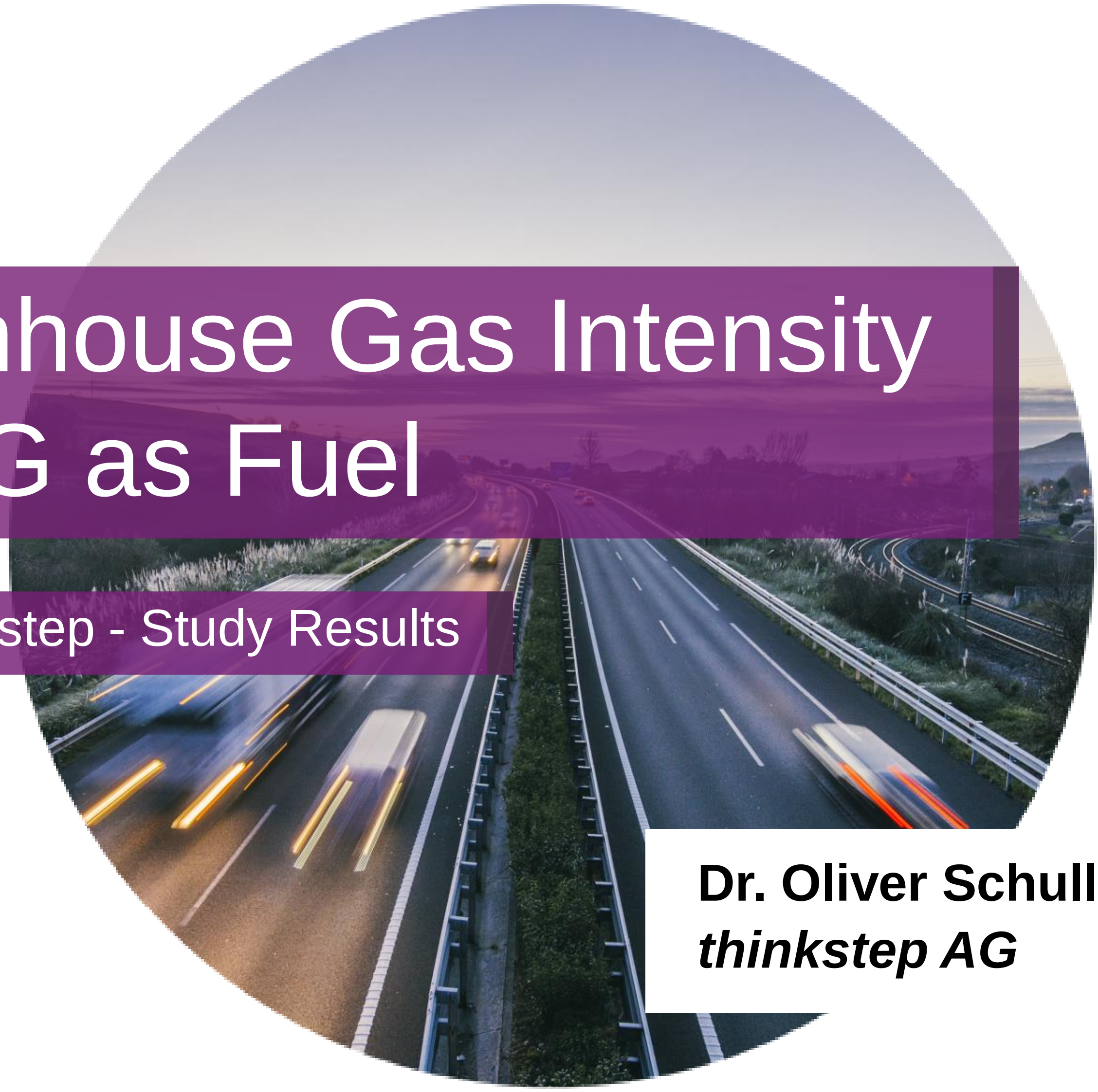


Greenhouse Gas Intensity of LNG as Fuel

NGVA-thinkstep - Study Results

Dr. Oliver Schuller
thinkstep AG

Royal Netherlands Society of Engineers, Oil & Gas Technology, December 2017

Agenda

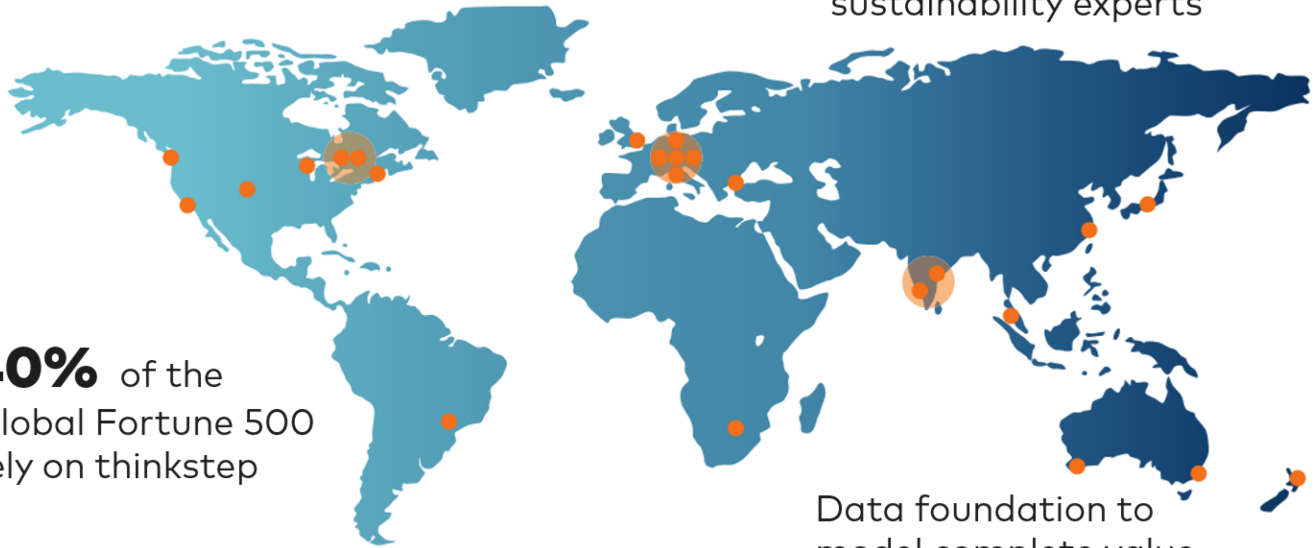
1. About thinkstep
2. Motivation
3. Scope and Methodology
4. Results
5. Lessons Learned and Key Findings

About thinkstep

Sustainability Consulting, Software and Data

4.000+ Customers worldwide

250+ International sustainability experts



40% of the Global Fortune 500 rely on thinkstep

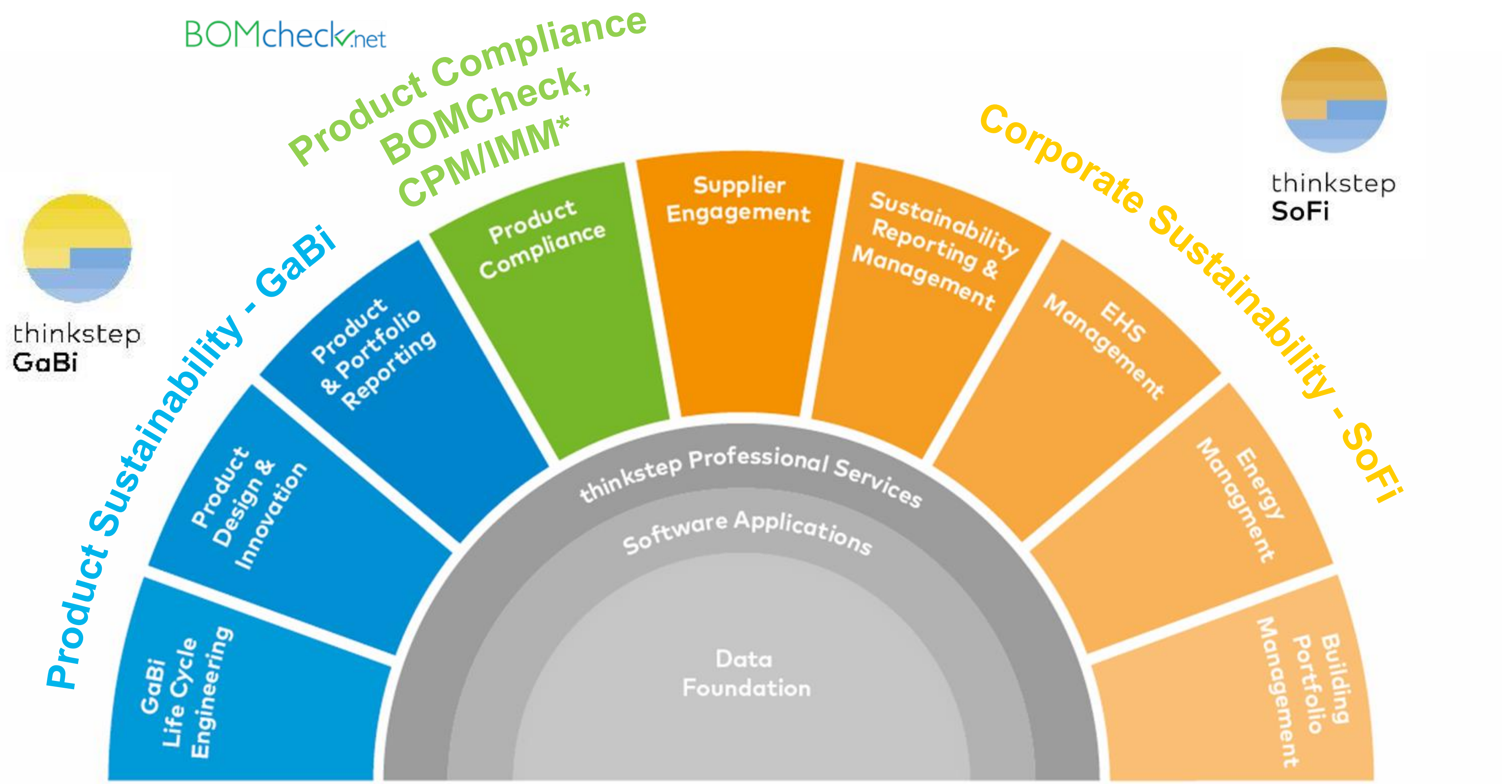
20.000+ Users of our software solutions

Data foundation to model complete value chains and products in **20+** sectors

thinkstep enables organizations worldwide to succeed sustainably. Our industry-leading software, data and consulting services help businesses drive operational excellence, product innovation, brand value and regulatory compliance.

About thinkstep

Competencies



* BOM = Bill of Material; CPM = Compliance Process Manager; IMM = Integrated Material Management

About thinkstep

Professional Consulting Services

Strategic Planning

Sustainability Strategy Development

- thinkstepGO™ Workshop
- Materiality Assessment
- Benchmarking
- Vision, Focus areas and target setting
- Governance and policies
- Business Value of Sustainability

Sustainable Solution Steering™

Performance Improvement

- Life Cycle Assessment (LCA)
- Product Environmental Footprinting (PEF)
- Corporate Environmental Footprinting
- Product Portfolio Improvement (Eco-Design)
- Energy Management (EN 16247, ISO 50001)
- Environmental Management (ISO 14001, EMAS)
- Sustainable Supply Chain Management (SSCM)

Communication

- Environmental Product Declaration (EPD)
- Environmental Health Declaration (HPD)
- GRI-Reporting
- CDP-Reporting
- Green Building Certification (DGNB, LEED, BREEAM)
- Stakeholder Engagement

2,000 Customers

thinkstep

Motivation

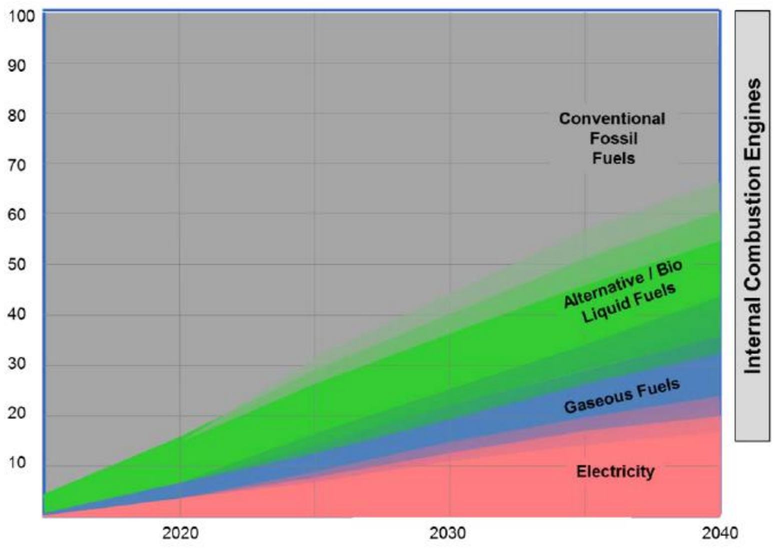
Motivation

Roadmap of Road Transport

- Road transport system is asked to move from the **current oil derived monopoly** towards a more complex system composed by different propulsion systems, based on both Internal Combustion Engines and Electrified powertrains.

- Those systems should rely on **different** forms of **energies**, produced with very different processes, incl. primary energy sources.

- When referring to **decarbonisation**, it is fundamental to consider the entire fuel chain (from extraction to its end usage, meaning from **Well-to-Wheel**) to have a proper comparison among different solutions.

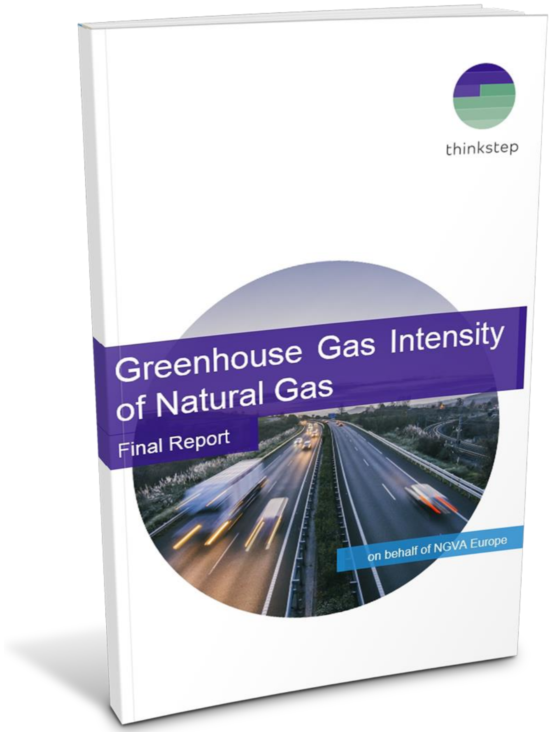


Source: Roadmap of road transport energy towards 2040, ERTRAC, June 2016

In this way **technology neutrality** is guaranteed.

Motivation

Why a new study?



- The gas industry is increasingly challenged in the EU on how the **greenhouse gas intensity (GHG)** of NG compares with other fuels.

- This topic will be a key point under the review of the Fuel Quality Directive which will, inter alia, set the default values of fuels used in transport.

- **Accurate, updated** and **reliable** GHG inventory data is key to understand the current benefits, as well as the future potential for supporting Europe's activities in developing a strategic vision for **a real sustainable mobility**.

NGVA-thinkstep GHG Intensity study

thinkstep

Partners

- NGVA Europe, supported through a partnership of 27 industry organisations, commissioned an **industry-wide analysis of the supply and use of natural gas in Europe**. More than 50 companies provided data.

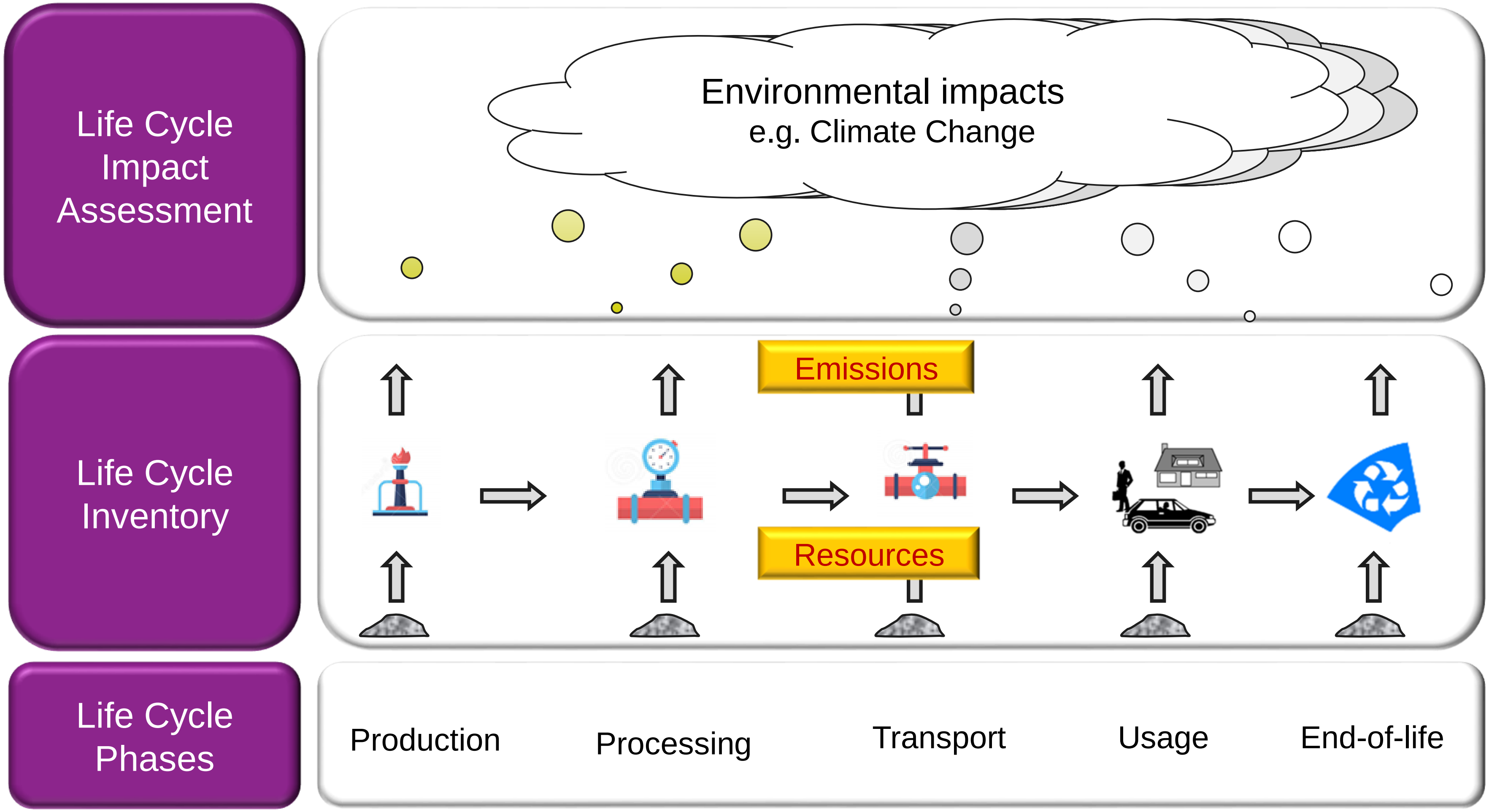
- The study covers road vehicles (Well-to-Wheel), maritime vessels (Well-to-Wake) and power generation (Well-to-Grid).

- This is a deep and exhaustive analysis of the **current state and an outlook to 2030** about the natural gas supply chain, natural gas vehicles (NGVs) and shipping vessels performance.

Scope and Methodology

What does “*Greenhouse Gas Intensity*” mean?

Life Cycle Thinking

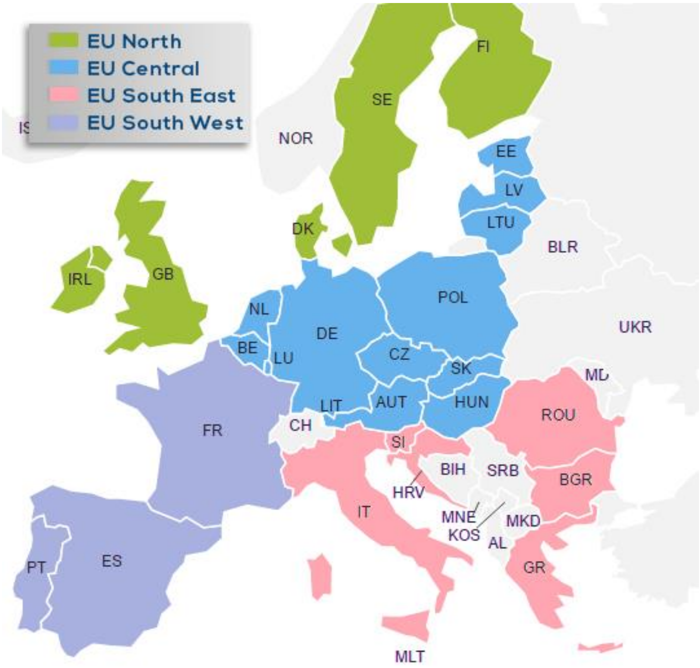


Source: thinkstep, 2017

Scope and Methodology

Geographical boundaries and critical review

- The analysis was performed for four EU regions, corresponding to the Exergia study.
- The LCA software system GaBi is used to synthesise the collected data and information and to build the basis for the GHG model.
- The study is subject to critical review by a panel of independent experts according to ISO 14044.

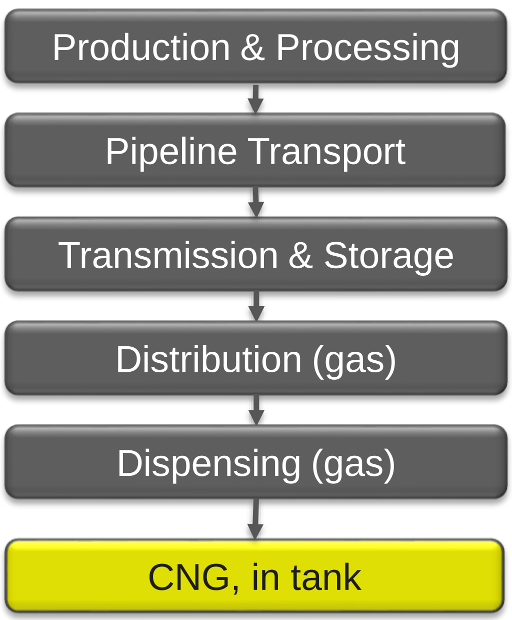


Source: NGVA Europe, 2017

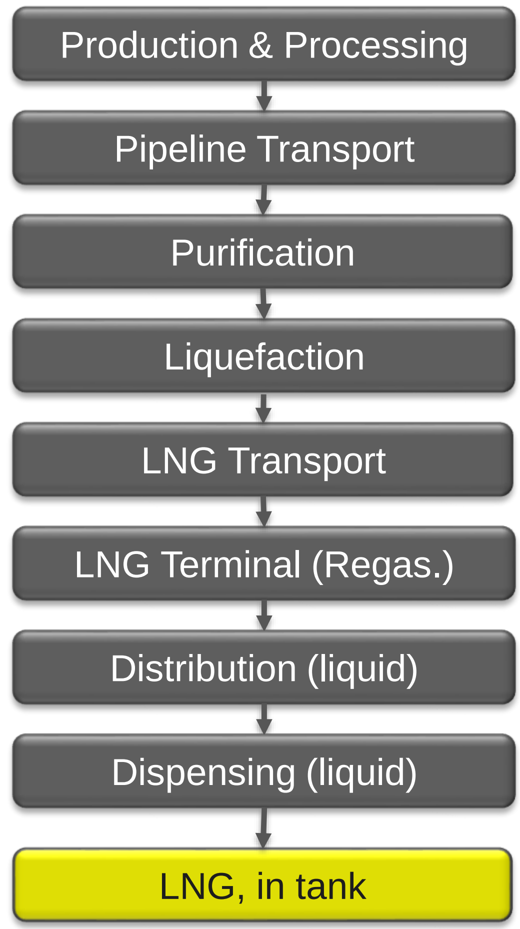
Scope and Methodology

System boundaries

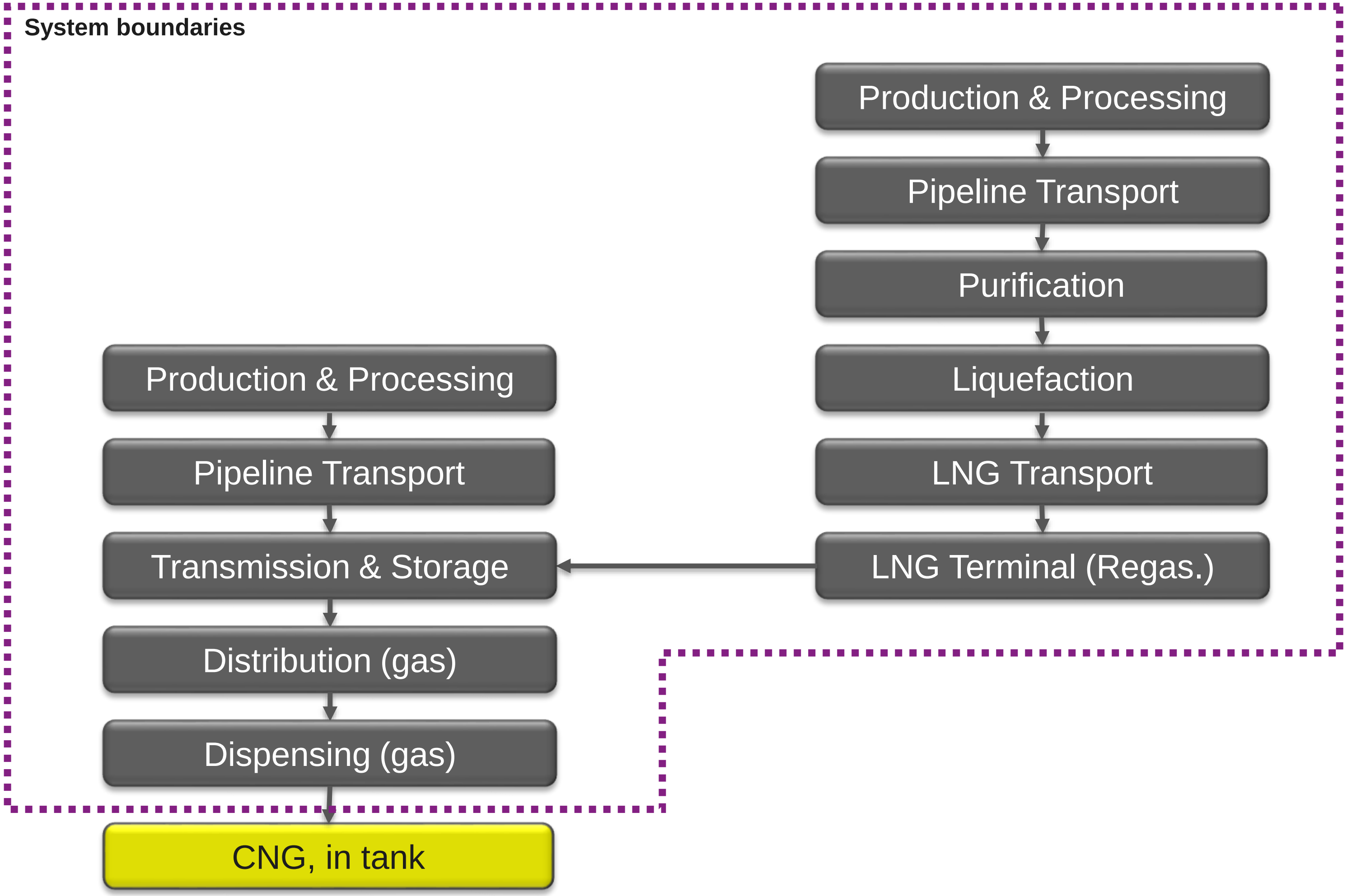
Pipeline supply chain



LNG supply chains

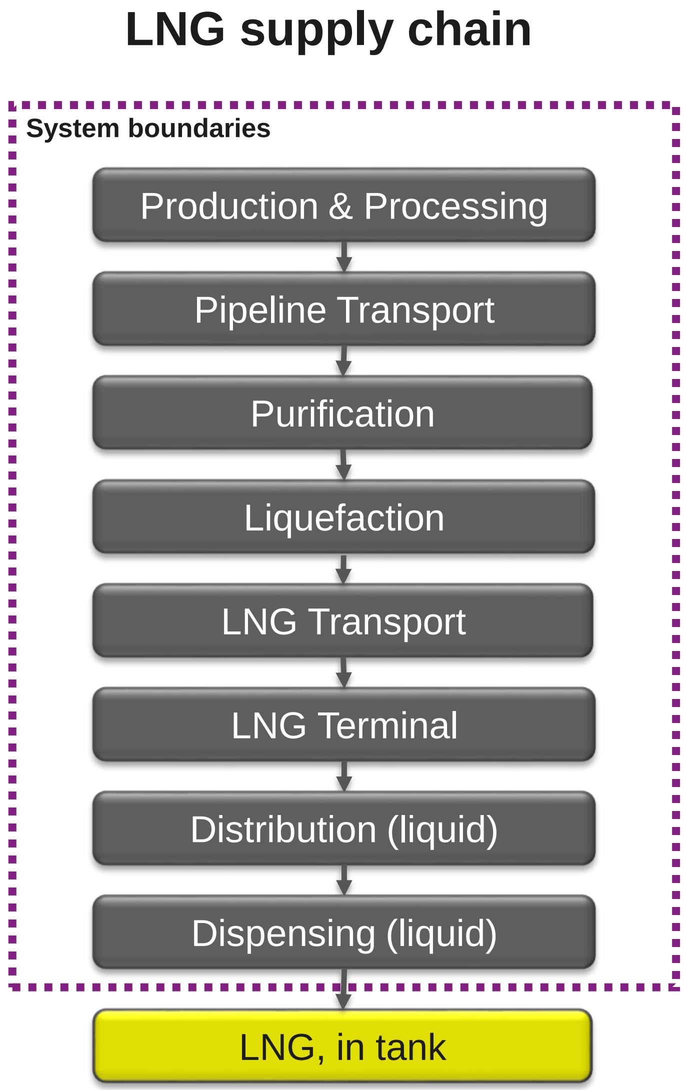


CNG supply chain



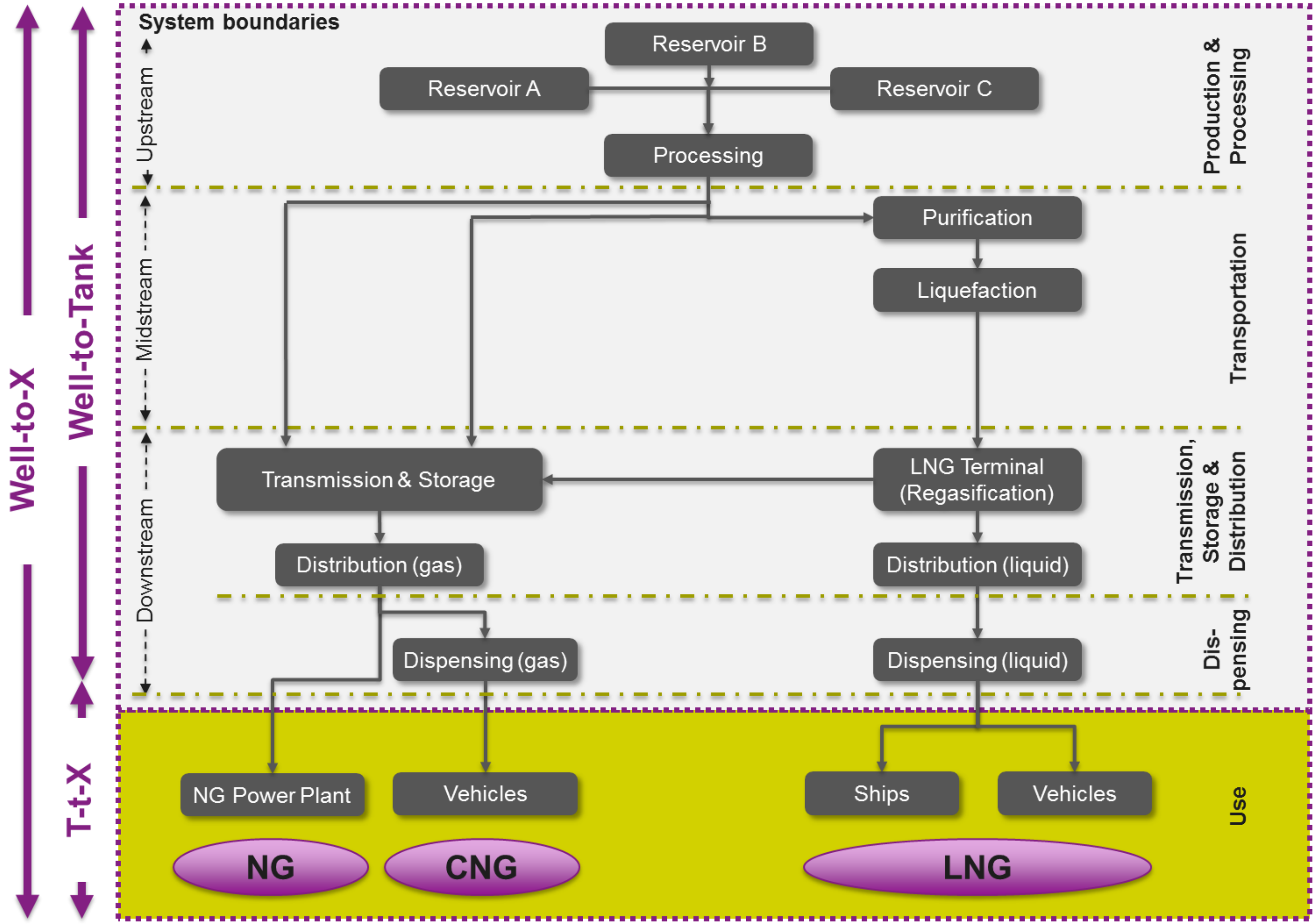
Scope and Methodology

LNG supply chain



Scope and Methodology

System boundaries



Source: thinkstep, 2017

Scope and Methodology

Included and excluded elements or activities

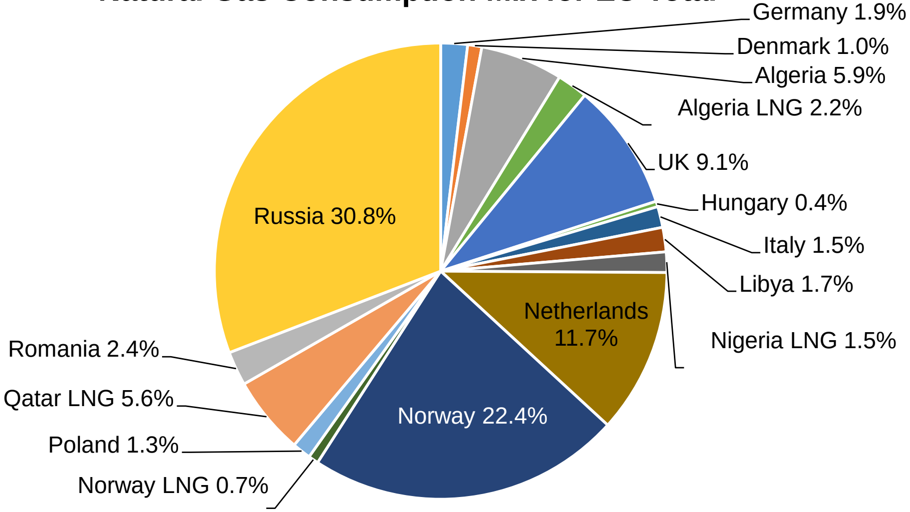
Included	Excluded
✓ Well drilling and well installation	✗ Seismic exploration and exploratory drilling
✓ Production & processing (CO_2 removal, water removal, H_2S removal)	✗ Maintenance efforts for infrastructure (e.g., pipeline, LNG carriers, liquefaction plants)
✓ Pipeline transport	✗ Auxiliary materials, 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, LPG)	
✓ Life cycle burdens of infrastructure (e.g., pipelines, LNG carriers, liquefaction plants, etc.)	

p

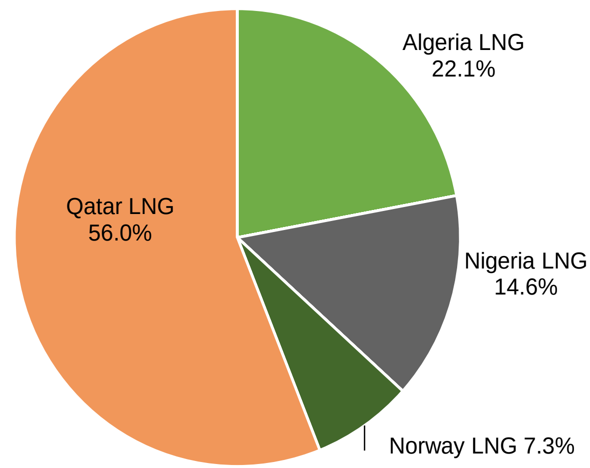
Natural gas supply – Total EU

CNG and LNG consumption mix used in the study

Natural Gas Consumption Mix for EU Total



LNG Consumption Mix for EU Total



- For 90.3% primary data are collected (i.e. 8 countries)
- For 8.3% literature data were used (i.e. 6 countries)
- 1.4% were neglected and the remaining mix scaled to 100%

- For 95.2% primary data are collected (i.e. 4 countries)
- 4.8% were neglected and the remaining mix scaled to 100%

Source: Own calculations based on IEA – Natural Gas mix 2015p, 2016

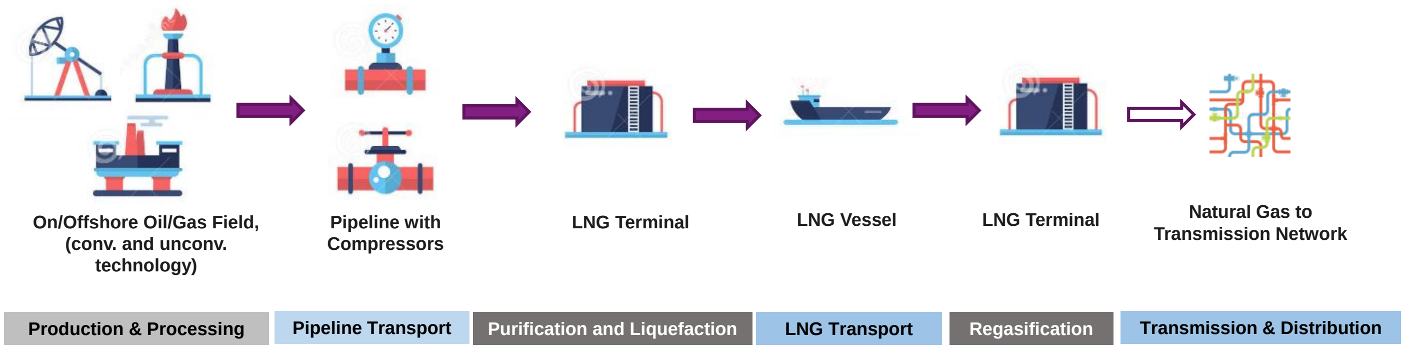
EU-28 LNG supply

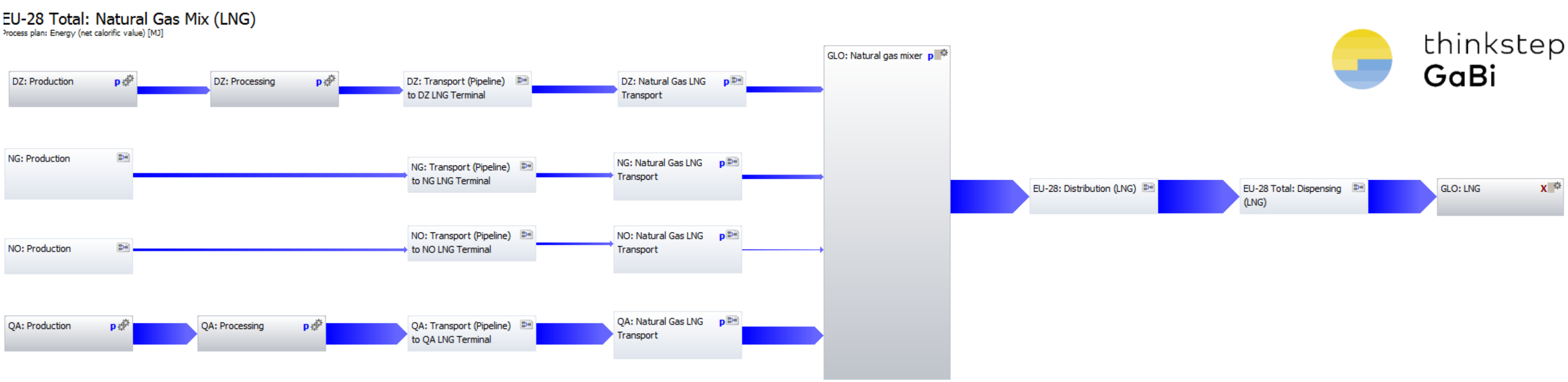
Imports to Europe

Source: thinkstep

EU-28 LNG supply

GaBi Screenshot



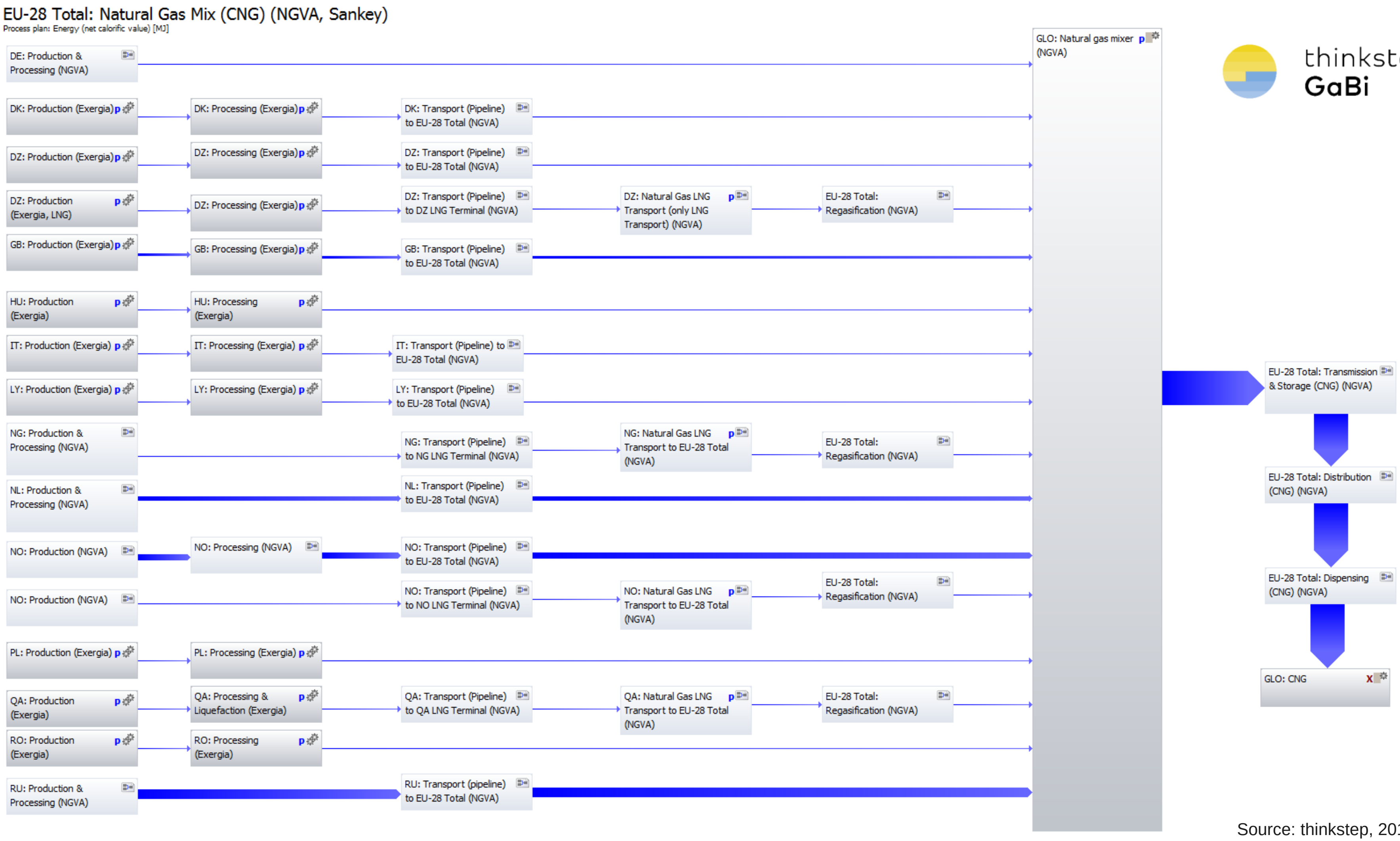


→ Each box represented a stage/process in the life cycle

Source: thinkstep, 2017

EU-28 CNG supply

GaBi Screenshot



Source: thinkstep, 2017

EU-28 LNG supply

Qatar: Production & Processing and Pipeline Transport

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

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.%	-

EU-28 LNG supply

Qatar: 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

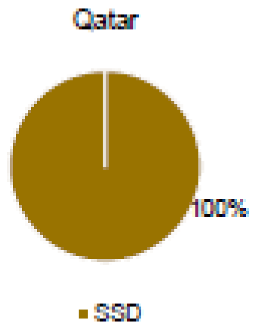
EU-28 LNG supply

Qatar: LNG Transport

thinkstep

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 and IGU.
- The shortest route for the maritime LNG transportation from Qatar to Europe is considered, i.e., through the Suez Canal, since Q_{Flex} are able to pass the canal.

EU-28 LNG supply

LNG carrier fuel consumption (LHV) and methane emissions

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 [m³]	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 crosschecked with literature and were considered good proxies for LNG transport by representatives of ENGIE and Shell.

EU-28 LNG supply

LNG Terminals

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

- The inventory data 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.

thinkstep

LNG Distribution

- 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).

LNG Dispensing

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

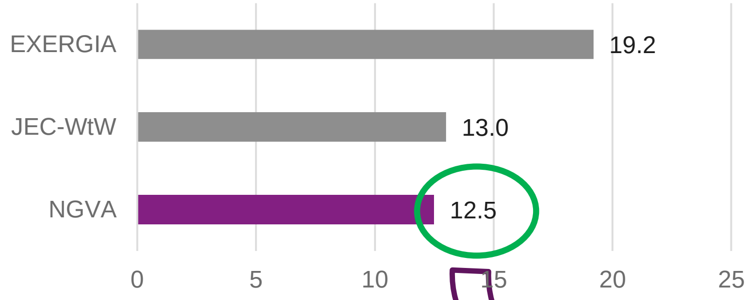
- The modelled station is equipped with boil-off gas (BOG) treatment.
- LNG dispensing data were provided by GrDF and are based on averaged industry data for the year 2016.
- In addition, the data were discussed with industry experts of the NGVA and Shell and are considered as technology representative industry average.

Results

Well-to-Tank (GHG) emissions

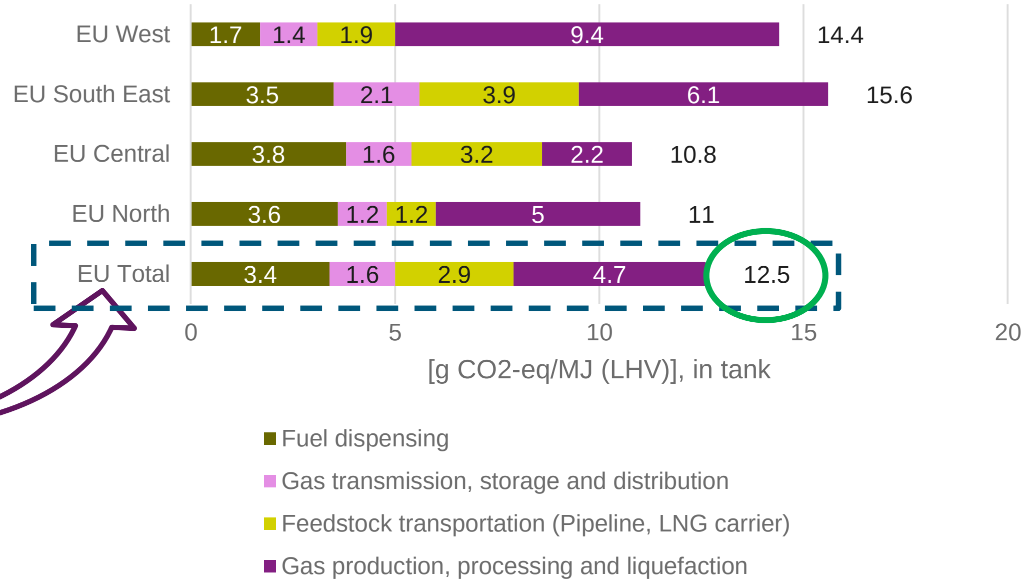
CNG

Well-to-Tank - CNG, in tank - GHG (EU Total) [g CO_2-eq/MJ]

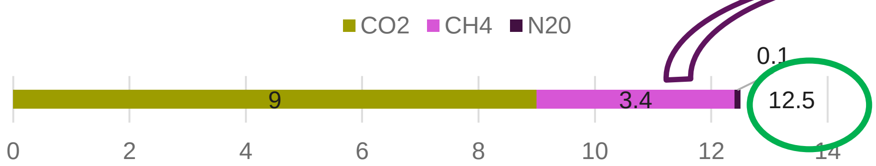


Source: Exergia (2015), JEC (2014)

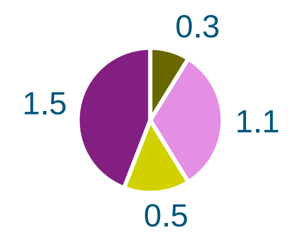
Well-to-Tank – GHG Emissions: CNG supply Breakdown by main individual emissions per region



Well-to-Tank – GHG Emissions: CNG supply breakdown by main individual emissions



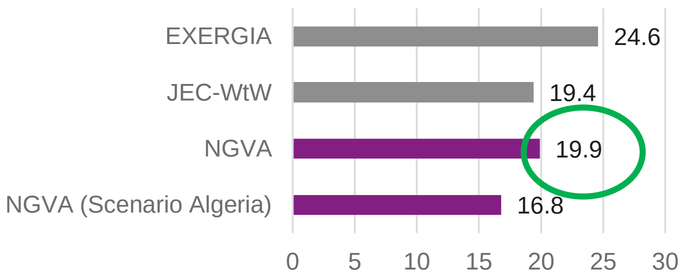
Well-to-Tank – CNG, in tank - Methane Emissions



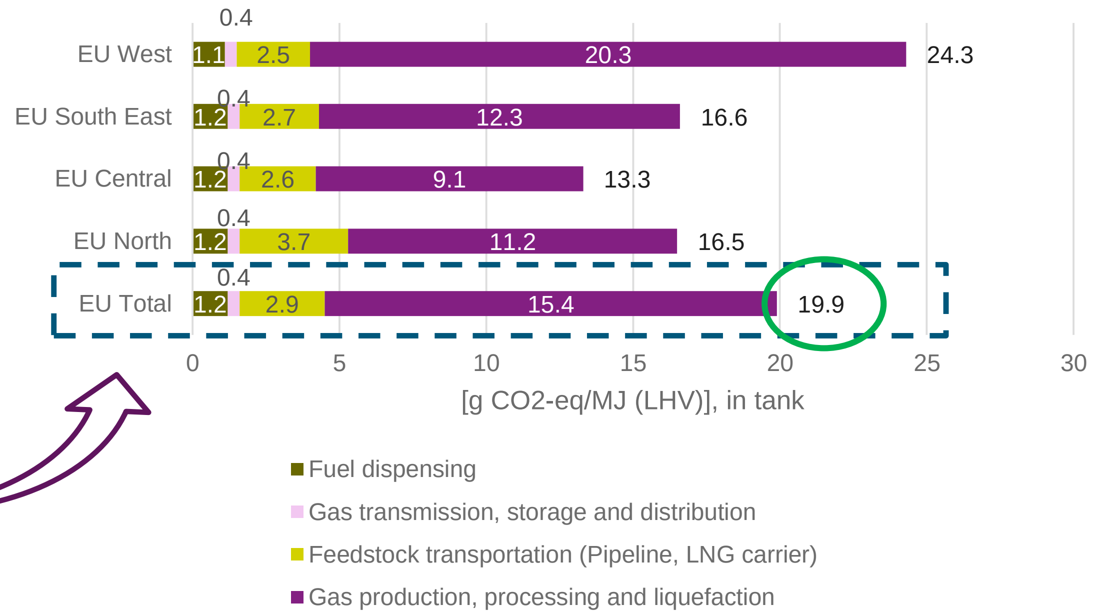
Well-to-Tank (GHG) emissions

LNG

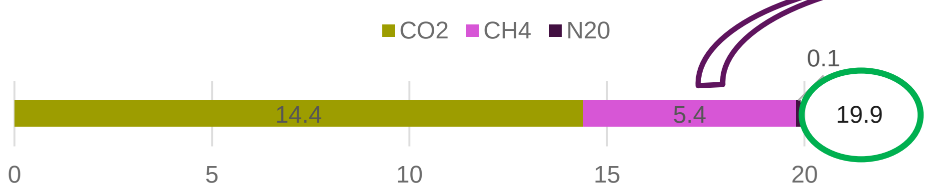
Well-to-Tank - LNG, in tank - GHG (EU Total) [g CO_2-eq/MJ]



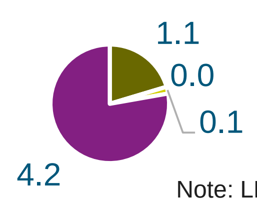
Well-to-Tank – GHG Emissions: LNG supply Breakdown by main individual emissions per region



Well-to-Tank – GHG Emissions: LNG supply breakdown by main individual emissions



Well-to-Tank - LNG, in tank - Methane Emissions



Note: LNG distribution is incl. in fuel dispensing

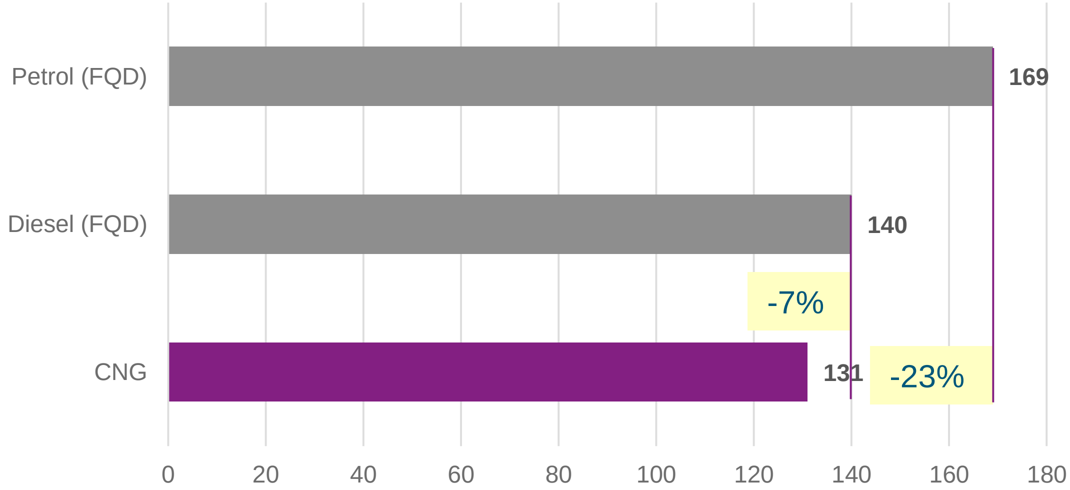
Well-to-Wheel (GHG) emissions

Passenger Vehicles

thinkstep

	CNG	Petrol	Diese
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	-	-

Well-to-Wheel - Passenger Vehicles - GHG Intensity [g CO_2-eq/km]



Vehicle from the C-segment being used according to the New European Driving Cycle

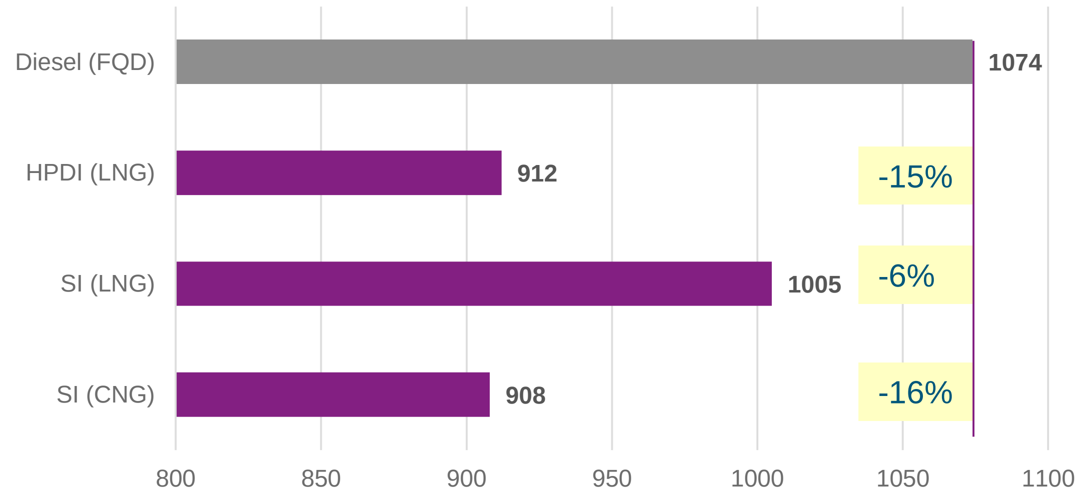
Benefits and reduced GHG emissions from passenger cars are possible with CNG.

Well-to-Wheel (GHG) emissions

Heavy-Duty Vehicles

Parameter	Natural Gas (SI)	Natural Gas (HPDI)	Diese
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	-

Well-to-Wheel - Heavy-Duty Vehicles - GHG Intensity [g CO_2-eq/km]



40 t tractor + trailer combination with 75% payload in long haul use

For long-haul missions, both CNG and LNG are having lower emissions compared with diesel.

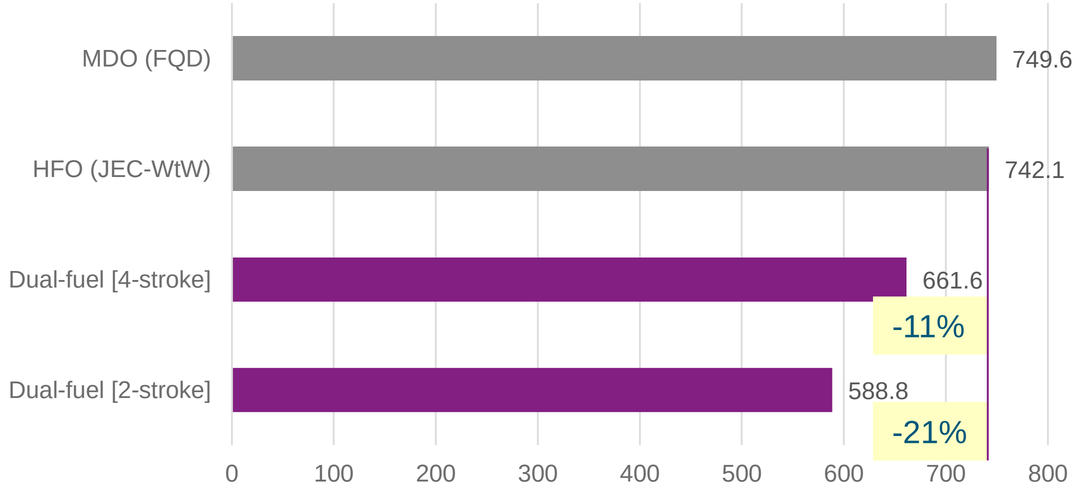
Well-to-Wheel (GHG) emissions

Ships

	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

at 85 % load

Well-to-Wake - Ships - GHG Intensity [g CO_2-eq/kWh]

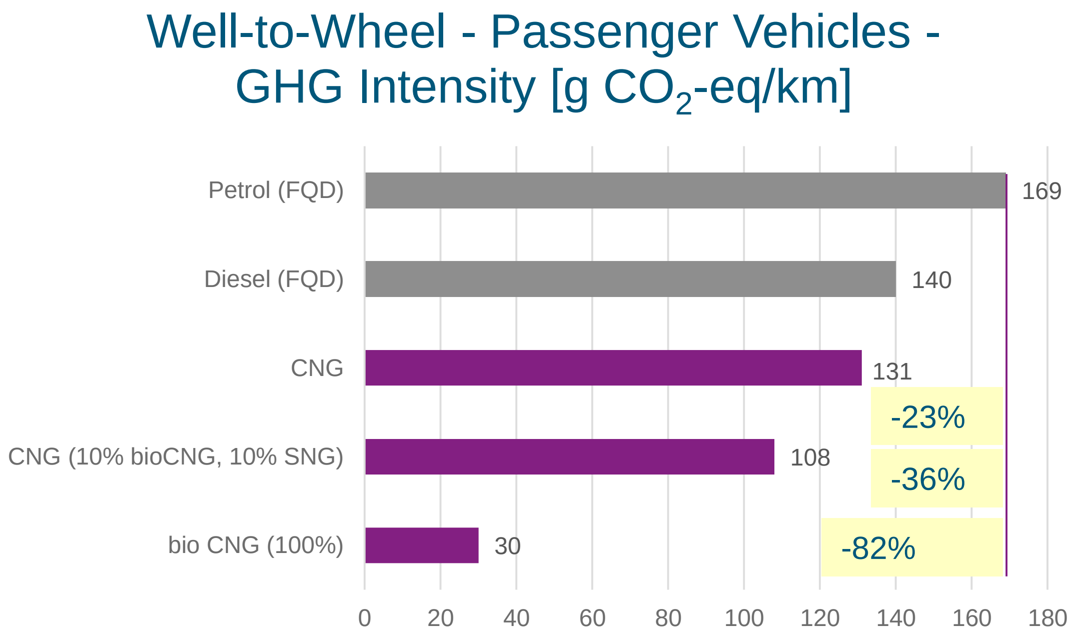


The benchmark for maritime comparison here is Heavy-Fuel Oil, results from JEC.

In maritime applications, the use of LNG provides a clear Well-to-Wake benefit compared with petroleum based fuels.

Well-to-Wheel (GHG) emissions

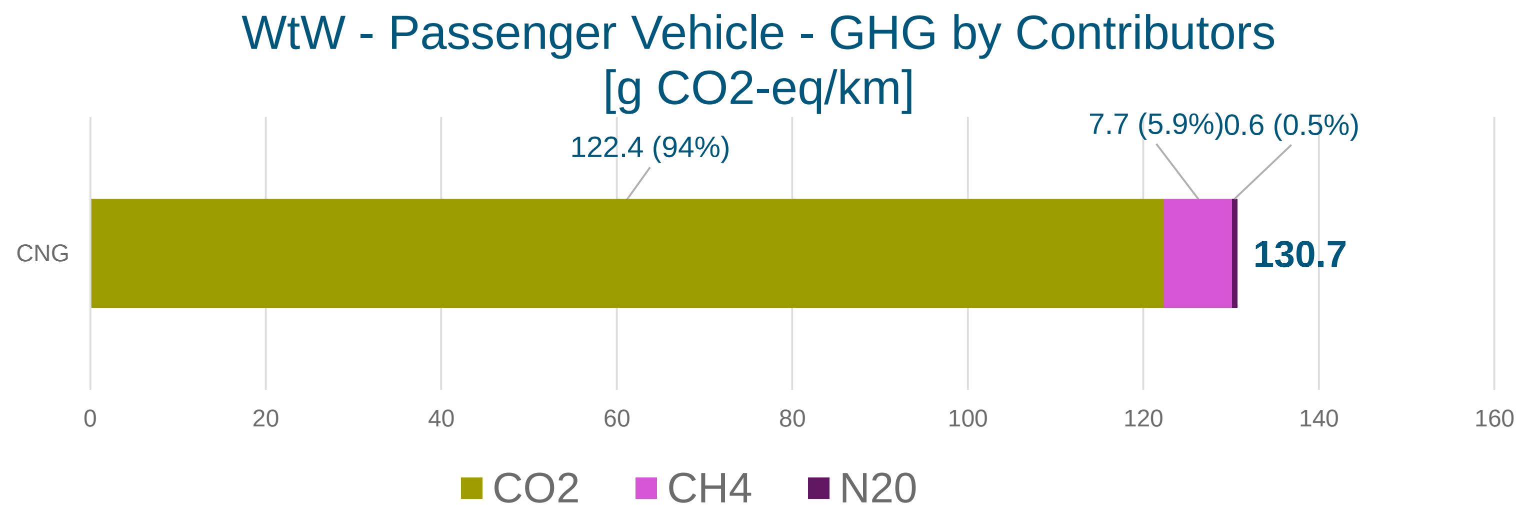
Renewable gas



- Renewable gas has the key property to be **100% compatible with natural gas**, being easily blended or used directly as a neat fuel in engines
- Locally produced
- Renewable gas represents a fast drive towards decarbonisation

Well-to-Wheel (GHG) emissions

Passenger Vehicle – GHG by Contributors



On both CNG and LNG applications no leakage is admitted at vehicle level. CH_4 emissions are generated as unburned hydrocarbon at the exhaust and considered as CO_2 equivalent.

Lessons learnt

Lessons Learned

Key Findings

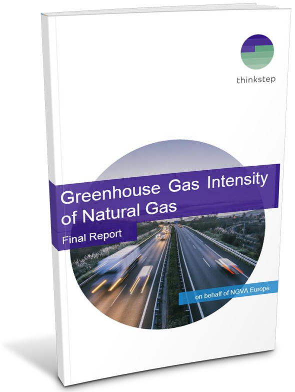
- GHG studies give **valuable insights** in the whole natural gas (NG) supply chain
- GHG emissions of the NG supply chains to Europe **differ by region/country**. Country of origin and technology used for production, processing, transport does matter as well as methane emissions
- **Standardised environmental analysis** (ISO 14044) is key to support EU goals
- Results were confirmed by three independent experts
- Uncertainty of results can be reduced by **collecting most accurate data**. These will increase validity of results → **Good data quality is key!**

➡ **CNG and LNG fuelled transport is having benefits** and **lower emissions** than conventional fuels.

Recommendations

Take away

1. Well-to-Wheel GHG emissions must be taken into account when comparing vehicles.
   → This is the main way to achieve true **technology neutrality**.
2. NGVs must be acknowledged as a solution to ensure **improved air quality** (NOx, PM) in a cost efficient way.
3. Continuous **development of CNG and LNG infrastructure** to further reduce footprint.
4. Company specific **supply chains may differ** from the average
   → Perform your own analyses → lower your risks, reduce costs, increase revenue and enhance your brand!
5. Read more:



Full report available under:
http://ngvemissionsstudy.eu/

thinkstep

Your contact at thinkstep AG

Dr. Oliver Schuller
Principal Consultant
Team Lead Energy and Oil & Gas

oliver.schuller@thinkstep.com
Phone +49 711 341817-20

Hauptstraße 111-113
70771 Leinfelden-Echterdingen
Germany

Phone: +49 711 341817-0
Fax: +49 711 341817-25

info@thinkstep.com
www.thinkstep.com