part the energy required and greenhouse gas emissions in the vehicle - fuel combinations are considered.

The different fuel pathways include fossil fuels, such as diesel, petrol, liquefied petroleum gas (LPG), and Natural Gas (CNG, LNG), biofuels, such as bio-ethanol, bio-diesel, compressed biomethane (bioCNG), Synthetic Gas, and the supply of hydrogen for fuel cell vehicles and electricity for electric cars. To model all the different pathways, a modular structure is used. Consequently, different parts

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[43] The following main CO_2-eq factors have been used: carbon dioxide 1, methane 25, nitrous oxides: 298

along the supply chains are calculated separately, which can then be combined to the respective pathways.

Information on these pathways were elaborated by a consultant and based on publicly available literature with the reference year 2010. In addition to the 2010 data, outlooks to the situation in 2020 to 2025 are made. The statistical data for electricity production in Europe, for instance, are from the year 2009 and the one for Natural Gas production from year 2010. Often global data is considered, which is not sensitive to the differences in production technology, feedstock quality and other regional differences.

For the Well-to-Wheel part, a representative European compact car (a 5-seater sedan) is chosen for the calculation of required energy and emitted GHGs. The generic reference vehicle is created based on data taken from different models in this vehicle class. These data are provided by EUCAR member companies. Different powertrains with different energy sources are applied to the vehicle, including petrol fuels, hybrids, battery, fuel cell, ethanol, biodiesel, syndiesel and mixtures of fossil and biofuels. The vehicle performance was calculated using a dedicated vehicle simulation software. The New European Drive Cycle (NEDC) is used. Light commercial and heavy-duty vehicles are not addressed in the JEC-WtW study.

The JEC-WtW study focuses on the energy and greenhouse gas emissions of current (2010) and future technologies. Furthermore, materials (e.g., manufacturing of pipeline), the end of life activities (e.g., decommissioning of a pipeline), and the associated emissions are not included as the focus is on the fuels and powertrains only.

Critical Evaluation of default Values for the GHG Emissions of the Natural Gas Supply Chain (DBI)

The study “Critical Evaluation of default Values for the GHG Emissions of the Natural Gas Supply Chain”, was prepared by DBI Gas- und Umwelttechnik GmbH and commissioned by Zukunft Erdgas e.V., both located in Germany.

As outlined in their study, the analysis was initiated because *“the EXERGIA study reaches greatly different conclusions regarding the ecological evaluation of Natural Gas than previous studies (e.g., JEC study from 2013)”*. It is further pointed out that *“This analysis should compare its results with the results of the EXERGIA study, should identify and correct weaknesses, and, thereby, improve the public available database for further research.”* For that reason, the data in the DBI study refer to 2012 (being 1:1 comparable with Exergia), 2013 and 2014.

The DBI study presents the carbon footprint of Natural Gas from its production assets to its distribution in Central Europe (Central EU). The following major supplying countries for Central Europe are analysed: the Netherlands, Norway, and Russia. In addition, Germany as the main consuming and important transit country is considered in detail. The study focusses on gaseous Natural Gas supply since only small amounts of LNG are imported to Central EU. Dispensing of Natural Gas was not part of the analysis.

In addition to public available statistical data, the DBI study is based on best available industry data (several Natural Gas industry partners supported the project). For the gas production and processing for all countries analysed (except Russia) the national energy balances were used. Distribution data came from the National Inventory Reports and transmission data came partly from the National Inventory Reports and partly from the industry. So, the main part of data was publicly available statistical data.

The study is oriented towards the requirements by ISO 14040/14044. However, a third party critical review was not performed. For the calculation of the GHG results, the modified GHGenius tool and methodology was used as in the Exergia study, and the GHG results presented in the same manner as done by Exergia for the for the sake of better comparability.

Since Zukunft Erdgas and some data providing companies were also supporting this study, a close cooperation and exchange between DBI and *thinkstep* took place. The DBI study was published in December 2016.

The Role of Natural Gas and Biomethane in the Transport Sector (Ricardo)

"The role of Natural Gas and Biomethane in the transport sector" published by Transport and Environment (T&E) in February 2016 [36] was conducted by Ricardo Energy & Environment. The study focuses on the GHG, NO_X, SO_2 and PM emissions of fuels based on Natural Gas such as CNG or LNG used for transportation in Europe (road and shipping). These emissions are compared with emissions of conventional oil-based fuels. Apart from Natural Gas based fuels, Biomethane from different sources, either in compressed or liquefied form, is also considered. The total supply chain from Well-to-Wheel for road transport and Well-to-Wake for shipping is analysed. The economic cost situation of the gaseous fuel is also analysed in detail in the study. However, the study seems not to have undergone an independent critical review according to ISO 14044.

The total supply chain is divided into two parts: the Well-to-Tank part including production and conditioning at source, transformation at source, transportation to market, transformation near market, conditioning and distribution of the different fossil fuels; and the Tank-to-Wheel part including the combustion pathways for road and ship transport using Natural Gas and Biomethane (road transport only). Many data points are taken from the Exergia study (Well-to-Tank), the JEC Well-to-Wheels study (Well-to-Wheel) and the Danish Maritime Authority (Tank-to-Wake) and completed by other literature sources. Some data, especially data on Biomethane, are provided by Ricardo themselves. The reference year of the literature is not explicitly named but the dates range from 2011 to 2015.

In order to analyse the differences between conventional fuels, Natural Gas and Biomethane in detail, different scenarios are considered. Different emission scenarios for the fossil and renewable fuels are considered for the upstream operations:

For Well-to-Tank fossil fuels:

- Low emission factor scenario: using lower estimates for all fuels from the JEC-WtW study (EU-mix for Natural Gas),
- Central emission factor scenario: using central estimates for all fuels from the JEC-WtW study (EU-mix for Natural Gas),
- High emission factor scenario: EU average emissions factors for petrol, diesel and CNG from (Exergia study) and the mean of emissions factors for small-scale production of LNG from (Exergia study).

For Well-to-Tank Biomethane:

- Low emission factor scenario: assumes that bioCNG and bioLNG are produced solely from landfill gas,
- Central emission factor scenario: assumes that production of bioCNG and bioLNG is split 50:50 between landfill gas derived production and anaerobic digestion,
- High emission factor scenario: assumes all bioCNG and bioLNG is produced via anaerobic digestion.

For Tank-to-Wheel:

- Consideration of different driving cycles,
- Four passenger cars (CNG, bioLNG, Petrol, Diesel),
- Two categories for heavy-duty vehicles, [61]
    - Urban vehicles, with 3.5 - 16 tonnes and gas fuelled spark ignition (SI) engine (Euro V),
    - Long-haul vehicles with 16 - 44 tonnes dual-fuel compression ignition (CI) engine (Euro V).

For Tank-to-Wake:

- Four different ship types (RoRo, Coastal Tanker / bulk carrier, Container ship, Large RoRo)
- Three different fuel types (HFO, MDO, LNG),
- Two different methane slip rates for dual-fuel LNG vessels (1.8 % and 3.5 %).

Based on these scenarios, low, central and high (i.e., min, medium and max) results are calculated and compared with each other.

Summary of the relevant Studies for Comparison and Benchmarking

Table A-1 summarises the main studies identified for the GHG result comparison and benchmarking.

Table A-1: Overview of identified relevant studies for comparison and benchmarking

Study	LC Approach	Focus	ISO 14044 critical reviewed	Reference Year	Main Data Sources
Ricardo*	Yes	WtW*	No	2012-2015	Literature
Exergia	Yes	WtT	No	2012	Literature
DBI	Yes	WtT	No	2012, 2013, 2014	Industry / Literature
JEC-WtW	Yes	WtW	No	2010	Industry / Literature

* Mainly based on Exergia and JEC-WtW study.

A.2. Literature Overview

The Literature Overview (see Table A-2) contains all relevant recent documents collected and studies in the field of GHG intensity and methane leakage for the Natural Gas industry. The list is sorted by the date of publication. This overview was compiled through the whole project duration.

Table A-2: Literature overview (sorted by date of publication)

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context - Version 5	ongoing	Luxembourg, Luxembourg	European Commission Joint Research Centre (JRC) Institute for Energy and Transport	n.a.	WtW	Europe
	Emissions Testing of Gas-Powered Commercial Vehicles	2017	London, UK	Department of Transport, Low Carbon Vehicle Partnership (LowCVP)	B. Robinson, A. Eastlake	WtW	UK
	Summary report on hydrocarbon emissions from NGVs	2016	Paris, France	Gaz Réseau Distribution France (GrDF)	P. Larrive	TtW	France
	GHG Emissions Related To The Life Cycle Of Natural Gas And Coal In Different Geographical Contexts	2016	Montréal, Canada	International Reference Centre for the Life Cycle of Products, Processes and Services (CIRAIG), prepared for TOTAL	P.-O. Roy, P. Tirado, V. Patreau, R. Samson	WtW	Global
	The Role of Natural Gas and Biomethane in the Transport Sector	2016	Harwell, UK	Ricardo Energy & Environment prepared for Transport & Environment (T&E)	S. Kollamthodi, J. Norris, C. Dun, C. Brannigan, F. Twisse, M. Biedka, J. Bates	WtW	Europe
	Survey methane emissions for gas transmission and distribution in Europe	2016	Brussels, Belgium	Marcogaz	n.a.	WtT	Europe
	Inventory of U.S. GHG Emissions and Sinks: Revision Under Consideration for Gathering and Boosting Emissions	2016	Washington D.C., USA	U.S. Environmental Protection Agency (EPA)	n.a.	WtT	USA
	Inventory of U.S. GHG Emissions and Sinks: Revision Under Consideration for Natural Gas and Petroleum Production Emissions	2016	Washington D.C., USA	U.S. Environmental Protection Agency (EPA)	n.a.	WtT	USA

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Greenhouse Gas Emissions in the Netherlands 1990-2014, National Inventory report 2016	2016	Bilthoven, Netherlands	National Institute for Public Health and the Environment (RIVM)	P.W.H.G. Coenen, C.W.M. van der Maas, P.J. Zijlema, E.J.M.M. Arets, K. Baas, A.C.W.M. van den Berghe and other	WtT	Netherlands
	Sustainability Report – Qatargas - 2015	2016	Doha, Qatar	Qatargas	n.a.	WtT	Qatar
	Iveco Stralis LNG Natural Power	2016	Warsaw, Poland	CRYOGAS M&T Poland, IVECO	n.a.	TtW	Europe
	Finding the Facts on Methane Emissions: A Guide to the Literature	2016	Fairfax, VA, USA	The Natural Gas Council, ICF International	n.a.	WtT	USA
	Analysis of key trends and drivers in greenhouse gas emissions in the EU between 1990 and 2014	2016	Copenhagen, Denmark	European Environment Agency (EEA)	n.a.	-	Europe
	Annual European Union Greenhouse Gas Inventory 1990–2014 and inventory report 2016	2016	Copenhagen, Denmark	European Environment Agency (EEA), European Commission (EC)	A.M. Danila, R. Fernandez, S. Ntemiri, N. Mandl, E. Rigler	-	Europe
	World Energy Outlook Special Report 2016 - Energy and Air Pollution	2016	Paris, France	International Energy Agency (IEA)	n.a.	-	Global
	Options for Reduction of Upstream Emissions from Oil Production: Significance, Implementation and Consequences	2016	Berlin, Germany	Verband der Deutschen Biokraftstoffindustrie e. V., Verband der ölsaatenverarbeitenden Industrie in Deutschland e. V.	T. Goumas, K. Ntrenogianni, I. Stefanou	WtT	Europe
	Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems	2016	Fairfax, VA, USA	ICF International	n.a.	WtT	USA
	Integrated Fuels and Vehicles Roadmap to 2030+, Study and Study results	2016	Munich, Germany	Roland Berger	A. van der Slot, Dr. T. Schlick, W. Pfeiffer, M. Baum	TtW	Europe

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Progress in the development of natural gas high pressure direct injection for Euro VI heavy-duty trucks	2016	Berlin, Germany	Springer Fachmedien	P. Ouellette, D. Goudie, G. McTaggart-Cowan	TtW	Europe
	CO_2 emissions from new passenger cars in the EU: Car manufacturers' performance in 2015	2016	Washington D.C., USA	International Council on Clean Transportation (ICCT)	S. Díaz, U. Tietge, P. Mock	TtW	Europe
	Science for Environment Policy	2016	Brussels, Belgium	European Commission DG Environment	M. Anderson	TtW	Europe
	Effective reduction of CO_2 emissions through the coupling of efficient vehicles with renewable energy	2016	Dübendorf, Switzerland	Empa	Dr. B. Buchmann, C. Bach, Prof. Dr. A. Wokaun, Prof. Dr. T. J. Schmidt, Dr. F. Büchi, Prof. Dr. A. Vezzini	TtW	Switzerland
	Renewables in Transport 2050	2016	Frankfurt, Germany	Research Association for Combustion Engines (FVV), Ludwig-Bölkow-Systemtechnik (LBST)	P. R. Schmidt, W. Zittel, W. Weindorf, T. Raksha	WtW	Europe
	Building a scientific basis for tackling anthropogenic methane emissions	2016	Washington D.C., USA	National Aeronautics and Space Administration (NASA)	F. M. Hopkins	TtW	USA
	Upward revision of global fossil fuel methane emissions based on isotope database	2016	London, UK	Nature – Journal of Science, Springer	S. Schwietzke, O. A. Sherwood, L. M. P. bruhwiler, J. b. Miller, G. Etiope, E. J. Dlugokencky and others	WtW	Global
	Der Golf Technik und Preise	2016	Wolfsburg, Germany	Volkswagen (VW)	n.a.	TtW	Europe
	Der e-Golf Technik und Preise	2016	Wolfsburg, Germany	Volkswagen (VW)	n.a.	TtW	Europe

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Progress in the development of natural gas high pressure direct injection for Euro VI heavy-duty trucks	2016	Vancouver, Canada	Westport Innovation	P. Ouellette, D. Goudie, G. McTaggart-Cowan	TtW	Europe
	Effective Powertrain Solutions for Greenhouse Gas Emission Reduction	2016	Warrendale, PA, USA	SAE International, AVL	L. Walter	TtW	Global
	New Near Zero NOx natural gas engine under production	2016	Houston, TX, USA	NGV Journal	n.a.	TtW	USA
	NGVA statement T&E study: “The role of natural gas and biomethane in the transport sector”	2016	Brussels, Belgium	Natural & bio Gas Vehicle Association (NGVA)	n.a.	WtW	Europe
	Die Suche nach dem saubersten Antrieb	2016	Munich, Germany	Allgemeiner Automobil Club (ADAC) Motorwelt	n.a.	TtW	Germany
	Carnival orders three additional LNG-powered cruise ships	2016	Miami, FL, USA	Carnival Corporation	n.a.	TtW	Europe
	Report of Activities	2016	Brussels, Belgium	Natural & bio Gas Vehicle Association (NGVA)	n.a.	TtW	Europe
	Natural Gas Information 2014	2016	Paris, France	International Energy Agency (IEA)	n.a.	WtT	Global
	Summary of Expansions and Updates in GREET® 2016 Suite of Models	2016	Lemont, IL, USA	Argonne National Laboratory (ANL)	n.a.	WtT	Global
	Fleets Run Cleaner on Natural Gas	2016	Washington D.C., USA	NGV America (NGVA)	n.a.	WtW	USA
	Top Ten Green Cars	2016	Bern, Switzerland	Verkehrsclub der Schweiz (VCS)	n.a.	TtW	Switzerland
	Verbrennungsmotor wird mit „e-fuels“ klimaneutral – Elektromobilität wird deutlich zunehmen	2016	Berlin, Germany	Verband der Automobilindustrie e. V. (VDA)	U. Botterschulte	TtW	Germany
	Annual Report 2015	2016	Groningen, Netherlands	Gasunie	J. van Hoof	WtT	Netherlands
	Global Gas Security Review	2016	Paris, France	International Energy Agency (IEA)	n.a.	WtT	Global
	LNG as a marine fuel - Methane emissions	2016	Paris, France	CRIGEN of Engie	n.a.	WtT	Global

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	The LNG industry 2015	2016	Paris, France	The International Group of Liquefied Natural Gas (GIIGNL)	n.a.	WtT	Global
	Cold venting and fugitive emissions from Norwegian offshore oil and gas activities – summary report	2016	Trondheim, Norway	Norwegian Environment Agency (NEA)	G. Husdal, L. Osenbroch, Ö.Yetkinoglu, A. Østebrøt	WtT	Norway
	Transports Mariné – Oral presentations – workshop fleet operators	2016	Brussels, Belgium	The LNG Blue Corridors (LNGBC), European Commission (EC)	n.a.	TtW	Europe
	Natural Gas Experience on a LNG Vehicles fleet – Monfort Transportes – Oral presentations – workshop fleet operators	2016	Brussels, Belgium	The LNG Blue Corridors (LNGBC), European Commission (EC)	M. Monfort-Colom	TtW	Europe
	Revision of the EU green public procurement criteria for transport – JRC technical report – DRAFT	2016	Brussels, Belgium	European Commission (EC)	R.R. Quintero, H. Moons, I. Skinner, A. v. Grinsven et al.	-	Europe
	Identifizierung des Marktpotentials von LNG in Österreich	2016	Graz, Austria	Johanneum Research		TtW	Austria
	Die umweltfreundlichsten Autos (EcoTest ab Dez. 2016)	2016	Munich, Germany	Allgemeine Deutsche Automobil Club e.V. (ADAC)		TtW	
	Final Report – Critical Evaluation of Default Values for the GHG emissions of the natural gas supply chain	2016	Leipzig, Germany	DBI Gas- und Umwelttechnik GmbH	G. Müller-Syring, C. Große, J. Glandien, M. Eyßer	WtT	Europe
	Management Summary – Critical Evaluation of Default Values for the GHG emissions of the natural gas supply chain	2016	Leipzig, Germany	DBI Gas- und Umwelttechnik GmbH	G. Müller-Syring, C. Große, J. Glandien, M. Eyßer	WtT	Europe
	DBI – Carbon Footprint of Natural Gas – Critical Evaluation of Default Values for the GHG emissions of Natural Gas Supply Chain – Final presentation	2016	Leipzig, Germany	DBI Gas- und Umwelttechnik GmbH	G. Müller-Syring, C. Große, M. Eyßer, J. Glandien	WtT	Europe
	IGU – World LNG Report 2016 – LNG 18 Conference & Exhibition Edition	2016	Fornebu, Norway	IGU – International Gas Union sponsored by Chevron	n.a.	WtT	Global

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	ACS – Pump-to-Wheels Methane Emissions from the Heavy-Duty Transportation Sector	2016	Washington D.C., USA	Environmental Science & Technology, ACS Publications	N.N. Clark, D.L. McKain, D.R. Johnson, W.S. Wayne, H. Li, V. Akkerman	PtW	North America
	Evaluation of the Fuel Quality Directive 98/70/EC of 13 October 1998 relating to the quality of petrol and diesel fuels as amended	2015	Brussels, Belgium	European Commission (EC)	n.a.	WtW	Europe
	Study on Actual GHG Data For Diesel, Petrol, Kerosene and Natural Gas - Final Report	2015	Brussels, Belgium	European Commission (EC) DG ENER	EXERGIA S.A. et al.	WtT	Europe
	Methane Emissions from United States Natural Gas Gathering and Processing	2015	Washington D.C., USA	American Chemical Society (Environmental Science & Technology)	A.J. Marchese, T.L. et al.	WtT	USA
	Fahrzeugzulassungen (FZ) Neuzulassungen von Kraftfahrzeugen nach Umwelt-Merkmalen	2015	Flensburg, Germany	Kraftfahrt-Bundesamt (KBA)	n.a.	TtW	Germany
	Value Chain Methane Loss Update – Review of Public Available Studies	2015	Houston, TX, USA	ConocoPhillips	n.a.	WtT	USA
	Carbon Calculator for Land Use Change from Biofuels Production	2015	Lemont, IL, USA	Argonne National Laboratory (ANL)	J. B. Dunn, S. Mueller, Z. Qin, M. Q. Wang	WtT	USA
	ETUDE - Evaluation des impacts GES de l’injection du biométhane dans les réseaux de gaz naturel	2015	Paris, France	Gas Résau Distribution France (GrDF)	M. Vargas Gonzalez, B. Verzat, E. Carlu, F. Graveaud	WtT	France
	Life Cycle Assessment of LNG	2015	Fornebu, Norway	International Gas Union (IGU)	T. Williams, F. Al-Mejlad, F. Al-Naimi, P. Freens, B. Taha, V. Sarkova, O. Senina	WtW	Global

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Methane and CO_2 Emissions from the Natural Gas Supply Chain - an Evidence Assessment	2015	London, UK	Imperial College, Sustainable Gas Institute (SGI)	P. Balcombe, K. Anderson, J. Speirs, N. Brandon, A. Hawkes	WtT	Global
	Estimating U.S. Methane Emissions from the Natural Gas Supply Chain: Approaches, Uncertainties, Current Estimates, and Future Studies	2015	Golden, CO, USA	Joint Institute for Strategic Energy Analysis (JISEA)	G. Heath, E. Warner, D. Steinberg, A. Brandt	WtT	USA
	Controlling Methane Emissions in the Natural Gas Sector: A Review of Federal & State Regulatory Frameworks Governing Production, Gathering, Processing, Transmission, and Distribution	2015	Golden, CO, USA	Joint Institute for Strategic Energy Analysis (JISEA)	E. Paranhos, T. G. Kozak, W. Boyd, J. Bradbury, D. C. Steinberg, D. J. Arent	WtT	USA
	Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol	2015	Washington D.C., USA	American Chemical Society (ACS)	R. Subramanian, L. L. Williams, T. L. Vaughn, D. Zimmerle, J. R. Roscioli and others	WtT	USA
	Measurements of Methane Emissions from Natural Gas Gathering Facilities and Processing Plants: Measurement Results	2015	Göttingen, Germany	Atmospheric Measurement Techniques (AMT)	J. R. Roscioli, T. I. Yacovitch, C. Floerchinger, A. L. Mitchell, D. S. Tkacik, R. Subramanian, D. M. Martinez and others	WtT	USA
	Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States	2015	Göttingen, Germany	Atmospheric Measurement Techniques (AMT)	B. K. Lamb, S. L. Edburg, T. W. Ferrara, T. Howard, M. R. Harrison and others	WtT	USA
	Oil Production Greenhouse Gas Emissions Estimator (OPGEE)	2015	Sacramento, CA, USA	California Environmental Protection Agency (CEPA), Air Resources Board	H. M. El-Houjeiri, K. Vafi, J. Duffy, S. McNally, A. R. Brandt	WtT	USA

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	The Facts about fugitive Methane Emissions	2015	London, UK	Centre for Policy Studies (CPS)	E. A. Muller, R. A. Muller	WtT	Global
	Untapped Potential - Reducing Global Methane Emissions from Oil and Natural Gas Systems	2015	New York, NY, USA	Rhodium Group (RHG)	Kate Larsen, Michael Delgado and Peter Marsters	WtT	Global
	LNG and Coal Life Cycle Assessment of Greenhouse Gas Emissions	2015	Fairfax, VA, USA	Pace Global	n.a.	WtT	USA
	Adjusted historic emission data, projections, and optimized emission reduction targets for 2030 – A comparison with COM data 2013	2015	Laxenburg, Austria	International Institute for Applied Systems Analysis (IIASA)	M. Amann, I. Bertok, J. Borken-Kleefeld, J. Cofala, C. Heyes and others	-	Europe
	Solid and gaseous bioenergy pathways: input values and GHG emissions	2015	Ispra, Italy	European Commission (EC), Joint Research Centre (JRC)	J. Giuntoli, A. Agostini, R. Edwards, L. Marelli	WtT	Europe
	Mind the Gap	2015	Brussels, Belgium	Transport and Environment (T&E)	J. Dings, G. Archer	TtW	Europe
	Assessment of Heavy-Duty Natural Gas Vehicle Emissions: Implications and Policy Recommendations	2015	Washington D.C., USA	International Council on Clean Transportation (ICCT)	O. Delgado, R. Muncrief	WtW	USA, Europe
	Methane Emissions from the Natural Gas Transmission and Storage System in the United States	2015	Washington D.C., USA	American Chemical Society (ACS)	D. J. Zimmerle, L. L. Williams, T. L. Vaughn, C. Quinn, R. Subramanian and others	TtW	USA
	Methane Emissions from Leak and Loss Audits of Natural Gas Compressor Stations and Storage Facilities	2015	Washington D.C., USA	American Chemical Society (ACS)	D. R. Johnson, A. N. Covington, N. N. Clark	TtW	USA
	Annual European Union Greenhouse Gas Inventory 1990–2013 and inventory report 2015. Full report	2015	Copenhagen, Denmark	European Energy Agency (EEA), European Commission (EC)	E. Turano, R. Fernandez, S. Ntemiri, N. Mandl, E. Rigler	-	Europe

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Spatial patterns and source attribution of urban methane in the Los Angeles Basin	2015	Los Angeles, USA	American Geophysical Union (AGU) Publication	F. M. Hopkins, E. A. Kort, S. E. Bush, J. R. Ehleringer, C.-T. Lai, D. R. Blake and J. T. Randerson	TtW	USA
	Study on the Completion of an EU Framework on LNG-fuelled Ships and its Relevant Fuel Provision Infrastructure Lot 1 - 3	2015	Brussels, Belgium	European Commission (EC)	E .Erginel, J. Faber, D. Nelissen, S. Ahdour, J. Harmsen, S. Toma, L. Lebesque	TtW	Europe
	Proposed Method for Dealing with Boil-off Gas on board LNG Carriers during Loaded Passage	2015	Marina Del Rey, CA, USA	International Journal of Multidisciplinary and Current Research (IJMCR)	W. M. Bahgat	WtT	Global
	Zukünftige Maßnahmen zur Kraftstoffeinsparung und Treibhausgasminderung bei schweren Nutzfahrzeugen	2015	Dessau, Germany	Umweltbundesamt (UBA)	n.a.	TtW	Germany
	Energy Use on board LNG DFDE ships	2015	London, UK	LCS – Low Carbon shipping, University College London	E.E. Attah, R. Bucknall	TtW	Global
	Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context - Version 4a	2014	Luxembourg, Luxembourg	European Commission Joint Research Centre (JRC) Institute for Energy and Transport	R. Edwards, H. Hass, J.-F. Larivé, L. Lonza, H. Maas, D. Rickeard	WtW	Europe
	Lifecycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States	2014	Washington D.C., USA	United States Department of Energy (DOE), National Energy Technology Laboratory (NETL)	T.J. Skone, G. Cooney, M. Jamieson, J. Littlefield, J. Marriott	WtW	Europe; North America
	Life Cycle Analysis of Natural Gas Extraction and Power Generation	2014	Washington D.C., USA	United States Department of Energy (DOE), National Energy Technology Laboratory (NETL)	T.J. Skone, J. Littlefield, Dr. J. Marriott, G. Cooney, M. Jamieson, J. Hakian, G. Schivley	WtW	USA

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Annex III: Technology-specific cost and performance parameters	2014	Geneva, Switzerland	Intergovernmental Panel on Climate Change (IPCC)	S. Schlömer, T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, R. Wiser	WtW	Global
	The Potential of Natural Gas as a CO_2-Mitigation Option	2014	Cologne, Germany	Energiewirtschaftliches Institut an der Universität zu Köln (ewi)	Dr. C. Growitsch	WtT	Europe
	Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries	2014	Fairfax, VA, USA	ICF International	n.a.	WtT	USA
	Greenhouse gas impact of marginal fossil fuel use	2014	Utrecht, Netherlands	ECOFYS Netherlands B.V. prepared by EOA, EBB, FEDIOL	van den Bos, C. A. Hamelinck	WtT	Europe
	EU Bulk Assessment Inputs	2014	Washington D.C., USA	International Council on Clean Transportation (ICCT)	C. Malins, S. Galarza	WtT	Europe
	Crude Oil Greenhouse Gas Emissions Calculation Methodology for the Fuel Quality Directive	2014	Washington D.C., USA	International Council on Clean Transportation (ICCT)	C. Malins, S. Galarza, A. Baral	WtT	Europe
	Upstream Emissions of fossil fuel feedstocks for transport fuels consumed in the EU	2014	Washington D.C., USA	International Council on Clean Transportation (ICCT)	C. Malins, S. Galarza, A. Baral, D. Kodjak	WtT	Europe
	The Final Policy Scenarios of the EU Clean Air Policy Package	2014	Laxenburg, Austria	International Institute for Applied Systems Analysis (IIASA)	M. Amann, J. Borken-Kleefeld, J. Cofala, C. Heyes and others	-	Europe
	The Reduction of Upstream Greenhouse Gas Emissions from Flaring and Venting	2014	Washington D.C., USA	International Council on Clean Transportation (ICCT)	C. Malins, S. Searle, A. Baral, S. Galarza, H. Wang	WtT	Global
	GHG reduction measures for the Road Freight Transport sector	2014	Brussels, Belgium	European Automobile Manufacturers' Association (ACEA), Transport & Mobility Leuven	T. Breemersch, L. Akkermans	TtW	Europe

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	LNG als Alternativkraftstoff für den Antrieb von Schiffen und schweren Nutzfahrzeugen (DE/EN)	2014	Berlin, Germany	Bundesministeriums für Verkehr und digitale Infrastruktur (BMVI)	R. Wurster, W. Weindorf, W. Zittel, P. Schmidt, C. Heidt, U. Lambrecht, A. Lischke, Dr. S. Müller	WtW	Europe, Germany
	EU renewable energy targets in 2020: Revised analysis of scenarios for transport fuels	2014	Luxembourg, Luxembourg	European Commission (EC) Joint Research Centre (JRC), Institute for Energy and Transport	H. D.C. Hamje, H. Hass, L. Lonza, H. Maas, A. Reid, K. D. Rose, T. Venderbosch	WtW	Europe
	Liquefied Natural Gas: A Marine Fuel for Canada's West Coast	2014	Ottawa, Canada	Canadian Natural Gas Vehicle Alliance (CNGVA)	n.a.	TtW	Canada
	LNG Trucks Euro V technical solutions: LNG Blue Corridors	2014	Brussels, Belgium	European Commission (EC), LNG Blue Corridors	J. L. Pérez Souto, M. Ferrera, N. Leclerq, M. Matchett, I. Magnusson	TtW	Europe
	Cost Effective Reduction of Life Cycle GHG Emissions in the Heavy Duty Sector	2014	Houston, TX, USA	Shell	Dr. S. Hartman, Dr. M. Kofod	TtW	Global
	Der e-Golf Umweltprädikat – Hintergrundbericht	2014	Wolfsburg, Germany	Volkswagen (VW)	n.a.	TtW	Germany
	VOS Logistics in LNG: a pioneer`s tale	2014	LW Oss, Netherlands	VOS Logistics	A. Timmermans	WtW	Europe
	MAN – ME-GI Dual Fuel MAN B&W Engines – A Technical, Operational and Cost-effective Solution for Ships Fuelled by Gas	2014	Augsburg, Germany	MAN Diesel & Turbo			Global
	EMEP/EEA air pollutant emission inventory guidebook 2013 (update 2014)	2013 /2014	Luxembourg, Luxembourg	European Environment Agency (EEA)	O.-K. Nielsen, M. Plejdrup, M. Nielsen, M. Winther, P. Fauser, L. Hoffmann,	WtT	Europe
	5th Assessment Report	2013	Geneva, Switzerland	Intergovernmental Panel on Climate Change (IPCC)	n.a.	-	Global

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	GHGenius Model 4.03 Manual - Model Background and Structure (Vol.1) / Data and Data Sources (Vol.2)	2013	Delta, Canada	Natural Resources Canada	D. O'Connor ((S&T)² Consultant Inc.)	WtW	Global
	Natural Gas Information 2013	2015	Paris, France	International Energy Agency (IEA)	n.a.	WtT	Global
	Potenziale für Erdgas im Straßenverkehr – eine ökonomische Analyse	2013	Cologne, Germany	Energiewirtschaftliches Institut an der Universität zu Köln (ewi)	Dr. C. Growitsch, H. Hecking, C. John, S. Nick, H. Schwind	TtW	Germany
	Economic and environmental effects of the FQD on crude oil production from tar sands	2013	Delft, Netherlands	CE Delft	A. de Buck, M. Afman, B. Kampman, J. van den Berg, G.-J. Otten	WtT	Europe
	Independent Assessment of the European Commission's Fuel Quality Directive's "Conventional" Default Value	2013	Ottawa, Canada	ICF International	n.a.	WtT	Europe
	Schemes for Fossil Fuel Greenhouse Gas Upstream Reductions – Evaluating and Selecting Schemes and Standards for the Purpose of Article 7a of the FQD	2013	London, UK	ICF International prepared for European Commission	n.a.	WtT	Europe
	Impact Analysis of Options for Implementing Article 7a of Directive 98/70/EC (Fuel Quality Directive)	2013	London, UK	ICF International prepared for European Commission	n.a.	WtT	Europe
	Desk Study on Indirect GHG Emissions from Fossil Fuels	2013	London, UK	ICF International prepared for European Commission	n.a.	WtT	Europe
	Well-to-Wheel LCI data for fossil and renewable fuels on the Swedish market	2013	Gothenburg, Sweden	The Swedish Knowledge Centre for Renewable Transportation fuels (f3)	L. Hallberg, T. Rydberg, L. Bolin, L. Dahllöf, H. Mikaelsson, E. Iverfeldt, J. Tivander	WtW	Sweden
	LNG Emissions Benchmarking	2013	Ottawa, Canada	Delphi Group	J. Rogers	WtT	Global
	High efficiency and low emission natural gas engines for heavy duty vehicles	2013	Vancouver, Canada	Westport Innovation	M. E. Dunn, G. P. McTaggart-Cowan, J. Saunders	TtW	Canada
	Utsläpp av metan i den svenska fordonsgaskedjan En sammanställning av nuläget	2013	Malmo, Sweden	Svenskt Gastekniskt Center (SGC)	L. Göthe	WtW	Sweden

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Gefährdungsanalyse und Risikobewertung beim Betankungsvorgang von Erdgas- / Biogasfahrzeugen	2013	Dübendorf, Switzerland	EMPA, Basler & Hofmann	n.a.	TtW	Europa
	Milieubalans CNG & LNG	2013	Antwerp, Belgium	Vito NV	T. Denys, K. Boonen, B. Degraeuwe	WtW	Belgium
	Well-to-Wheel LCI data for fossil and renewable fuels on the Swedish market database	2013 & 2014	Gothenburg, Sweden	The Swedish Knowledge Centre for Renewable Transportation fuels (f3)	L. Hallberg, T. Rydberg, L. Bolin, L. Dahllöf, H. Mikaelsson, E. Iverfeldt, J. Tivander	WtW	Sweden
	LCS – Energy Use Onboard LNG Steam ships	2013	London, UK	LCS – Low Carbon Shipping, University College London	E. E. Attah, R.W.G. Bucknall	TtW	Global
	Lifecycle Greenhouse Gas Emissions of Natural Gas	2012	Ottawa, Canada	The Canadian Natural Gas Initiative (CNGI)	ICF Consulting Canada	WtW	Global
	Reducing CO_2 emissions in the EU Transportation Sector to 2050	2012	n.a.	European Gas Forum (EGaF)	n.a.	TtW	Europe
	Oil Production Greenhouse Gas Emissions Estimator (OPGEE)	2012	Washington D.C., USA	International Council on Clean Transportation (ICCT)	H. M. El-Houjeiri, A. R. Brandt, C. Malins, S. Galarza	WtT	USA
	Reduction of greenhouse gases: a technology guide	2012	Kuala Lumpur, Malaysia	International Gas Union (IGU)	J. Puertas	WtT	Global
	Future emissions of air pollutants in Europe – Current legislation baseline and the scope for further reductions	2012	Laxenburg, Austria	International Institute for Applied Systems Analysis (IIASA)	M. Amann, J. Borken-Kleefeld, J. Cofala, C. Heyes and others	-	Europe
	North European LNG Infrastructure Project: A feasibility study for an LNG filling station infrastructure	2012	Valby, Denmark	Danish Maritime Authority (DMA)	n.a.	WtT	EU Europe
	Directives to the quality of petrol and diesel fuels and on the promotion of the energy of from renewable sources	2012	Brussels, Belgium	European Commission (EC)	n.a.	WtW	Europe
	Der Passat Umweltprädikat – Hintergrundbericht	2012	Wolfsburg, Germany	Volkswagen (VW)	n.a.	TtW	Germany

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Lifecycle Greenhouse Gas Inventory of Natural Gas Extraction, Delivery and Electricity Production	2011	Washington D.C., USA	United States Department of Energy (DOE), National Energy Technology Laboratory (NETL)	T.J. Skone, J. Littlefield, Dr. J. Marriott	WtW	USA
	Life-Cycle Analysis of Shale Gas and Natural Gas	2011	Chicago, USA	Argonne National Laboratory (ANL)	C.E. Clark, J. Han, A. Burnham, J.B. Dunn, M. Wang (Argonne)	WtW	Global
	LCA of the European Gas Chain: Challenges and Results	2011	Seoul, South Korea	International Gas Union Research Conference (IGRC) 2011	A. Prieur-Vernat, P. Pacitto, D. Hec, V. Bichler	WtW	Europe
	Life cycle assessment of marine fuels A comparative study of four fossil fuels for marine propulsion	2011	Gothenburg, Sweden	Department of Shipping and Marine Technology (DSMT)	S. Bengtsson, K. Andersson, E. Fridell	TtW	Europe
	Life Cycle Inventory of Natural Gas Supply	2010	Bern, Switzerland	Swiss Federal Office of Energy (SFOE)	S. Schori, R. Frischknecht	WtT	Europe
	Greenhouse Gas Emissions reporting from the Petroleum and Natural Gas Industry	2010	Washington D.C., USA	Environmental Protection Agency (EPA)	n.a.	WtT	USA
	ILCD Handbook Reviewer qualification of Life Cycle Inventory data set	2010	Luxembourg, Luxembourg	European Commission (EC) Joint Research Centre - Institute for Environment and Sustainability:	n.a.	-	Global
	Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry	2010	Washington, D.C., USA	Environmental Protection Agency (EPA)	n.a.	WtW	North America
	EU Transport GHG: Routes to 2050? Regulations for vehicles and energy carriers	2010	Brussels, Belgium	European Commission (EC)	R. Smokers, H. van Essen, B. Kampman, E. den Boer, R. Sharpe	WtW	Europe
	Natural Gas Unlocking the Low Carbon Future	2010	Oslo, Norway	International Gas Union (IGU)	n.a.	WtW	Global

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Communication from the Commission on voluntary schemes and default values in the EU biofuels and bioliquids sustainability scheme	2010	Brussels, Belgium	European Commission (EC)	n.a.	WtT	EU
	How to influence CO_2	2010	Augsburg, Germany	MAN Diesel & Turbo	n.a.	TtW	Global
	AP 42: Compilation of Air Emission Factors	2010	Washington D.C., USA	US Environmental Protection Agency (US EPA)	n.a.	-	Europe
	European Gas Imports: GHG Emissions from the Supply Chain	2009	Turin, Italy	Altran Italia	A. Taglia, N. Rossi	WtW	Europe
	Life Cycle Analysis of GHG and Air Pollutant Emissions from Renewable and Conventional Electricity, Heating, and Transport Fuel Options in the EU until 2030	2009	Darmstadt, Germany	The European Topic Centre on Air and Climate Change (ETC/ACC)	U. Fritsche, L. Rausch	WtT	Europe
	Renewable Energy Directives promotion of the use of energy from renewable sources	2009	Brussels, Belgium	European Commission (EC)	n.a.	WtT	EU
	Energy Sector Methane Recovery and Use	2009	Paris, France	International Energy Agency (IEA)	n.a.	-	Global
	Field Measurement Program to Improve Uncertainties for Key Greenhouse Gas Emission Factors for Distribution Sources	2009	Des Plains, IL, USA	Gas Technology Institute	K. Cruz, J. McCarthy	TtW	US
	Renewable Energy Directives promotion of clean and energy-efficient road transport vehicles	2009	Brussels, Belgium	European Commission (EC)	n.a.	TtW	EU
	Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry	2009	Washington D.C., USA	American Petroleum Institute	n.a.	WtT	USA
	Results and Input Data for Biofuels Pathways	2008	Brussels, Belgium	European Commission (EC)	n.a.	WtT	EU

-	Title	Year (sorted)	Location	Publisher	Authors	Life Cycle Stages	Region
	Lifecycle Assessment of the European Natural gas Chain, A Eurogas - Marcogaz Study	2007	Brussels, Belgium	Eurogas – Marcogaz	M. Papadopoulo, S. Kaddouh, A. Cigni, D. Gullentops, S. Serina, J. Vorgang, T. Veenstra, F. Dupin	WtW	Europe
	The Natural Gas Chain, Toward a Global Lifecycle Assessment	2006	Delft, Netherlands	CE Solutions for environment, economy and technology	M.N. Sevenster, H.J. Croezen	WtW	Global
	National Emission Ceilings Directive Review; Additional Task - Methane	2005	London, UK	European Commission (EC) - DG Environment	M. Sponar, K. Wilson, B. Grebot, A. Stavrakaki, C. Corden, A. Ritchie, A. McIntyre	-	Europe
	Greenhouse Gas Emissions from the Russian Natural Gas Export Pipeline System	2005	Wuppertal, Germany	Wuppertal Institute for Climate, Environment and Energy, (E.ON Ruhrgas AG)	S. Lechtenböhmer, Dr. S. S. Assonov, C. Dienst, Dr. C. Brenninkmeijer, Dr. M. Fischedick, T. Hanke. T. Langrock	WtT	Russia
	European Standard Test gases – Test pressures – Appliance categories (EN 437)	2003	Brussels, Belgium	European Committee for Standardization (CEN)	n.a.	TtW	Europe
	Environmental Impact of Underground Freight Transport	2003	Utrecht, Netherlands	Utrecht University (UU)	J. Willigers, B. van Wee	WtT	n.a.
	Commission directive: measures to be taken against the emission of gaseous and particulate pollutants from compression ignition engines	1999	Brussels, Belgium	European Commission (EC)	n.a.	TtW	Europe
	Technology Assessment of Refueling-Connection Devices for CNG, LNG, and Propane	1998	Washington D.C., USA	Transit Cooperative Research Program (TCRP) sponsored by Federal Transit Administration	C. W. Jenks	WtT	Global

Annex B: Natural Gas and LNG

Natural Gas

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 minor amounts of impurities, 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), 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:

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 minor amounts of impurities, such as sulphur (e.g., H_2S), 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, environment conditions (deep sea, natural reserve, mountains) or political reasons.

Annex C: Default Values

Number Format

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

Natural Gas

The values were defined in accordance with the JEC-WtW study [8] as first data source, completed and modified were necessary. (The present study assume Natural Gas CH_4 content of 94.4 Vol.% (leads to a LHV of 47.5 MJ/kg) while the JEC-WtW study assumes only 90.0 Vol.% (45.1 MJ/kg). As pointed out, wherever individual values are provided, individual values are used for any conversion.

Table C-1: Natural Gas properties and default values [8], [33]

Properties	Unit	Natural Gas[44] (EU average)	Natural Gas G20 standard [45]	Methane
CH_4	Vol.%	94.4		100.0
C_2H_6	Vol.%	2.7	No need to be defined	0.0
C_3H_8	Vol.%	0.4		0.0
C_4H_{10}	Vol.%	0.1		0.0
C_5H_{12+}	Vol.%	0.0		0.0
CO_2	Vol.%	0.8		0.0
CO	Vol.%	0.0		0.0
N_2	Vol.%	1.6		0.0
H_2	Vol.%	0.0		0.0
H_2S	Vol.%	0.0008		0.0
H_2O	Vol.%	0.0		0.0
TOTAL	Vol.%	100.0	100.0	100.0
Density	kg/Nm³	0.763	0.722	0.714
HHV[46]	MJ/kg	52.5	54.7	55.6
LHV[47]	MJ/kg	47.5	49.5	50.0
HHV/LHV	-	1.10	1.10	1.11
CO_2-Emission Factor	g CO_2/$MJ_{combusted}$	55.6	55.1	55.0

Please note that all energy related numbers in this report refer to the lower heating value (LHV). Collected primary data on fugitive emissions were either reported as gas losses (mixture of

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[44] The Natural Gas Vol. % properties are based on GHGenius [11], and slightly modified.

[45] For more details on G20 standard please have a look at: [37] and [38].

[46] HHV = Higher Heating value, also known as gross calorific value (GCV)

[47] LHV = Lower Heating value, also known as net calorific value (NCV)

components, see above) or as methane losses (pure CH_4), and often reported in Volume percentage (Vol.%) or weight percentage (wt.%).

Liquefied Natural Gas (LNG)

Table C-2 summarises the main properties for LNG.

Table C-2: Liquefied Natural Gas (LNG) properties and default values [8], [33]

Properties	Unit	LNG (EU average)
Density[48]	kg/m³	450
HHV	MJ/kg	54,7
LHV	MJ/kg	49.5
HHV/LHV	-	1.10
CO_2-Emission Factor	g CO_2/MJ	55.1

Crude Oil, Diesel fuel, Petrol, Heavy Fuel Oil, Marine Diesel Oil

In Table C-3 properties and default values for other fuels are illustrated. These figures were taken from the JEC-WtW study [8]. MDO is assumed to have the same properties like diesel fuel.

Table C-3: Other fuel properties and default values [8]

Fuel	LHV [MJ/kg]	LHV [MJ/l]	Density [kg/m³]	CO_2-Emission factor [g CO_2/MJ]
Crude oil	42.0	34.4	820	75.5
Diesel fuel	43.1	35.9	832	73.2
Petrol	43.2	32,2	745	73.4
Heavy Fuel Oil (HFO)	40.5	39.3	970	80.6
Marine Diesel Oil (MDO)	43.1	35.9	832	73.2

GHG Intensity of modelled Electricity Grid Mixes

Table C-4 GHG intensity of modelled Electricity Grid Mixes 2014, own calculations, based on GaBi databases 2016 [33]

Country	GHG intensity [g CO_2-eq/kWh]
EU Total	485.4
EU North	515.2
EU Central	544.9
EU South East	507.9
EU South West	240.4

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[48] average value, published by GIIGNL [65]

GHG Intensity of Country Specific Electricity Grid Mixes

Table C-5: GHG intensity of selected Electricity Grid Mixes (1kV-60kV) 2014, taken from GaBi databases[49] [13]

Country	Abbreviation	GHG intensity [g CO_2-eq/kWh]
Algeria	DZ	769.6
Austria	AT	319.9
Belgium	BE	239.4
Bulgaria	BG	728.1
Croatia	HR	504.5
Czech Republic	CZ	687.9
Denmark	DK	304.4
Estonia	EE	1 216.4
EU	EU	443.6
EU (2030)	EU	278.2
Finland	FI	263.0
France	FR	90.7
Germany	DE	581.9
Greece	GR	1 009.4
Hungary	HU	454.8
Ireland	IE	582.6
Italy	IT	462.1
Latvia	LV	597.1
Lithuania	LT	592.8
Luxembourg	LU	517.4
Netherlands	NL	503.1
Nigeria	NG	575.0
Norway	NO	26.9
Poland	PL	992.3
Portugal	PT	482.1
Qatar	QA	588.7
Romania	RO	580.8
Russia	RU	613.2
Slovak Republic	SK	452.5
Slovenia	SI	425.1
Spain	ES	399.1
Sweden	SE	59.7
United Kingdom	GB	539.7

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[49] Electricity mix information as well as power plant efficiencies, power plant own consumption values and transmission losses are derived from IEA statistics.

Annex D: Inventory Analysis

D.1. Algeria

Algeria is suppling Natural Gas to Europe via pipelines and by LNG carriers. Unfortunately, it was not possible within the defined time schedule to acquire any data regarding production and processing. Hence, the production and processing data are taken from the Exergia study [7], but anyway, displayed in the following. In general, the quantity of flared gas is included in the quantity of Natural Gas for energy use within the Exergia study. The following tables specify the key parameters.

Production and Processing

Table D-1: Energy use (LHV) and gas losses for gas production in Algeria 2012, taken from the Exergia study [7]

Parameter	Value	Unit	DSI
Electricity	201.000	kJ/t	literature
Diesel fuel	0	kJ/t	literature
Crude oil	34.405	kJ/t	literature
Natural gas	730.658	kJ/t	literature
TOTAL	**966.064**	**kJ/t**	**-**
Gas losses	1.80	Vol.%	literature

Table D-2: Energy use (LHV) and gas losses for gas processing in Algeria 2012, taken from the Exergia study [7]

Parameter	Value	Unit	DSI
Electricity	201.000	kJ/t	literature
Diesel fuel	0	kJ/t	literature
Crude oil	0	kJ/t	literature
Natural gas	730.658	kJ/t	literature
TOTAL	**931.658**	**kJ/t**	**-**
Gas losses	0.20	Vol.%	literature
CO_2 vented	1.00	Vol.%	literature

Pipeline Transport

Table D-3: Distance, onshore share of pipeline, energy use (LHV) and gas losses for gas transport from the Algerian gas production and processing fields to liquefaction plants (Arzew/Skikda) [33]

Parameter	Value	Unit	DSI
Distance	542	km	estimated
Onshore share of pipeline	100	%	literature
Electricity	0	J/(J*km)	-
Diesel fuel	0	J/(J*km)	-
Natural gas[50]	3.00E-05	J/(J*km)	literature
Gas losses[51]	8.67E-03	Vol.%	estimated

Purification and Liquefaction

For purification and liquefaction limited primary information were available. However, the Algerian LNG industry has invested heavily recently in new LNG plants and first new plants came on-stream 2015. Derived from the annual reports of IGU [27] and GIIGNL [26] further new plants are expected to become online in the next years. Since the old LNG plants, counting to the first LNG plants worldwide, they may have a quite poor plant efficiency. Considerable improvements are to be expected in the upcoming years. However, in 2015 approx. 56 % of the produced LNG was produced from modern new LNG plants as outlined by Sonatrach [71] (see Table D-4).

Table D-4: Share between new and old LNG technology 2015 in Algeria, primary data from Sonatrach [71] (provided via Enagas)

Technology	Value	Unit	DSI
New plants	56	%	primary
Old plants	44	%	primary

Since new plants have not been built in 2012 were the Exergia study refers to, the following approach was chosen to address the LNG technology improvements.

- The GHG intensity of old plants is estimated with literature (Exergia study [7]).
- The GHG intensity of new plants is calculated by the help of thinkstep's own GaBi LNG model, based on average technical parameters representing new technologies (own calculations [33] and datasets [18]), see Table D-7.

Table D-5: Energy use (LHV) for gas purification and liquefaction (old technology) in Algeria 2012, taken from the Exergia study [7]

Parameter	Value	Unit	DSI
Electricity	89.700	kJ/t	literature
Diesel fuel	0	kJ/t	literature
Natural gas	11.217.917	kJ/t	literature
TOTAL	**11.307.617**	**kJ/t**	**-**

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[50] Defined average energy use value for pipeline transport

[51] Calculated based on Libyan transport gas losses, taken from [8]

Table D-6: Technology mix of liquefaction (new technology) in Algeria 2015, based on GIIGNL [26] and IGU [27]

Technology	Value	Unit	DSI
C3MRsplit	100	%	literature

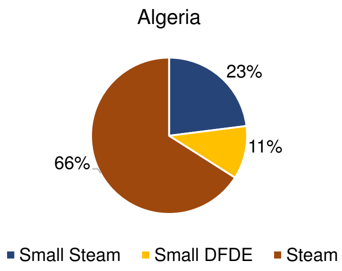
Table D-7: Energy use (LHV) and boil-off gas rate and recovery for gas liquefaction (new technology) in Algeria 2015, taken from GaBi databases [18]

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	185,846	kJ/t	literature	GaBi LNG model	ts
Diesel fuel	0	kJ/t	literature	GaBi LNG model	ts
Natural gas	4,639,455	kJ/t	literature	GaBi LNG model	ts
TOTAL	**4,825,302**	**kJ/t**	**-**	**-**	**-**
Boil-off gas rate	3	wt.%	literature	GaBi LNG model	ts
of which: BOG recovery	99	wt.%	literature	GaBi LNG model	ts
of which: CH$_4$ emissions	1	wt.%	literature	GaBi LNG model	ts

LNG Transport

Table D-8: Sea distances for LNG imports from Algeria [72] and share of LNG carriers by vessel type for LNG imports from Algeria

Country of origin	Destination	Distance [km]	DSI
Algeria (Arzew, Skikda)	EU Total	1 466	literature
Algeria (Arzew, Skikda)	EU North	2 900	literature
Algeria (Arzew, Skikda)	EU Central	3 000	literature
Algeria (Arzew, Skikda)	EU South East	1 540	literature
Algeria (Arzew, Skikda)	EU South West	1 380	literature



The share of the LNG carriers by vessel is assumed based on GIIGNL [21] and IGU [22] in collaboration with ENGIE [73].

D.2. Germany

The German data are based mainly on primary data collected and provided by DBI.

Production and Processing

Table D-9: Energy use (LHV) and gas losses for gas production in Germany 2014, provided by DBI [9]

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	251,229	kJ/t	primary	DE: Electricity grid mix 1kV-60kV	ts
Diesel fuel	2,070	kJ/t	primary	DE: Diesel mix at filling station	ts
Crude oil	0	kJ/t	primary	-	-
Natural gas	1,011,007	kJ/t	primary	-	-
TOTAL	**1,264,306**	**kJ/t**	**-**	**-**	**-**
Gas losses	0.0126	Vol.%	primary	-	-

Table D-10: Energy use (LHV) and gas losses for gas processing in Germany 2015, provided by DBI [9]

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	30,000	kJ/t	primary	DE: Electricity grid mix 1kV-60kV	ts
Diesel fuel	0	kJ/t	primary	DE: Diesel mix at filling station	ts
Crude oil	0	kJ/t	primary	-	-
Natural gas	664,152	kJ/t	primary	-	-
TOTAL	**694,152**	**kJ/t**	**-**	**-**	**-**
Gas losses[52]	0.0158	Vol.%	primary	-	-
CO_2 vented	4.5603	Vol.%	primary	-	-

Pipeline Transport

As outlined previous, “pipeline transport” represents the transport from the country of origin to the border of the EU resp. from an offshore field to the shore of the EU. The Natural Gas pipeline transport in Germany is included in the EU Central transmission and storage data.

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[52] Gas losses were derived from the National Inventory Reports by DBI and refer to 2014

D.3. The Netherlands

For the Netherlands, primary data from Shell has been provided [74]. Since the provided data are basically congruent to the data used by DBI, it was decided to refer to the DBI data for two reasons. These data are:

1) mainly based on public available information, and
2) representing Dutch industry average, i.e., average across all companies.

Production and Processing

Table D-11: Energy use (LHV) and gas losses for gas production in the Netherlands 2015, provided by DBI [9]

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	206,331	kJ/t	primary	NL: Electricity grid mix 1kV-60kV	ts
Diesel fuel	0	kJ/t	primary	-	-
Crude oil	2,144	kJ/t	primary	NL: Crude oil mix	ts
Natural gas	595,848	kJ/t	primary	-	-
TOTAL	**804,323**	**kJ/t**	**-**	**-**	**-**
Gas losses[53]	0.0260	Vol.%	primary	-	-

Table D-12: Energy use (LHV) and gas losses for gas processing in the Netherlands 2015, provided by DBI [9]

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	26,919	kJ/t	primary	NL: Electricity grid mix 1kV-60kV	ts
Diesel fuel	0	kJ/t	primary	-	-
Crude oil	0	kJ/t	primary	-	-
Natural gas	0	kJ/t	primary	-	-
TOTAL	**26,919**	**kJ/t**	**-**	**-**	**-**
Gas losses	0	Vol.%	primary	-	-
CO_2 vented[54]	0.0017	Vol.%	primary	-	-

Pipeline Transport

Transport from Dutch offshore gas fields to the Dutch transmission network.

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[53] Gas losses were derived from the National Inventory Reports by DBI and refer to 2014

[54] CO_2 vented were derived from the National Inventory Reports by DBI and refer to 2014

Table D-13: Distance, onshore share of pipeline, energy use (LHV) and gas losses for gas transport from Dutch offshore gas fields to Dutch the transmission network [33]

Parameter	Value	Unit	DSI
Distance	50	km	estimated
Onshore share of pipeline	0	%	-
Electricity	0	J/(J*km)	-
Diesel fuel	0	J/(J*km)	-
Natural gas[55]	3.00E-05	J/(J*km)	literature
Gas losses	0	Vol.%	-

For offshore pipeline transport, the gas losses are set to zero, since the pipeline is a close system and there is no re-compression taking place. Potential methane emissions of the initial compression unit are included in the processing data.

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[55] Defined average energy use value for pipeline transport

D.4. Nigeria

For Nigeria Shell [74] and ENI [75] provided data for the production and processing. Both data are used. For liquefaction, *thinkstep's* own GaBi LNG model was used to calculate the corresponding GHG intensity.

Production and Processing

Table D-14: Energy use (LHV) and GHG emissions from gas flaring, venting and fugitive emissions for gas production and processing in Nigeria 2015, averaged primary data taken from gas producers Shell [74], and ENI [75].

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	281	kJ/t	primary	NG: Electricity grid mix 1kV-60kV	ts
Diesel fuel	4 782	kJ/t	primary	IN: Diesel mix at filling station (proxy)[56]	ts
Crude oil	0	kJ/t	primary	-	-
Natural gas	2 778 789	kJ/t	primary	-	-
TOTAL	**2 783 852**	**kJ/t**	**-**	**-**	**-**
CH_4 emissions	1.1228	kg/t	primary	-	**-**
CO_2 emissions	69.8887	kg/t	primary	-	-
N_2O emissions	0.0011	kg/t	primary	-	-

Pipeline Transport

Transport from Nigerian offshore gas fields to the LNG plant.

Table D-15: Distance, onshore share of pipeline, energy use (LHV) and gas losses for gas transport from Nigerian gas fields to liquefaction plant (Bonny Island Terminal), [33]

Parameter	Value	Unit	DSI
Distance	200	km	estimated
Onshore share of pipeline	0	%	-
Electricity	0	J/(J*km)	-
Diesel fuel	0	J/(J*km)	-
Natural gas[57]	3.00E-05	J/(J*km)	literature
Gas losses	0	Vol.%	-

For offshore pipeline transport, the gas losses are zero, since the pipeline is a close system and there is no re-compression taking place. Potential methane emissions of the initial compression unit are included in the processing data.

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[56] Since a Nigerian diesel mix dataset was not available

[57] Defined average energy use value for pipeline transport

Purification and Liquefaction

Table D-16: Technology mix of liquefaction in Nigeria 2015, based on GIIGNL [26] and IGU [27]

Technology	Value	Unit	DSI
C3MR	100	%	literature

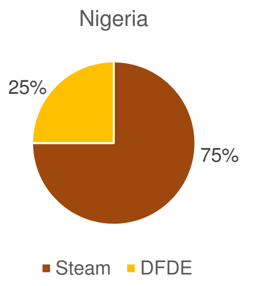
Table D-17: Energy use (LHV) and boil-off gas rate and recovery for gas purification and liquefaction in Nigeria 2015, taken from GaBi databases [18]

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	190 219	kJ/t	literature	GaBi LNG model	ts
Diesel fuel	0	kJ/t	literature	GaBi LNG model	ts
Natural gas	4 927 872	kJ/t	literature	GaBi LNG model	ts
TOTAL	**5 118 091**	**kJ/t**	**-**	**-**	**-**
Boil-off gas rate	3	wt.%	literature	GaBi LNG model	ts
of which: BOG recovery	99	wt.%	literature	GaBi LNG model	ts
of which: CH_4 emissions	1	wt.%	literature	GaBi LNG model	ts

LNG Transport

Table D-18: Sea distances for LNG imports from Nigeria [72], and shares of LNG carriers by vessel type for LNG imports from Nigeria

Country of origin	Destination	Distance [km]	DSI
Nigeria (Bonny)	EU Total	6 952	literature
Nigeria (Bonny)	EU North	8 000	literature
Nigeria (Bonny)	EU Central	8 200	literature
Nigeria (Bonny)	EU South East	-	literature
Nigeria (Bonny)	EU South West	6 910	literature



The share of the LNG carriers by vessel is assumed based on GIIGNL [21] and IGU [22] in collaboration with ENGIE [73] and Shell [74].

D.5. Qatar

The sustainability report from Qatargas [69] and RasGas [70], both communicate carbon intensities for the supply of LNG, from the gas field to the LNG export terminal. None of both sources provides a split into main process steps. However, both provide similar values for the energy consumed. Hence, for the study a value of 7 160 000 kJ/t LNG is chosen. By using the *thinkstep's* own GaBi LNG model [18] to calculate the energy demand for purification and liquefaction themselves, the remaining energy is allocated to production and processing.

Production and Processing

Table D-19: Energy use (LHV) and gas losses for gas production in Qatar 2014, own calculation [33], based on [69] and [70]

Parameter	Value	Unit	DSI
Electricity	0	kJ/t	literature
Diesel fuel	0	kJ/t	literature
Crude oil	0	kJ/t	literature
Natural gas	452 700	kJ/t	literature
TOTAL	**452 700**	**kJ/t**	**-**
Gas losses	0.05	Vol.%	literature

Table D-20: Energy use (LHV) and gas losses for gas processing in Qatar 2014, own calculation [33], based on [69] and [70]

Parameter	Value	Unit	DSI
Electricity	0	kJ/t	literature
Diesel fuel	0	kJ/t	literature
Crude oil	0	kJ/t	literature
Natural gas	1 026 973	kJ/t	literature
TOTAL	**1 026 973**	**kJ/t**	**-**
Gas losses	0.01	Vol.%	literature
CO_2 vented	0.56	Vol.%	literature

Pipeline Transport

Transport from Qatari offshore gas fields to the LNG plant.

Table D-21: Distance, onshore share of pipeline, energy use (LHV) and gas losses for gas transport from Qatar gas fields to Qatar liquefaction plant (Ras Laffan), own calculations [33]

Parameter	Value	Unit	DSI
Distance	80	km	estimated
Onshore share of pipeline	0	%	-
Electricity	0	J/(J*km)	-
Diesel fuel	0	J/(J*km)	-
Natural gas	3.00E-05	J/(J*km)	literature
Gas losses	0	Vol.%	-

For offshore pipeline transport, the gas losses are set to zero, since the pipeline is a close system and there is no re-compression taking place. Potential methane emissions of the initial compression unit are included in the processing data.

Purification and Liquefaction

Table D-22: Technology mix of liquefaction in Qatar 2015, based on GIIGNL [26] and IGU [27]

Technology	Value	Unit	DSI
AP-X	61	%	literature
C3MR	21	%	literature
C3MRsplit	18	%	literature

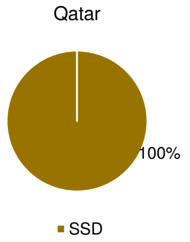
Table D-23: Energy use (LHV) and boil-off gas rate and recovery for gas purification and liquefaction in Qatar 2015, taken from GaBi databases [18]

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	260 225	kJ/t	literature	GaBi LNG model	ts
Diesel fuel	0	kJ/t	literature	GaBi LNG model	ts
Natural gas	5 415 856	kJ/t	literature	GaBi LNG model	ts
TOTAL	**5 676 081**	**kJ/t**	**-**	-	**-**
Boil-off gas rate	3	wt.%	literature	GaBi LNG model	ts
of which: BOG recovery	99	wt.%	estimated	GaBi LNG model	ts
of which: CH_4 emissions	1	wt.%	estimated	GaBi LNG model	ts

LNG Transport

Table D-24: Sea distances for LNG imports from Qatar [72], and share of LNG carriers by vessel type for LNG imports from Qatar

Country of origin	Destination	Distance [km]	DSI
Qatar (Ras Laffan)	EU Total	10 292	literature
Qatar (Ras Laffan)	EU North	11 300	literature
Qatar (Ras Laffan)	EU Central	11 700	literature
Qatar (Ras Laffan)	EU South East	8 200	literature
Qatar (Ras Laffan)	EU South West	9 650	literature



The share of the LNG carriers by vessel is based on GIIGNL [21] and IGU [22]. The shortest route for the maritime LNG transportation from Qatar to Europe is considered, i.e., through the Suez Canal,[58] since Q_{Flex} are able to pass the canal.

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[58] Suez Canal was enlarged in the last years

D.6. Russia

Following information provided by Gazprom, the main Russian logistics portfolio development moved in line with the shifting resource base northwards to Yamal away from the Nadym Pur-Taz region.

These particularly for exports to Europe designated natural gas production fields are considered in this study. These gas fields are comparable to the Bovanenkovo gas field of the Yamal project. Taking into account that natural gas production for exports to Europe are moving towards new designated fields in the North of Russia, Gazprom has built a new resource centre – the Yamal gas production centre.

The energy consumption during gas production in Russia is presented at the “State report on energy-saving and on improvement of energy efficiency in the Russian Federation in 2015” which is publicly available from the Ministry of Energy of Russia [76]. For this report, data on the Natural Gas production, processing and transport from Russia to Europe are provided by Gazprom [77]. The same data basis is used as in the DBI study [9], however the present study is referring to 2015, while the DBI study is referring to 2012, 2013 and 2014.

Production and Processing

Table D-25: Energy use (LHV) and gas losses for gas production and processing in Russia (weighted average) 2015, primary data provided by Gazprom via DBI [77]

Parameter	Value	Unit	DSI	Background dataset / Comment	Dataset provider
Electricity	14 167	kJ/t	primary	RU: Electricity grid mix 1kV-60kV	ts
Diesel fuel	0	kJ/t	primary	-	-
Crude oil	0	kJ/t	primary	-	-
Natural gas	645 782	kJ/t	primary	-	-
TOTAL	**659 949**	**kJ/t**	**-**	**-**	**-**
Gas losses	0.0092	Vol.%	primary	-	-
CO_2 vented[59]	0.0049	Vol.%	primary	-	-

The table presents average figures for the main export production fields according to input data from the main producers (Gazprom dobycha Urengoy, Gazprom dobycha Yamburg, Gazprom dobycha Nadym, etc.).

Pipeline Transport

Designated export pipelines to Europe transport the gas directly via the shortest route to the designated export market. Three export corridors were evaluated for the purpose of assessing the carbon footprint of Russian natural gas as outlined in the following table. Data for each corridor are provided by different subsidiaries within Gazprom (transmission operators).

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[59] CO_2 vented were derived from the National Inventory Reports by DBI and refer to 2014

Table D-26: Distance, onshore share of pipeline and gas losses for Natural Gas imports from Russia 2015, primary data provided by Gazprom via DBI [77]

Country of origin	Destination	Distance [km]	Onshore share of pipeline [%]	Gas losses [Vol.%]	DSI
Russia	EU Border (Ukrainian Corridor)[60]	4,738	100	0.4225	primary
Russia	EU Border (Belarussian Corridor)	3,948	100	0.3591	primary
Russia	EU Border (Northern Corridor)	4,166	71	0.1789	primary

The “Ukrainian Corridor”, consisting of the pipelines “Urengoy – Uzhgorod”, ”Elets – Kremenchug – Krivoy Rog” and “Progress” (GIS Sudzha). The “Belarussian Corridor”, includes the pipeline “Yamal – Europe” (GIS Kondratki). The “Northern Corridor”, representing the gas transport within the corridor from Bovanenkovo till Greifswald, including the “Nord-Stream Pipeline”. Since, the transport via the Northern Corridor includes 1 226 km offshore pipeline, the total gas losses are smaller compared with the other corridors. 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-27: The energy use (LHV) for gas pipeline transport from Russian gas production and processing fields by gas pipeline corridors 2015, primary data provided by Gazprom [77]

Parameter	Ukrainian Corridor [J/(J*km)]	Belarussian Corridor [J/(J*km)]	Northern Corridor [J/(J*km)]	DSI
Electricity	0	0	0	primary
Diesel fuel	0	0	0	primary
Natural gas	2.39E-05	2.39E-05	1.58E-05	primary

The gas pipeline network that runs from the Yamal gas production centre is a new and modern transmission system. These pipeline operate at a high pressure of ~120 bar, which makes a big difference for gas transmission efficiency. Also, a continuous maintenance is conduced and leak detection programs are carried out (LDAR).The northern corridor is very different from the central corridor that currently conveys gas to Europe via a transit route across Ukraine or Belarus. For instance, the pipeline in that corridors operate at a pressure of approx. 55–75 bar [77], while the northern corridor operates at high pressure and consist to a large extend of offshore pipelines with no emissions.

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[60] The distance considers the Russian pipeline (3 578 km) and the Ukrainian one (1 160km). The Gas losses for the Ukrainian part were extrapolated based on Russian values by DBI.

Table D-28: Weighting of Russian Corridors for Natural Gas pipeline transport from Russian gas production and processing fields to European transmission network 2015, primary data provided by Gazprom [77]

Country of origin	Destination	EU Total (+ all EU Regions)	DSI
Russia	Baumgarten, Austria (Ukrainian Corridor)	37.8%	primary
Russia	Mallnow, Germany (Belarussian Corridor)	28.9%	primary
Russia	Greifswald, Germany (Northern Corridor)	33.3%	primary
Sum	-	100.0%	-

Since distribution to the internal Russian market is not part of this study, only transmission pipelines and infrastructure (for gas exports) were taken into account.

As explained by Gazprom documentation, methane is in accordance with Russian legislation not only a greenhouse gas, but also a pollutant (in other countries, including OECD countries, methane is not a pollutant). Therefore, methane emissions monitoring is carried out by legal entities and individual entrepreneurs under the state account of harmful effects on the atmosphere and the pollutant emissions inventory. The results are presented in the annual federal statistical data sheet № 2-TP (air). The completed forms signed by the respective management create the basis for the levying of charges for negative impact on the environment. The inventory of methane emissions is mandatory for all production processes of the oil and gas industry. In addition, the Federal Service for Supervision of Natural Resources proves the information provided and carries out regular spot checks. A violation of these requirements leads to administrative liability. Thereby transparency and completeness of the data collection in terms of methane emissions is guaranteed. Methane emissions data from all industries are presented at the website of Russian statistic service [77].

D.7. United Kingdom (UK)

For the UK, primary data has been provided by Shell [74]. Since the provided data are similar to the data used by the Exergia study [7], it was decided to refer to these values for two reasons. These data are:

1) mainly based on public available information, and
2) representing UK industry average, i.e., average across all companies.

Production and Processing

Table D-29: Energy use (LHV) and gas losses for gas production in United Kingdom 2012, taken from the Exergia Study [7], but crosschecked with primary data

Parameter	Value	Unit	DSI
Electricity	0	kJ/t	literature
Diesel fuel	341 311	kJ/t	literature
Crude oil	0	kJ/t	literature
Natural gas	1 204 686	kJ/t	literature
TOTAL	**1 545 996**	**kJ/t**	**-**
Gas losses	0.5510	Vol.%	literature

Table D-30: Energy use (LHV) and gas losses for gas processing in United Kingdom 2012, taken from the Exergia Study [7], but crosschecked with primary data

Parameter	Value	Unit	DSI
Electricity	27 570	kJ/t	literature
Diesel fuel	0	kJ/t	literature
Crude oil	0	kJ/t	literature
Natural gas	530 687	kJ/t	literature
TOTAL	**558 257**	**kJ/t**	**-**
Gas losses	0.0100	Vol.%	literature
CO_2 vented	0.0520	Vol.%	literature

Pipeline Transport

Transport from UK offshore gas fields to the shore of the EU, either EU Central or EU North.

Table D-31: Distance, onshore share of pipeline, energy use (LHV) and gas losses for gas pipeline transport from United Kingdom offshore gas production and processing fields to corresponding transmission network.

Parameter	Value	Unit	DSI
Distance to EU Total	600	km	estimated
Distance to EU North	600	km	estimated
Distance to EU Central	230	km	estimated
Onshore share of pipeline	0	%	-
Electricity	6.89E-06	J/(J*km)	estimated
Diesel fuel	6.28E-07	J/(J*km)	estimated
Natural gas	1.71E-07	J/(J*km)	estimated
Gas losses	0	Vol.%	-

For offshore pipeline transport, the gas losses are zero, since the pipeline is a close system and there is no re-compression taking place. Potential methane emissions of the initial compression unit are included in the processing data.

D.8. Inventory Results

Table D-32 contains the Well-to-Tank inventory of the eight individual emissions with highest contribution to the GWP_{100} (AR4). Except for the three substances listed at the bottom of the table, the supply of LNG usually leads to larger emissions than the supply of CNG. The inventory of the Tank-to-X emissions is indicated in Table 6-2 to Table 6-4.

Table D-32: Well-to-Tank - Inventory Results by individual emissions for EU Total CNG/LNG, in tank

	CNG	LNG
Substance	**Mass [g/MJ]**	**Mass [g/MJ]**
Carbon dioxide	9.03E+00	1.44E+01
Methane	1.37E-01	2.17E-01
Nitrous oxide	2.49E-04	3.75E-04
Tetrafluoromethane	3.57E-08	3.72E-08
R 116 (hexafluoroethane)	4.02E-09	4.71E-09
R 23 (trifluoromethane)	2.99E-09	1.62E-10
R 114 (dichlorotetrafluoroethane)	1.08E-09	5.96E-10
R 245fa	7.72E-09	4.19E-10

Annex E: Real Life Emissions vs. NEDC and WLTP Emissions

E.1. Real Life Emissions vs. NEDC and WLTP Emissions of Passenger Vehicles

This study assesses the fuel consumption and the emissions of passenger vehicles within the conditions set by the New European Driving Cycle (NEDC) (see section 6.2.2). This driving cycle comprises multiple phases with different constant speeds and linear transitions reaching the maximum speed of 120 km/h for a few seconds. Since this does not reflect common driving characteristics today, usually NEDC results do not reflect well the real driving emissions. Nevertheless, it is the best available basis of comparison for vehicles with different powertrain technologies since related standardised data is widely available.

The Worldwide Harmonised Light Vehicles Test Procedure (WLTP) with its developed Worldwide Harmonised Light-Duty Vehicles Test Cycle (WLTC) for passenger vehicles and light commercial vans will be introduced as new legally binding test procedure within the EU expectedly starting in 2017. The results on fuel consumption and emissions derived based on the WLTC are expected to be more realistic, since the cycles are more dynamic than the NEDC. However, due to a maximum vehicle speed of about 131 km/h and the absence of any hill climbing, the emissions caused in real may still be higher than the ones determined by the WLTP.

For these reasons, real fuel consumption and the related emissions are above those indicated by the NEDC and probably also above those of the WLTP. The ADAC assessed the differences between real driving emissions and NECD emissions for different powertrains and determined a gap of 8.7 % for CNG vehicles, whereas the gap was found to be 10.2 % for petrol vehicles and 14.4 % for diesel vehicles. For hybrid and electric vehicles, the real driving emissions were determined to be more than 20 % and more than 40 % above the NEDC values, see NGVA [78].

E.2. Real Life Emissions of Heavy-Duty Vehicles

The test conditions for HDV lead to more realistic fuel consumption and emission results than the NEDC used for passenger vehicles. The Euro VI emission regulation uses the world harmonised steady-state test cycle (with hot start) and the world harmonised transient test cycle (both with hot and cold start), which reflects real driving characteristics significantly better than the NEDC assessment, and requires individual emission limits for both test modes.

Within the Equilibre project, several HDV with Natural Gas SI engine were tested in real life use with a focus on the methane emissions. The results indicated that the Euro VI emission limit of 0.5 g CH_4/kWh was reached by all vehicles and in all modes of driving [51].

Annex F: Collected Data used in the TtW Assessment

F.1. Passenger Vehicles

The data in Table F-1 was provided from different European manufacturers of passenger vehicles using Natural Gas engines assuming the G20 standard for CNG (Annex C). The values in brackets reflecting the CO_2 emissions from diesel and petrol vehicles are not used for the emission modelling within the assessment. Instead, the reported petrol and diesel consumption and the related energy consumption determines the overall WtW emissions according to FQD [1].

All Natural Gas Vehicles listed in Table F-1 show lower CO_2 emissions than the comparable petrol vehicles. Apart from two exceptions, their emissions are also below those of the comparable diesel vehicles. In average, the CO_2 emissions of these Natural Gas Vehicles are 18 % below those of a petrol vehicle (-27 % to -11 %) and 3 % below those of a diesel vehicle (-10 % to +8 %).

This assessment compares only vehicles from the C segment (see section 6.2.2), for which the mean of these vehicles has been used for the modelling of each powertrain technology. No further weighting has been applied.

Table F-1: Data provided by different European manufacturers of passenger vehicles using Natural Gas [45], [46], [47] [48]

Manu-facturer	Model	Seg-ment	Power-train	Fuel consumption (kg/100 km, l/100 km)	CO_2 emissions (g CO_2/km)	CH_4 emissions (mg CH_4/km)
Fiat	Panda	A	CNG	3.1	85	30
Fiat	Panda	A	Petrol	4.6	(105)	-
Fiat	Panda	A	Diesel	3.6	(94)	-
Fiat	500 L	C	CNG	3.9	105	40
Fiat	500 L	C	Petrol	6.1	(143)	-
Fiat	500 L	C	Diesel	4.1	(107)	-
VW	eco-up! (50 kW)	A	CNG	2.9	82	28
VW	up! (44 kW)	A	Petrol	4.1	(96)	-
VW	Golf 1.4 TGI DSG (81 kW)	C	CNG	3.4	92	34
VW	Golf 1.4 TSI DSG (92 kW)	C	Petrol	5.0	(116)	-
VW	Golf 1.6 TDI DSG (81 kW)	C	Diesel	3.9	(102)	-
VW	Caddy 1.4 TGI (81 kW)	M	CNG	4.1	111	63
VW	Caddy 1.4 TSI (92 kW)	M	Petrol	5.9	(135)	-
VW	Caddy 2.0 TDI (75 kW)	M	Diesel	4.6	(119)	-
Volvo	V60	D	CNG	-	125	75
Volvo	V60	D	Petrol	6.7	(152)	-
Volvo	V60	D	Diesel	4.4	(116)	-

Manu-facturer	Model	Seg-ment	Power-train	Fuel consumption (kg/100 km, l/100 km)	CO_2 emissions (g CO_2/km)	CH_4 emissions (mg CH_4/km)
I	I	C	CNG	4.4	118	52[61]
I	I	C	Petrol	5.8	(133)	-
I	I	C	Diesel	4.4	(113)	-

F.2. Heavy-Duty Vehicles

Data on vehicle consumptions are results from simulations and calculations based on engine dynamometer tests as well as on real-life measurements of the vehicle performance. The assessments were done considering a 40 t tractor and trailer combination in long-haul use with 75 % payload. Daimler, IVECO, Scania, Volvo and Westport each delivered results for one representative SI and/or HPDI gas engine, as well as results for comparable diesel engines. The reduction potentials in Table F-2 is the average relative reduction (in %) over the data sets provided by the five OEMs.

Table F-2: Average CO_2 reduction of Natural Gas HDVs compared with diesel HDVs in long haul use [54], [55], [56], [47], [57]

Natural Gas HDV	CO_2 improvement compared with comparable diesel baseline HDV
Average (HDV with SI engine)	- 12.0 %
Average (HDV with HPDI engine)	- 20.4 %

The data in Table F-2 were used to derive the parameters for the CO_2 emission modelling of the heavy-duty vehicles, which are displayed in Table 6-3 together with more details, e.g., on fuel and energy consumption as well as other emission quantities.

F.3. Ships

The emissions from different ships were modelled based on primary data as well as literature data considering the fuel properties as summarised in Annex C.

Table F-3: CO_2 emissions, fuel consumption and efficiency (assuming complete combustion) of ships using different fuels at 85 % load, [33], [38], [40], Wärtsilä [39].

Maritime ships using	g CO_2/kWh	g CH_4/kWh	MJ/kWh	Efficiency
HFO	607	n/a	7.5	47.8 %
MDO	577	n/a	7.9	45.7 %
LNG+MDO (4-stroke)	427	3.1	7.9	45.7 %
LNG+MDO (2-stroke, high pressure injection)	427	0.3	7.7	46.6 %

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[61] Value indicates total hydrocarbon (THC) emissions. Worst case estimation: THC = CH_4 emissions

Annex G: Comparative Screening with Electric Vehicles

Unquestionably, battery electric vehicles (BEV) will play a key role in the future GHG reductions of the transport sector, especially for passenger mobility. These vehicles are equipped with a high voltage battery that is usually charged with electricity from the electric grid, and an electric motor converts the electric energy into propulsion. Since the powertrain of a BEV is significantly different from powertrains with internal combustion engines running on petrol, diesel, or Natural Gas, the scope of a Well-to-Wheel analysis is insufficient for including BEV in the assessment. Instead, the complete life cycle of the vehicle, including its production and end-of-life, needs to be integrated into the analysis, since especially the production of the vehicle battery causes high GHG emissions. In the following, a comparative screening analysis is conducted for petrol, diesel, Natural Gas Vehicles and BEV using approximate values of the different powertrain technologies in the Volkswagen Golf, as an illustration of what the related GHG emission impacts might be and the different origins of the emissions.

It is important to keep in mind that the assessment conducted here is completely independent from the GHG emission study in this report and that the figures determined in the following are approximate values within a screening analysis. Nevertheless, the assessment provides a sound estimation of the life cycle emissions from different powertrains, making possible a parallel assessment of Natural Gas vehicles and BEV.

Volkswagen has assessed life cycle emission data for many years and published reports on the results for numerous models with different powertrain technologies. The comparison of the e-Golf (providing a range of 190 km in the NEDC, status Nov. 2016) with the alternatives using petrol and diesel (Golf VII 1.2 TSI BMT and Golf VII 1.6 TDI BMT) serves as the starting point for the following considerations [79]. The report mentioned does not include a CNG powertrain. Such a comparison, however, exists for a larger vehicle, the VW Passat (Passat 1.4 TSI BMT and Passat 1.4 TSI EcoFuel) [80].

The information from the sources mentioned above indicates that the production and the use phase are of importance for the GHG emissions from the vehicles with all powertrains. The end-of-life emissions of the vehicles with internal combustion engine can be neglected, whereas those of a BEV need to be taken into account. The production of a CNG vehicle causes GHG emissions that can be estimated to be about 280 kg CO_2-eq above those of a comparable petrol vehicle (data from VW Passat 1.4 TSI EcoFuel vs. VW Passat 1.4 TSI BMT). The GHG emissions from the BEV production are higher than the emissions from the production of the other vehicles.

The fuel consumption of the petrol, diesel and Natural Gas Vehicle have been chosen based on the collected primary data (see Annex F) and the electricity consumption of the e-Golf set according to Volkswagen sources [79]. The emissions for the CNG Golf also consider the reported CH_4 emissions and the approximated N_2O emissions (see section 6.2.2). For the electricity supply, the emission factor for the European electricity mix of 465 g CO_2-eq/kWh (voltage < 1 kV) reported in the GaBi databases 2016 [13] was considered. The emissions caused during the CNG supply were related to the results of the Well-to-Tank analysis of this study. For the petrol and diesel powertrain, the GHG emissions were determined by using the Well-to-Wheel values provided in the documents related to the Fuel Quality Directive (FQD), Council Directive (EU) 2015/652 [5]. The following table summarises the life cycle GHG emissions that are caused by the assessed vehicles with different powertrains for a life cycle mileage of 150 000 km.

Table G-1: **Estimated GHG emissions from production, use phase and EoL for passenger vehicles with different powertrains based on estimates derived from [79], [80]**

	Petrol	Diesel	BEV	CNG
GHG emissions from vehicle production (kg CO_2-eq)	3 850	5 100	9 600	4 150
Fuel consumption (l/100 km, kWh/100 km, kg/100 km)	5.0	3.9	12.7	3.4
GHG emissions from vehicle use (kg CO_2-eq)	22 520	19 950	8 860	17 160
GHG emissions from EoL of vehicles (kg CO_2-eq)	n/a	n/a	600	n/a
Total GHG emissions (kg CO_2-eq)	26 370	25 050	19 060	21 310

The petrol and diesel vehicles cause the highest GHG life cycle emissions. Whereas the emissions from using the BEV are smaller than the emissions from using the vehicles with the internal combustion engine, the emissions related to the production and end-of-life of a BEV are above those of the alternative vehicles. For the BEV, the figures in the previous table should be regarded as a best case scenario, as several important aspects need to be noted. The first is the still open question of whether the expected life cycle mileage of a BEV can be assumed to be similar to that of vehicles with internal combustion engine considering the limited range and lifetime of its battery. It still has to be proven that the annual mileage of 15 000 km for a period of 10 years, which is commonly assumed for passenger vehicles with internal combustion engine, is realistic for an average BEV. The second aspect is the fact that vehicle manufacturers are currently installing batteries with increased capacity into new BEV models to reduce the disadvantage of a limited range. This, however, may increase the GHG emissions from the vehicle production which may reduce the advantage of BEV with respect to the life cycle GHG emissions. Other, very important aspects are related to the origin of the electricity used. In this example, the current European average electricity consumption mix is assessed, which is related to rather low GHG emissions, due to the high share of nuclear power plants (almost 30 %)[62]. If this share of nuclear electricity production was to be substituted by the remaining currently existing electricity mix in Europe, the GHG emissions caused by electricity production would increase accordingly. Further, the future use of BEV (and superchargers that can merely be integrated into Smart Grid solutions) will increase the overall and the peak electricity demand within the European Union. This may increase the carbon footprint of the European electricity production and may lead to higher emissions related to the use of BEV, if carbon or lignite power plants have to increase their power output. If only CCGT power plants or green energy with high capacity storage systems were used for this extra electricity, this negative effect could be avoided.

In a second step, the cost related to the life cycle of the four different vehicle types should be evaluated. If the cost related to the vehicles is determined by using real market prices, which include VAT in the purchase price and excise taxes in the prices paid at the refuelling station, the results are biased by the current taxation regulations. In order to provide a more societal perspective on the cost situation, the influence of the current taxes needs to be removed from the calculation.

For this reason, the purchase price was taken from the current price lists (see [81], [82]) for the different vehicles (Golf TSI BMT DSG 92 kW, Golf TDI BMT DSG 81 kW, Golf TGI BlueMotion DSG

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[62] Based on IEA statistics: Nuclear: 27 %, Lignite: 11 %, Hard Coal: 16 %, Natural Gas: 18 %, Oil: 2 %, Renewables: 26 % [15]

81 kW, and e-Golf[63], all with 4 doors – see also Annex F) and 19 % VAT was deducted. Eurostat provides fuel and electricity prices both including and excluding taxes (see Eurostat [83]). The price per energy excluding taxes is very similar for petrol and diesel. For CNG, European price statistics excluding taxes are not readily available. However, this assessment assumes that the Natural Gas price per energy is similar to that of diesel and petrol, if taxes are not taken into consideration. This is a conservative estimation, since the common Natural Gas price on the commodity market is usually below that of crude oil. Besides the commodity price, the electricity that is required for the compression of the CNG is taken into account. The costs related to supply infrastructure, e.g. refuelling or charging stations, are not covered in this assessment. Further, maintenance costs and running expenses, such as motor vehicle taxes and insurance costs, are neglected for this assessment as well as potential residual value of the vehicles or costs for disposal[64]. The following table summarises the determined cost estimations.

Table G-2: Estimated costs related to passenger vehicles with different powertrains (excl. taxes)

	Petrol	Diesel	BEV	CNG
Purchase cost (without VAT)	21 470 €	22 690 €	29 330 €	23 570 €
Fuel prices without excise taxes (€/l, €/kWh, €/kg)	0.44	0.44	0.14	0.65
Fuel prices without excise taxes (€/MJ)	0.014	0.012	0.038	0.014
Fuel cost	3 300 €	2 570 €	2 570 €	3 330 €
Residual value / Cost for disposal	-	-	-	-
Total cost	24 770 €	25 260 €	31 900 €	26 900 €

The comparative screening shows that the determined costs related to a CNG vehicle are above those of the petrol and diesel vehicle, but below those of a BEV. Combining the previous analysis of the life cycle GHG emissions and the cost analysis shows that the cost of GHG emission reductions is determined to be 1.11 €/kg CO_2-eq for the BEV compared with diesel and 0.44 €/kg CO_2-eq for the Natural Gas Vehicle.

Of course, the purchase price of a BEV is expected to decrease considerably in the future, especially due to the economies of scale from the mass production of vehicle batteries. On the other hand, increasing expectation for higher ranges of BEVs and potential cost increases may neutralise this effect. Nevertheless, the lower (CNG vehicle) resp. not existent (BEV) expenses for exhaust gas after-treatment will decrease the cost difference of both, the CNG vehicle and BEV with respect to diesel and petrol vehicles in the future.

It is important to note once again that this comparative screening analysis is completely independent from the GHG emission analysis of this report. It uses numerous approximations and examples and its results are only valid based on these assumptions. The analysis of other vehicles with the same powertrains may lead to different results. However, this approximate screening analysis demonstrates various important aspects. Firstly, the assessment of the vehicle production and end-of-life is important and shall not be neglected. Secondly, the assessment of GHG emission reductions and of the related costs needs to go hand in hand, in order to pursue the economically most viable approach of emission reductions.

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[63] Note that a similar gross price difference of about 9 000 € (incl. VAT) between BEV and diesel vehicle applies to the vehicles of other vehicle manufacturers (compare [76] [77] [75] [74]), so the chosen vehicle prices seem representative.

[64] This is considered to be an interesting parameter with high uncertainty. If the battery needs to be replaced after the use period and/or costs occur for the battery disposal, the value of the BEV may be close to zero. If, in contrast, the vehicle is fully operative, it may have a considerable residual value, especially for areas with strict local emission regulations.

Annex H: Sensitivity Analysis

H.1. Sensitivity Analysis of Passenger Vehicles

The following graphs display the overall effect of the respective GHG result for a parameter variation of ± 50 %.

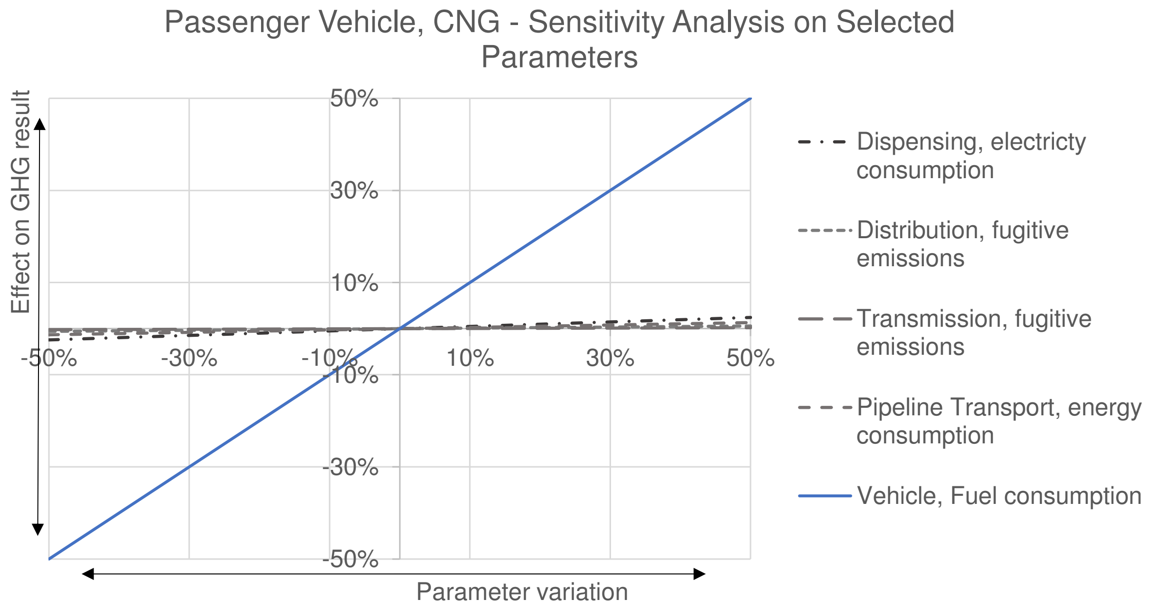

Figure H-1: Sensitivity analysis on various parameters from the Well-to-Wheel GHG model of Passenger Vehicle CNG [33]

Findings: Passenger Vehicles

- **Fuel use – Vehicle fuel consumption**
    - Effect: very high impact on Well-to-Wheel GHG result → 50 % per 50 % parameter variation). Both, GHG emissions of use phase and upstream GHG emissions are directly linked to fuel consumption (linear relation).
- **Dispensing – Electricity consumption**
    - Effect: low impact on Well-to-Wheel GHG result. Below 5 % per 50 % parameter variation → 2.42 %
- **Dispensing – Gas losses**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.09 % (not displayed in figure above)
- **Distribution – Gas losses**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.60 %
- **Transmission – Methane losses**

  - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.22 %
- **Transmission – Natural Gas consumption**
  - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.21 % (not displayed in figure above)
- **Pipeline transport – Energy consumption**
  - Effect: low impact on Well-to-Wheel GHG result. Below 5 % per 50 % parameter variation → 1.32 %
- **Pipeline transport – Methane losses**
  - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.35 % (not displayed in figure above)

H.2. Sensitivity Analysis of Heavy-Duty Vehicles (HDV)

The following graphs display the overall effect of the respective GHG result for a parameter variation of ± 50 %.

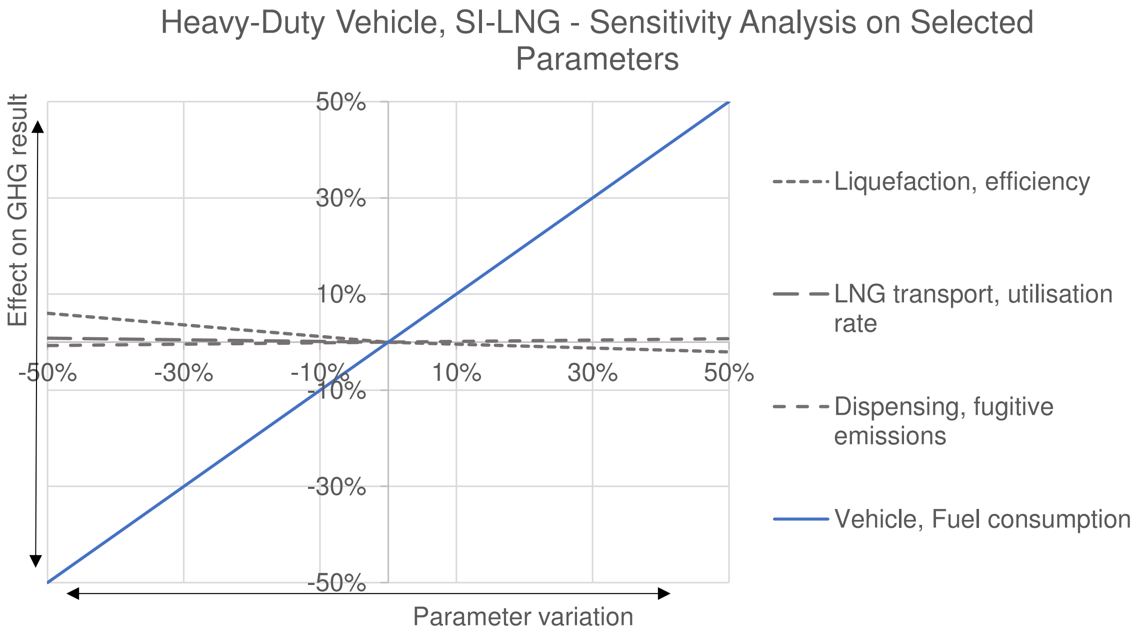

Figure H-2: Sensitivity analysis on various parameters from the Well-to-Wheel GHG model of Heavy-Duty Vehicle SI-LNG in long haul use [33]

Findings Heavy-Duty Vehicle SI-LNG:

- **Fuel use – Vehicle fuel consumption**
  - Effect: very high impact on Well-to-Wheel GHG result → 50 % per 50 % parameter variation). Both, GHG emissions of use phase and upstream GHG emissions are directly linked to fuel consumption.
- **Dispensing – Electricity consumption**
  - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.10 % (not displayed in figure above)
- **Dispensing – Gas losses (from LNG terminal to tank)**

    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.72 %
- **LNG transport – Utilisation rate**
    - Effect: very low impact on Well-to-Wheel GHG result. Below 1 % per 50 % parameter variation → 0.78 %. Since the utilisation rate is defined as 100 %, a sensitivity check only for values below 100 % were performed.
- **Liquefaction – Efficiency**
    - Non-linear relation between parameter variation and GHG results – higher effect for decreasing efficiencies, lower effect for increasing efficiencies.
    - Effect for decreasing efficiencies: medium impact on Well-to-Wheel GHG result. Below +10 % per -50 % parameter variation → +6.00 %
    - Effect for increasing efficiencies: low impact on Well-to-Wheel GHG result. Below -5 % per +50 % parameter variation → -2.01 %

Annex I: Critical Reviewer Statement

Critical Review Statement of the report “Greenhouse Gas Intensity of Natural Gas”

5th of May 2017

ISO 14 040 & ISO 14 044
ISO/TS 14071

SOL 16-043.1

5th of May 2017

for

NGVA Europe

1 Introduction

thinkstep has prepared a report "Greenhouse Gas Intensity of Natural Gas" dated 5th of May 2017. The goal of the report was to provide "high quality, reliable, and up-to-date industry-based life cycle data on Natural Gas to inform the public and to support dialogue with external stakeholders and policy makers".

This study states that ISO 14040:2006 and ISO 14044:2006 requirements have been applied in order to get GHG results. NGVA Europe has requested a Critical review (CR) panel to make a critical review of the third party report.

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 be integrated as a whole within the final third party report of NGVA Europe and thinkstep.

2 Composition of the panel

The CR panel consisted of the following members, independent from the overall study content, and external to NGVA Europe, thinkstep and the related business interests:

- Dipl. Eng. Philippe Osset, Solinnen, LCA expert. Philippe has acted as the chair of the Critical Review panel,
- Pr. Dr-Eng Stefan Hausberger, head of the research area "Emissions" at the Institute for Internal Combustion Engines and Thermodynamic at the University of Technology Graz
- M. Jean-Arnold Vinois, Honorary Director, European Commission and Energy Adviser to the Jacques Delors Institute

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 worked in order to check if:

- the methods used to carry out the LCA 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 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 use. Additionally, the present final critical review report *provides the future reader* of the LCA report and user of the LCI with information that will help understanding the report and the LCI data they use.

The Critical Review was performed after completion of the study. The analysis and the verification of individual datasets are outside the scope of the review. A plausibility check of the software model was performed.

The CR work has started in February 2017 and ended up in April 2017. During this period, different oral and written exchanges have been held between the CR panel, NGVA Europe and thinkstep, including clarification exchanges regarding the CR comments, and the production of one set of detailed comments by the CR panel, and one new version of the report by thinkstep. Nevertheless, no new LCI 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.

The CR set of 195 comments covered the following points:

- General (49 key comments),
- Methodology (51 key comments),
- Technical and Data (58 key comments),
- Other miscellaneous comment (37 comments).

thinkstep has taken into account most of the comments and modified and improved their report. A significant work has been done by NGVA Europe and thinkstep to provide a final report integrating answers to the CR points, and the final result has improved as compared to the first version, towards the requirement of the reference standards.

The present 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.

The present CR report is delivered to NGVA Europe. 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 report from NGVA Europe and no other report, extract or publication which may eventually been done. The CR panel conclusions have been set given the current state of the art and the information which has been received. These CR panel conclusions could have been different in a different context.

4 Conclusions of the review – Critical Review Statement

As a whole, the panel considers that the requirements of the reference standards have been applied.

The final report answers the goal which has been set up, within the scope of the limitations that are mentioned in the 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 vehicles and ships as well as gas fired power plants vis-à-vis non fossil fuels resources, such as renewables sources of energy (with the notable exception of biogas) and nuclear energy to produce electricity, or to power electric vehicles. The reader may find in annex of the LCA report some indications, but these may not be considered as responding to the strict criteria of the reference standards to allow comparative assertions.

Additionally, it must be clearly understood that GhG emissions only have been assessed in the report, and therefore that no conclusion should be taken regarding the overall environmental impacts (or benefits) associated to the studied life cycles – reduction of GhG does not imply reduction of other impacts, sometimes a reduction of GhG 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 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 of Chapter 6) is recommended.

5.1 Consistency of methods used with ISO 14044 requirements

The final structure of the report reflects the ISO standard requirements. The methods that have been selected for reference calculations are clearly presented. As a reminder for readers, and as written in the report, the current study was not a comparative assertion.

As mentioned in the report, ISO 14067, which is a standard developed to calculate carbon footprints in line with ISO 14044 requirements – meaning that 1) all requirements of 14044 have been taken into account in 14067 and that 2) additional requirements are provided in ISO 14067 to complement ISO 14044, has not been used as reference since this standard is under revision. Further revisions of the report should consider the relevance to take the future additional requirements of ISO 14067 when its revision will be done.

5.2 Scientific and technical validity

References to previous similar studies, like Exergia, JEC-WtW, Ricardo are numerous throughout the report and may sometimes lead to some confusion and questions regarding the consistency of all data used.

The case of Exergia is particularly relevant in this respect as, on the one hand, many results of this Exergia study are rejected and, on the other hand, the data of Exergia are taken into account by default.

It is appreciated that the authors of the report have been as clear as possible on the way they used the data from Exergia and from the other sources.

5.3 Appropriateness of data used in relation to the goal of the study

It is important to note that many data used in this report have been collected from the companies belonging to NGVA Europe, who is sponsoring this study. In some cases, data are coming from a single company, or from a limited number of companies which are in competition, so that averages are used.

In other words, as no specific on-site verification has been performed (which is out of the scope of a LCA critical review) nor external scrutiny has been done, these data had to be accepted while they are not necessarily reflecting the latest reality. One such case may be the data related to the huge Russian gas production and transport, representing about one third of EU gas consumption, where only Gazprom can be the provider.

Whatsoever, the use of these data represents an improvement as compared to existing LCA data related to GHG emissions of the studied life cycle.

The characterization factors of the 4th report of IPCC (AR4) have be used as reference case, when AR5 factors are available. A sensitivity analysis shows a negligible (less than 1%) difference for GWP between both calculations.

5.4 Validity of interpretations in the scope of the limitations of the study

Chapter 8, including the related limitations, describes accurately the findings and the context against which they have to be understood and used.

It is also recognizing that other studies are needed to give a full and accurate picture of the relative GHG advantages of the increasing variety of vehicles on the market, such as BEV, in a very dynamic and innovative environment.

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.

The specific energy consumption values of HDV in MJ/km for CNG from the 5 OEM in comparison to diesel are based on similar methodologies, and remain confidential so far. An update of these HDV CNG engine technology values, and their public release, together with new LCA calculations, will be appropriate when HPDI CNG engines enter the market.

6 Appendices

The detailed critical review tables exchanged during the work are the appendices of the present CR report. They recap the detailed exchanges between the CR panel and NGVA Europe.