LNG as an alternative fuel for the operation of ships and heavy-duty vehicles

Short study in the context of the

scientific supervision, support and guidance of the BMVI in the sectors Transport and Mobility with a specific focus on fuels and propulsion technologies, as well as energy and climate

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1 Summary

Background

The transport sector is characterised by distinct rises in energy consumption both throughout Europe and globally. In addition to its dependency on limited fossil resources (e.g. mineral oil), the transport sector is further recognised as a key contributor to the anthropogenic greenhouse effect. On a global scale, transport is responsible for about 22% of greenhouse gas (GHG) emissions. In Germany, the contribution of road transport to overall greenhouse gas emissions ranges between 17% and 20%.

A successful introduction of renewable energies in combination with a reduction of greenhouse gas emissions in the sectors ship and road transport is associated with a number of special challenges. These include calls for innovations in propulsion technology, infrastructure solutions as well as primary energy diversification. Liquefied natural gas (LNG) presents an alternative for simultaneous application with fossil fuels derived from crude oil (e.g. diesel), with a special focus on means of transport that require an extended operating range or a demand for high performance output.

For these reasons, the present study investigates technological components relevant for LNG supply and infrastructure including associated environmental impacts. In a second step, the study explores possible scenarios for the introduction of focal modes of transport: maritime transport, inland navigation and heavy-duty vehicles (HDVs). These scenarios include estimates on resulting future LNG demand followed by calculations of local emissions and greenhouse gases. Furthermore, recommendations for action regarding a potential LNG development plan are derived from the findings. However, the present study does not attempt in-depth cost analyses.

Key drivers

Key drivers for the introduction of LNG in the transport sector include an extended operating range in comparison with CNG as well as a distinct reduction of local emissions, or simplified exhaust gas aftertreatment measures. Decreases in fuel costs and greenhouse gas emissions may also be achieved.

The existing LNG infrastructure for a specific mode may act as a driver for preferential utilisation of LNG in other modes.

Stricter emission standards (SO_2, NO_x, particulate matter and heavy metals) in *maritime transport* necessitate a switch from heavy fuel oil (HFO) to marine diesel oil (comparable to diesel) or LNG. Among the key drivers in *inland navigation* are stricter emission standards (NO_x, PM), sector-specific GHG emissions reduction targets and decreased fuel costs.

For *heavy-duty vehicles*, decreased or moderately rising fuel costs in comparison with diesel fuel are expected in the foreseeable future. Furthermore, the operation of dual-fuel engines complying with EURO VI standards is expected to reduce greenhouse gas emissions. The extended operating range of LNG compared with CNG may present a relevant advantage in long-distance HDV transport.

Based on renewable methane, LNG may contribute to achieve the EU target of 10% renewable energies in the transport sector by 2020.

Availability of LNG

The availability of LNG is primarily determined by the availability of fossil natural gas or RE methane (methane derived from renewable electricity). Both options are associated with positive growth perspectives. Moreover, the presence of a suitable infrastructure for liquefaction, transport, supply and distribution of LNG, whether from maritime imports from global sources or via on-site liquefaction and distribution, is a vital factor for the availability of LNG on the market. In Europe, the development of LNG infrastructure will be supported by regulatory measures in the EC Clean Power for Transport package as well as through national LNG platforms or LNG corridor projects. However, the current projections do not expect LNG to play a major role on the global market by 2020. In Europe, ¾ of the overall demand is expected to be supplied by pipelines whereas only ¼ will be supplied with natural gas in the form of LNG.

The scenarios in the present study identify opportunities for the perspective to substitute a major share of the LNG demand with RE methane. Thus, GHG reduction potentials are recognised. However, these must be weighed against impediments associated with the supply of RE methane.

Key messages on the perspectives of LNG

The perspectives for LNG as an alternative fuel in ship transport and road freight transport were investigated with analyses of the LNG market, the technology for powertrains and infrastructure and the potential emissions reductions. As a result, the following key messages apply:

- Across applications
    - Introduction of LNG requires careful preparation including the identification and evaluation of all relevant technological and economic risks.
    - Increased security of energy supply with LNG through diversification of fuels
    - Suitability for long-distance freight transport as an alternative to diesel
    - Limited reduction of GHG emissions with fossil LNG produced with current techniques, relevant GHG reductions achievable only with RE methane
    - Few ships and vehicles operated with LNG at present
    - LNG infrastructure requires development from the ground up
    - LNG suppliers are unlikely to invest in additional infrastructure unless a robust perspective for increased LNG demand is evident
    - National regulations may impede or desynchronise infrastructure development
    - On-site liquefaction of natural gas or methane highly relevant as a perspective, primarily in the integration of (fluctuating) renewable energies
    - Expected future renewable electricity potentials allow relevant substitution of LNG with RE methane. However, substitution of LNG in competition with additional consumers (other transport, hydrogen/fuel cell vehicles, stationary sector)
    - The considerable energy input required for fuel synthesis demands careful application of synthetic fuels. The key tasks are the identification of transport sectors in which the application of synthetic fuels is essential and transport sectors in which synthetic fuels are economic. In ad-

dition, the evaluation of load-to-distance ratios that render additional fuel or engine alternatives with higher efficiency more appropriate is vital.

- Maritime transport
  - International maritime transport potentially the primary LNG consumer in transport by 2030
  - Technology for the application of LNG available on the market
  - Development initially in ports with predominantly fixed and short routes (e.g. RORO vessels) Existing port regulations currently prohibit the utilisation of LNG as fuel
  - Fuel costs are lower in comparison with middle distillates such as marine diesel oil, however, LNG exceeds the costs of HFO
  - GHG reduction possible with both fossil LNG and RE methane if methane slip can be avoided (e.g. with operation of high-pressure dual-fuel engines or catalytic converters for pure gas engines)
  - Compliance with or falling below targeted standards for NOx and sulphur content possible with LNG, further drastic reduction of emissions of particulate matter
- Inland navigation
  - Technology for the application of LNG available on the market
  - Application feasible and cost-efficient particularly in newer or larger vessels
  - Extensive coverage may be achieved through development of infrastructure along main inland waterways alone, e.g. along the river Rhine.
  - GHG advantage particularly for renewable LNG → total GHG reduction for inland navigation may reach up to 25% between 1990 and 2030 (EC target for transport: 20%)
  - Distinct reduction of pollutants with LNG in comparison with diesel possible (approx. -80% PM/NOx) → Diesel vessels may draw level with future stricter emissions standards (e.g. comparable to current HDV standards)
- Heavy-duty vehicles
  - Reduction or long-term calculability of fuel costs
  - LNG provides extended mileage over CNG (not always required)
  - Requires purpose-built infrastructure for HDVs
  - Potential for the reduction of absolute GHG emissions low and only achievable with RE methane
  - Development initially along main thoroughfares, potential synergies with inland navigation

Recommendations for action

The present study identifies a promising perspective for LNG application as an alternative fuel in ship transport. For HDVs, this result is valid with limited extent. Special efforts should be directed towards the integration of renewable energies into these modes of transport. The following recommendations address the establishment of a foundation for the introduction of LNG:

- Infrastructure
  - Consideration of decentralised liquefaction during infrastructure planning
  - Design of the LNG fuelling station network along heavy-traffic corridors and in coordination with inland navigation along major waterways→ Utilisation of synergies
  - Establishment of required legal authorisation and permits (e.g. ships and bunkering facilities)
  - Establishment of LNG fuelling stations initially for pilot projects (fleets and commuter traffic)
  - Cooperation for the purposes of connectivity (Europe and international)
- Ships
  - Support of stakeholders in pilot projects, e.g. matters of authorisation and permits
  - Subsidisation of low-emissions vessels and thus LNG, e.g. in ports
  - Definition of criteria for funding, in particular based on current and foreseeable market trends in the individual freight segments (freight type, vessel size).
  - Additional research and demonstration projects are required for the establishment of LNG as a relevant fuel options in maritime transport.
  - Establishment of a development agenda for ‘LNG as an alternative fuel in maritime transport and inland navigation’
- Heavy-duty vehicles
  - Acceptance among users requires investigation:
    - Of dual-fuel in diesel engines and pure methane in dedicated engines
    - Of LNG or CNG as fuels, depending on application
  - Conclusions drawn from the successful implementation of a development agenda for maritime transport and inland navigation should be applied to the commercial vehicle sector. A separate development agenda for HDVs that prepares the establishment of a fuelling station infrastructure, characterises legal procedures and examines framework parameters should be considered.

2 Background and aims

Freight transport by ship and road presents an extraordinary challenge for the technologies aimed at the introduction of renewable energies into the transport sector. This challenge extends to the mid-term aim to substitute petrol and diesel fuel in the transport sector for the purpose of diversification of the primary energy supply, and the reduction of greenhouse gas and pollutant emission including noise emissions from commercial vehicles.

In Germany, a major share of the primary energy consumption is supplied with fossil energy carriers, despite the fact that the percentage of renewable energies of the overall primary energy consumption has risen from 1% to 12% between 1990 and 2012. The total primary energy consumption decreased from 1990 to 2012 by 7.7%. The transport sector accounted for 19% of primary energy consumption in Germany in 2012. Thus, in the transport sector and in private households, energy consumption actually increased in the past years.

Both at the European and the global level, the transport sector is characterised by distinct increases in energy consumption. In addition to its dependency on limited fossil resources (e.g. mineral oil), the transport sector is further recognised as a key contributor to the anthropogenic greenhouse effect. The transport sector is associated with a share of 22% of the global CO_2 emissions. Thus, transport is the second-largest emitter after electricity and heat production (41%) followed by the industry with 20%. About two thirds of transport emissions are generated in road transport by passenger cars, HDVs, motor cycles and buses. The percentage of road transport-related emissions in Germany fluctuated in the past 20 years around a stable range between 17-20% of total emissions [BMWi 2013]. At present, there is no common consensus on a set of globally uniform and binding regulations targeting the reduction of CO_2 emissions in transport of any other sector. However, in the past decades a number of countries introduced numerous legal frameworks including instruments for regulation and taxation aimed at the significant reduction of CO_2 emissions by the year 2050.

In principle, a considerable number of renewable energy carriers are available for utilisation in the transport sector. In this context, transport is competing with other sectors for the utilisation of renewable energies. Moreover, competition for energy carriers exists within the transport sector between the individual transport modes (road, rail, water and air) as well as between the different vehicles/ means of transport (e.g. passenger cars versus HDVs).

On a global scale, next to air transport, maritime transport is on the rise with approx. 90% of global trade being transported by ship. Air transport and maritime transport are responsible for about 2% of global CO_2 emissions each. In Germany and in Europe, fuel consumption is rising primarily due to increased HDV transport. In consequence, pollutant and CO_2 emissions are also on the rise. The percentage of freight transport by maritime transport or inland navigation and HDVs dependent on crude oil far exceeds 90%. To alleviate this intense dependency, and further to reduce the considerable associated pollutant and greenhouse gas emissions, concepts for the integration of fossil natural gas or methane gas generated from renewable feedstocks into the transport sector are urgently needed. Additional data may be found in the MFS study ‘Renewable energies in transport’.

The present study explored the potential for LNG (liquefied natural gas) to meet the energy needs of maritime transport and inland navigation as well as those of HDVs while simultaneously reducing pollutant and greenhouse gas emissions.

From 2015, sulphur emissions in the North and Baltic Seas the will be reduced to such low standards that ocean-going vessels will not be able to operate on HFO anymore without elaborate purification procedures. The regulation is expected to be extended globally by 2025 [LR 2012]. Since 2011, inland waterway vessels are required to operate on ultra-low-sulphur diesel as already mandatory for HDVs. The European Union is expected to limit the CO_2 emissions for HDVs in the same manner as existing standards for passenger cars and delivery vehicles suggest. In consequence, significantly improved fuel efficiency will have to be achieved. If these high fuel efficiency targets are unattainable, the focus will be on CO_2-free fuel from primarily renewable feedstocks.

Any consideration of the integration of renewable energies into existing energy and transport systems has to pay due attention to energy conversion efficiency influencing both costs and emissions. Each additional energy conversion step is associated with primary energy losses and increasing costs. In consequence, retaining an existing system has to be weighed against switching to a novel fuel/drive system to evaluate the merits. A switch may be advisable when initially higher investment is set off by distinct advantages regarding emissions and raw material/ feedstock diversification maintained in the long-term. A simple yet graphic example for conversion efficiency chains and implicated costs is presented in Figure 1:

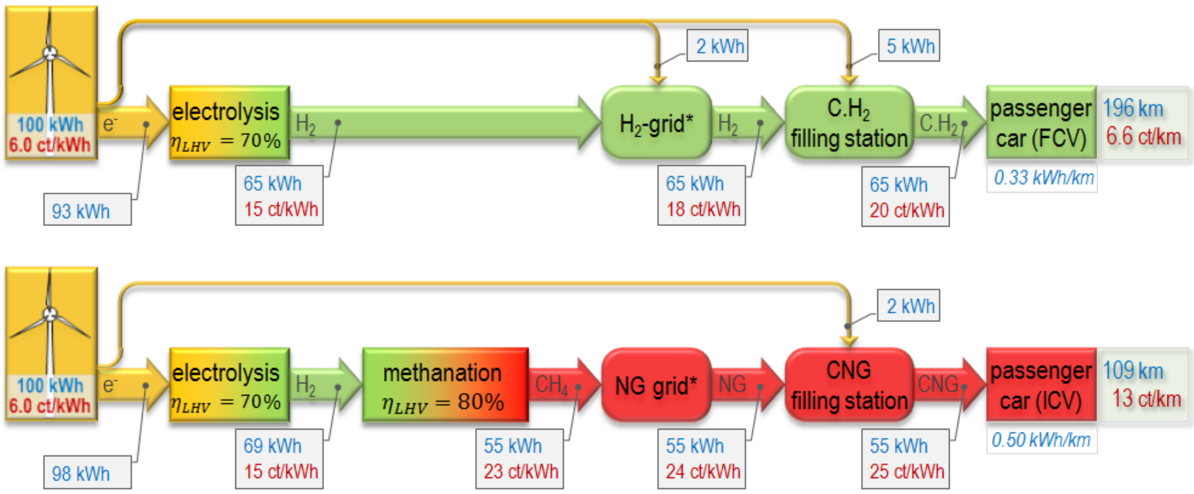

Figure 1: Comparison of H_2 and CH_4 as power-to-gas fuel options

Source: [Stolten 2013]

Natural gas as an alternative fossil fuel is already utilised in form of compressed natural gas (CNG) in passenger cars and city buses. In some countries like Argentina, Brazil, China, India, Iran and Pakistan, the proportion of CNG cars is considerable with a fleet exceeding 1.5 million units. To date, the application of liquefied, cryogenic natural gas (LNG) has been considered exclusively in locations where (a) LNG is readily available due to pre-established corresponding infrastructure. It was further proposed in cases where (b) LNG with its inherent higher energy density may be utilised in car classes that previously fell short of user expectations, thus surpassing alternative fuels such as CNG or alternative systems like electric cars. This is particularly relevant in the context of maritime transport and inland navigation or freight transport with HDVs. China is leading the global field of the natural gas fuelling station infrastructure with 3,350 CNG, 400 LCNG and 1,330 LNG fuelling stations [NGVAeurope 2013]. Early applications of LNG in ships and commercial vehicles are based on demonstration projects dating back to the late 1990ies.

At present, the utilisation of LNG is negligible in both ship and HDV transport. However, the current debate at the European and international level demonstrates that an in-depth analysis of the potential utilisation of this energy carrier in Germany will be essential in the near future.

For these reasons, the present short study analyses the state of the art in LNG technology and examines potential associated environmental impacts. Furthermore, it investigates the regional or global availability of LNG as a fuel in the transport segments defined above. The time horizon of the study extends to 2020 with a perspective aiming for 2030. An additional analysis explores relevant drivers for the application of LNG. The influence of economic, technological and environmental aspects is considered. The analysis is based on literature data and expert opinion (e.g. input from demonstration projects). Results of the study are presented as an overview of drivers, impediments and framework for the application of LNG in maritime transport, inland navigation and HDVs.

Based on the findings, the need for action with regard to a national development agenda for LNG as an alternative fuel for ship transport and HDVs is outlined. In this context, the present short study may inform and contribute to the current debate on the drafting of an EU infrastructure directive [COM 2013].

3 Drivers for the application of LNG in ship transport and heavy-duty vehicles

This chapter describes favourable characteristics of natural gas and LNG and points out associated potential environmental benefits. Furthermore, prospects for LNG in (maritime) ship transport are highlighted. The chapter further includes an overview of the drivers influencing the application of LNG in ocean-going and inland waterway vessels and HDVs.

The application of LNG as a fuel for ships and HDVs offers a distinctly higher volumetric energy density in comparison with common alternatives such as CNG or methanol (approx. factor 2 compared with CNG and factor 1.3 compared with methanol). However, the energy density of diesel may not be achieved with LNG (approx. factor 0.58). The loss in mileage and operating range in comparison with diesel may be considered acceptable in light of the comparable storage volume. The expected mileage for HDVs ranges between 600-1,000 km depending on tank volume [LO 2013]. Some transport relations such as container transports are transhipped in Germany several times and may thus be operated with considerably lower mileage below 300 km [MAN 2014].

LNG supply by ocean-going vessel allows a diversification of the natural gas market in central Europe and thus also a price attenuation. Rising prices for oil and pipeline-transported gas improve the economic viability of the utilisation of imported LNG as a fuel. Moreover, there is added value in remote natural gas deposits (‘stranded natural gas’). For instance, LNG as a vehicle fuel may thus be more cost-effective than diesel, although the infrastructure costs (fuel conditioning, supply, refuelling, storage) may be considerably higher. Moreover, the conversion of natural gas to LNG with subsequent transport to the end user may be favoured over the venting or flaring of natural gas in remote areas to save greenhouse gas emissions.

Due to the lower ratio of carbon per energy content, the combustion of LNG is potentially associated with lower CO_2 emissions compared with diesel. However, losses incurred due to methane slip have to be taken into account. In some cases, the lower CO_2 emissions compared with diesel are fully compensated by methane slip depending on engine concept (as a greenhouse gas, 1 g of methane equals 25 g of carbon dioxide). Dual-fuel engines with combined high-pressure injection of methane and diesel via diesel pilot flame represent a particularly efficient utilisation of LNG. In this set-up, the reduction in CO_2 emissions compared to diesel is an estimated 20% [Westport 2003]. Moreover, the combustion of natural gas in comparison with diesel is intrinsically cleaner with respect to pollutant emissions (NOx and particulate matter in particular). The reduced sulphur content further decreases sulphur oxide emissions. Stricter pollutant emission standards could thus drive the application of LNG.

These relationships are currently discussed in maritime transport where a distinct tightening of environmental standards is intended (Figure 2). Particular relevance applies to:

- Reduction of the sulphur content of ship fuels – in Emission Control Areas the limit for SOx is reduced to 0.1% as of 1.01.2015 (currently 1%) [ECG 2011], and according to MARPOL Annex VI the global SOx threshold will be lowered to 0.5% by 2020, or 2025 at the latest.

- Reduction of SO_2, NOx, particulate matter and heavy metal emissions
- Low-sulphur middle distillates instead of HFO for the operation of ships

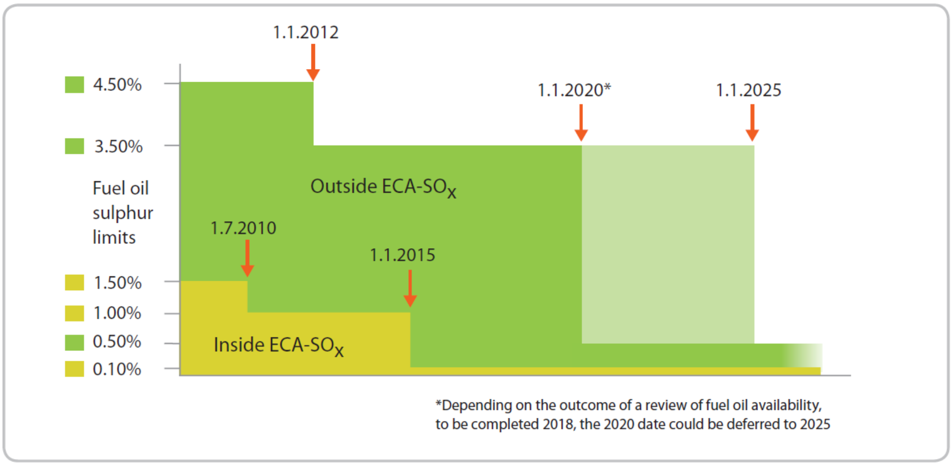

Figure 2: SO_x emission limits and reference years after IMO MARPOL Annex VI

Source: [LR 2012]

An overview of the most important bunkering ports for maritime transport is presented in Figure 3. In particular in Europe and North America, the majority of ports are located in already confirmed ECA areas.

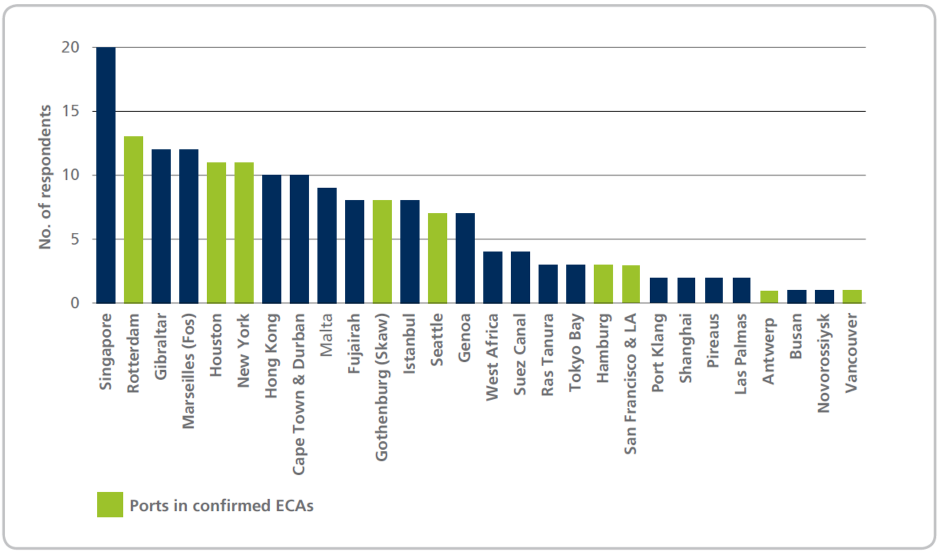

Figure 3: Major global bunkering ports for ocean-going transport vessels

Source: [LR 2012]

With respect to the individual stakeholders among providers in the transport industry, the current view identifies a number of factors that may act as drivers for the utilisation of LNG. In the following, these factors are presented for the transport modes maritime transport, inland navigation and heavy-duty vehicles.

Drivers in **maritime transport**:

- The conversion to LNG is currently associated with substantial additional costs for shipowners. These expenses would be avoided without the perspective of stricter emissions standards. Thus, regulations and implementation of new standards in combination with stringent controls act as major drivers for the utilisation of LNG.
- Fuel costs for LNG are currently lower than for ultra-low-sulphur diesel. Shipowners will make the decision between LNG, marine diesel oil and HFO in combination with scrubbing technology based on the cost development of the available technologies.
- Another driver may be seen in laws, standards and regulations that are currently not adequately adapted to the application of LNG, e.g. currently preventing refuelling of vessels by tankers in ports. A modification of the framework for bunkering procedures in ports may be a driver or rather a pre-requisite for the application of LNG.
- The draft directive COM (2013) proposes the establishment of refuelling facilities for inland waterway vessels by 2020. A driver for the utilisation of LNG is the availability of the fuel, ideally with a global scope, yet distinctly extended in the North and Baltic Seas.

Drivers in **inland navigation**:

- Reduced fuel costs of LNG in comparison with diesel (according to [Panteia 2013] by approx. 20%)
- Reduced pollutant emissions in comparison with diesel due to the fact that particulate filters or SCR systems are rarely applied in inland waterway vessel engines.
- Reduced noise emissions (up to 3 db) in dedicated natural gas engines with benefits especially for densely populated waterways and port areas.
- Development of additional potentials for the application of renewable energies (biomethane and methane from renewable electricity) in inland navigation, thus reducing greenhouse gas emissions.
- Freight terminals in inland ports could offer refuelling services for inland waterway vessels and HDVs (LNG could be supplied by inland waterway and further distributed by road transport if applicable, or pipeline-distributed natural gas could be liquefied on-site).

Drivers for **heavy-duty vehicles**:

- First and foremost, LNG is seen as a cost-efficient alternative fuel with stable pricing in the coming years that holds economic advantages over conventional diesel if an acceptable mileage can be achieved.
- Increasing diesel costs may be borne and balanced with more ease if part of the HDV fleet is partially or fully operated with LNG.
- For the individual stakeholders, low CO_2 emissions in comparison with diesel fuel may already present an important incentive for the utilisation of LNG. In case that the European Commis-

sion introduces CO_2 standards for HDVs in analogy to the standards for passenger cars and delivery vehicles, LNG holds a distinct advantage over diesel due to the lower carbon content. This may be reflected in lower prices for new heavy-duty vehicles operated with LNG.

- In comparison with CNG, LNG is at an advantage due to the lower volume that allows for better mileage and less frequent refuelling.
- The utilisation of dual-fuel engines appears particularly promising. The energy conversion efficiency compared with a diesel engine is virtually equal, yet a high proportion of LNG as fuel may be utilised. When the LNG tank is spent, the vehicle continues to operate on pure diesel fuel.

4 Analysis of the current LNG market

In the following, the current LNG market is characterised with an evaluation of relevant relations between sources and modes of utilisation. Furthermore, the expected development of current activities as well as potential trajectories for market volumes and stakeholders are described.

Chapter 4.1 addresses the availability from fossil sources as well as the local availability of RE methane from renewable electricity. Chapter 4.2 explores LNG production and logistics including existing LNG supply streams and initial clients in the transport sector. Chapter 4.3 identifies potential LNG distribution regions, whereas Chapter 4.4 illustrates the delivery of LNG in terminals via maritime transport. The chapter includes review of current gas pricing and the expected related delivery relations. Chapter 4.5 focuses on the drafting of the EU infrastructure directive and the first LNG corridor projects in Europe.

4.1 Availability and security of supply

4.1.1 Fossil sources of LNG

At present, LNG is produced from fossil natural gas. The current state of reserves and resources of natural gas is briefly summarised in the following. Reserves include the deposits that may be exploited economically with current state of the art technology. Confirmed reserves have generally been experimentally verified with drilling or specific mining plans. In contrast, resources are defined as unverified estimates of additional deposits. The existence and extent of these deposits is theoretical and subject to speculation.

More than half of the global natural gas reserves are concentrated in the three countries Iran, Russia, and Qatar. 70% of the reserves in Iran and Qatar refer to a joint deposit with a size that was estimated with a small number of exploratory drillings several decades ago. An approximated 4.3% of global natural gas reserves are located in the USA, with half of the deposits in form of coal bed methane and shale gas. However, US natural gas reserves are depleted disproportionally quickly due to the fact that the country is the world’s largest producer of natural gas.

North America (Canada, Mexico, USA) possesses more than 20% of the global shale gas resources, which amounts to 45% across all of the Americas, whereas China’s resources exceed 10%. Confirmed shale gas reserves are almost exclusively located in the USA [DERA 2011, EIA 2013, EIA 2011, BGR 2013, FAZ 2013a, Zittel 2013].These figures illustrate that the expectation for shale gas to act as a global replacement for conventional natural gas in the near future is not backed by reliable data. The coming years will show the proportion of resources that may be transferred into confirmed reserves and successfully exploited.

Conventional reserves of natural gas in Europe are located exclusively in Norway, the Netherlands and in the United Kingdom with distinctly fewer deposits. These reserves would cover the total gas consumption in Europe in a four year period. The assumption that all conventional gas resources actually exist and may be readily exploited would prolong this period to eight years.

Under consideration of shale gas reserves, the European gas resources extend to 21 trillion m³. However, these estimates are subject to considerable uncertainty. As recent as April 2011, the US Energy Information Administration reported a technological shale gas potential in Poland of 5290 billion m³ [EIA 2011], yet the same agency corrected the estimate to 4190 billion m³ in June 2013 [EIA 2013]. In December 2013, the German Federal Institute for Geosciences and Natural Resources estimated the total remaining gas potential of Poland at 885 billion m³ with 88 billion m³ of confirmed resources [BGR 2013]. Thus, over the course of two years the estimated Polish shale gas resources first jumped substantially to be later revised down by almost 90%.

Estimates for Germany amount to 1300 billion m³, a figure that exceeds current reserves by ten times, yet again the data lack reliability. Even the confirmed reserves in Germany of 123 billion m³ are annually shrinking and generally too minor to prevent the annual decline in gas production (-50% since 2000) to a low of less than 12 billion m³ (2013). Substantial influence of potential German shale gas production on the import price is unlikely given a consumption of approx. 100 billion m³/a, and a shale gas yield expected to be small, possibly below 1 billion m³/a.

The extensive shale gas resources in China (25 billion m³), Argentina (22 trillion m³) or Algeria (20 trillion m³) have to regarded critically due to the fact that the geographic locations of these regions are characterised by constant water shortage (e.g. the Argentine deposit is located in the formation ‘vaca muerta’ (sic!) with an annual precipitation of approx. 230 mm). Moreover, there is little or no established gas infrastructure for delivery of the minor outputs to potential consumers.

According to [Zittel 2013], estimates on European shale gas resources amount to less than 10% of the global total, whereas [IEA 2012] report the European share of global unconventional gas resources (shale gas, coal bed methane, tight gas) with a slight 2%.

In Germany, all hydrocarbon drilling that employs fracking techniques to break ground and enhance production rate is effectively subject to a moratorium initiated by action groups and public campaigns that formed rapidly since 2010. Public pressure resulted in an agreement between policy makers and relevant industries. A number of dedicated studies report potential risks associated with the mining technique. However, in light of a shortage of potentials for the development of conventional natural gas fields in Germany, the moratorium is expected to be revisited and possibly lifted.

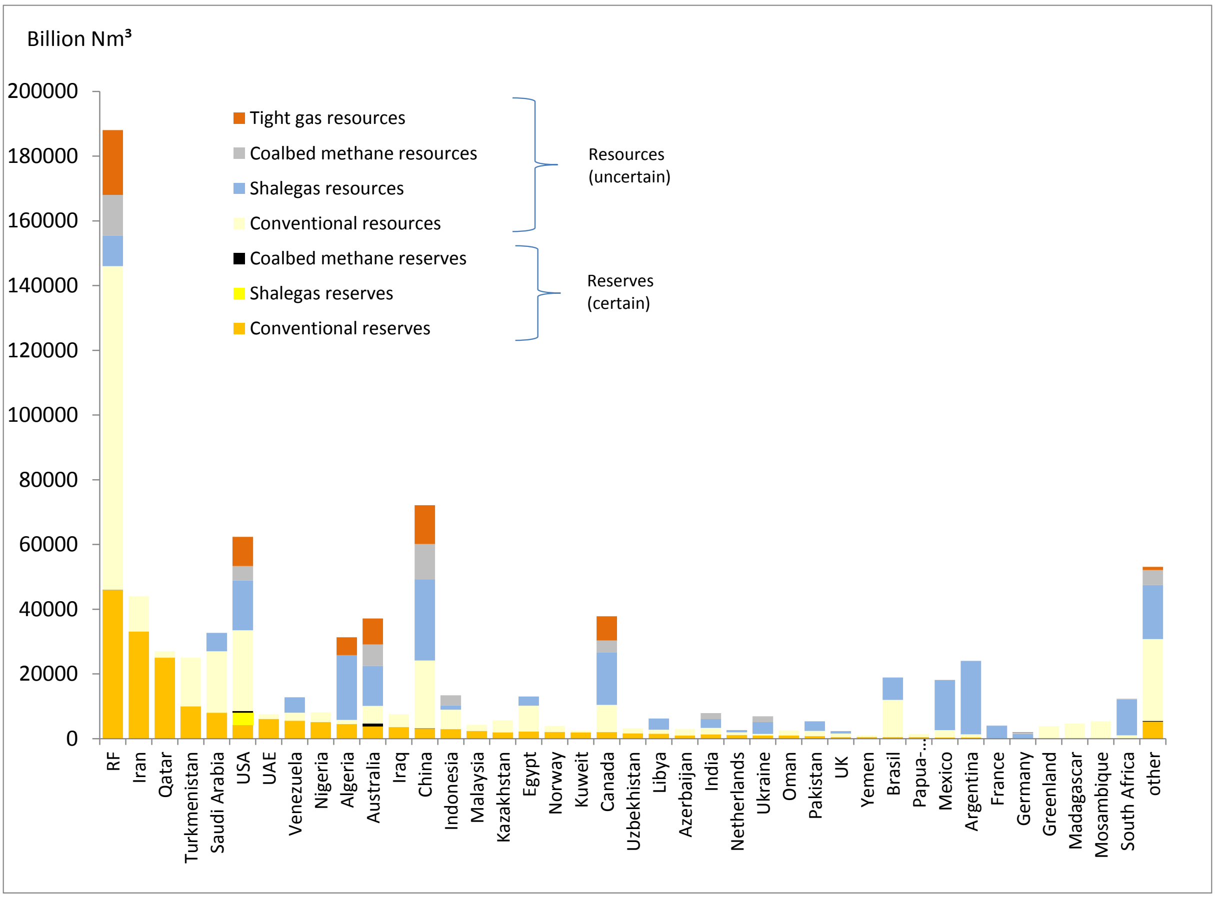

Figure 4: **Reserves and resource data for conventional and unconventional gas sources**

Source: Image by LBST based on data from [EIA 2013, BGR 2013]

The long-term development of a European and global LNG market depends on many factors. A pivotal question may be the transferability of identified natural gas resources (Figure 4) into confirmed exploitable natural reserves ready for production.

[BP 2011] predicted a share of 57% of natural gas in the USA to be derived from shale gas and coal bed methane in 2030. Thus, the USA could turn into a natural gas exporter, although such developments depend on the cost and access to unconventional gas reserves.

4.1.2 Renewable electricity as a source of LNG

The development of sustainable technical potentials[1] for the utilisation of renewable energies in Germany is in its infancy. Aside from hydroelectric resources which already realise major available potentials, other technologies under investigation are associated with substantial unexploited potentials for electricity generation, particularly in the wind and solar sector (see Table 1). A detailed description of

[1] Standard potential categories include (sorted by decreasing potential): theoretical potential, technical potential, economic potential. The assumed technical potentials in the present study consider environmental parameters, e.g. exclusion of conservation land (technical-sustainable potential), however, economic aspects (competitiveness) or social aspects (acceptance, acceptability) are excluded. Please consult MFS study 'Renewable energies in transport'for details on potential categories and the derivation of technical-sustainable potentials.

technical potentials of renewable energies may be found in the MFS study ‘Renewable energies in transport’.

Table 1: Technical potentials for renewable electricity in Germany (excl. biomass)

<table>
<tr><th rowspan="3">Technology</th><th colspan="3">Long-term technical-sustainable potential</th><th rowspan="3">Utilised potential 2012 [AGEB 2013]</th></tr>
<tr><th colspan="2">Literature analysis</th><th rowspan="2">Assumptions for the present study</th></tr>
<tr><th>Lower threshold</th><th>Upper threshold</th></tr>
<tr><td>Hydropower</td><td>25 TWh/a</td><td>42 TWh/a</td><td>25 TWh/a</td><td>21.8 TWh/a</td></tr>
<tr><td>Wind Onshore</td><td>195 TWh/a</td><td>2,897 TWh/a</td><td>390 TWh/a</td><td rowspan="2">50.7 TWh/a</td></tr>
<tr><td>Wind Offshore</td><td>64 TWh/a</td><td>280 TWh/a</td><td>280 TWh/a</td></tr>
<tr><td>Photovoltaics</td><td>163 TWh/a</td><td>405 TWh/a</td><td>284 TWh/a</td><td>26.4 TWh/a</td></tr>
<tr><td>Geothermal</td><td>15 TWh/a</td><td>300 TWh/a</td><td>15 TWh/a</td><td>0.03 TWh/a</td></tr>
<tr><td>Total</td><td>462 TWh/a</td><td>3.939 TWh/a</td><td>~1,000 TWh/a</td><td>~99 TWh/a</td></tr>
</table>

In addition to purely technological restrictions, environmental factors or competition for land use may play a vital role. In compliance with environmental regulations, the total electricity generation potential of hydropower is estimated at 25 TWh/a. The electricity generation potential of photovoltaics signifies the mean between the upper and lower threshold and amounts to 284 TWh/a.

Future development of onshore wind power primarily focuses on locations that carry little potential for conflict. A scenario with an area use of 2% after [IWES 2013] is assumed, thus generating 390 TWh/a. For offshore wind power, a long-term technical potential of 280 TWh/a with 70 GW installed power and 4000 hours of full utilisation per annum is assumed. Based on these assumptions, the annual electricity generation potential of wind power already exceeds the annual electricity consumption in Germany.

The electricity generation potential of geothermal energy concepts is estimated to amount to 15 TWh/a. The application of fracking technology, e.g. the hot dry rock processing in enhanced geothermal systems for electricity generation, is excluded from the calculation.

Discounting the present-day net electricity consumption of 535 TWh, the technical-sustainable potential remaining for fuel production amounts to approx. 465 TWh (see MFS study ‘Renewable energies in transport’). Table 2 illustrates the resulting fuel potentials under the theoretical assumption that the remaining 465 TWh are applied exclusively for fuel production of LNG via methanation and liquefaction. The electricity demand for methanation depends on the applied CO_2 source, please see energy conversion efficiency assumptions in Table 2.

Table 2: Energy conversion efficiencies and fuel potentials for the supply of LNG from renewable electricity

	CO_2 from air	CO_2 from flue gas, e.g. wood-fired CHP plants	CO_2 from biogas upgrading
Energy conversion efficiency	41%	50%	51%
CO_2 availability	No limit	7,700 Mio. Nm³/a 3)	330 Mio. Nm³/a 1) 625 Mio. Nm³/a 2)
LNG fuel potential	191 TWh/a (686 PJ)	77 TWh/a	3,3 TWh/a 1) 6,2 TWh/a 2)

1) Inventory of biogas plants feeding methane into the natural gas grid 2012 [DBFZ et al 2013]
2) Inventory of biogas plants > 1 MWel after [DBFZ et al. 2013]
3) wood-fired CHP plants > 1 MWel after [DBFZ et al. 2013]

In the case that only readily accessible CO_2 sources are considered (i.e. CO_2 from wood-fired CHP plant flue gas and CO_2 from biogas conditioning), the fuel potentials for technical-sustainable electricity potentials in Germany amount to approx. 86 TWh LNG. This represents the energetic equivalent of approx. 14% of the current fuel consumption in Germany. The technical-sustainable potential for synthetic fuels derived from renewable electricity in Germany is substantial, however, by itself it is insufficient to sustain demand (this finding is acutely relevant for the synthesis of liquid fuels from renewable electricity, please see MFS study 'Renewable energies in transport'). The considerable energy input required for fuel synthesis demands a considerate application of synthetic fuels in energy scenarios for the transport sector. Thus, the pivotal strategic question addresses prioritisation of transport sectors according to their dependency on synthetic fuels, i.e. for which transport sectors are synthetic fuels essential? Furthermore, for which transport sectors are synthetic fuels the most economic option, and which load-to-distance ratios render additional fuel or engine alternatives with higher efficiency, e.g. hydrogen (approx. 60% ex pump) in combination with fuel cells, more appropriate?

4.2 LNG market

LNG supply in Germany is feasible in principle with LNG supply via maritime transport (assumed supply source Qatar) with subsequent distribution and utilisation, as well as locally liquefied LNG with subsequent distribution and utilisation (Figure 5).On-site liquefaction in Germany at present is virtually non-existent. However, future development of an LNG infrastructure and the utilisation of synthetic methane (RE methane) may increasingly employ the process.

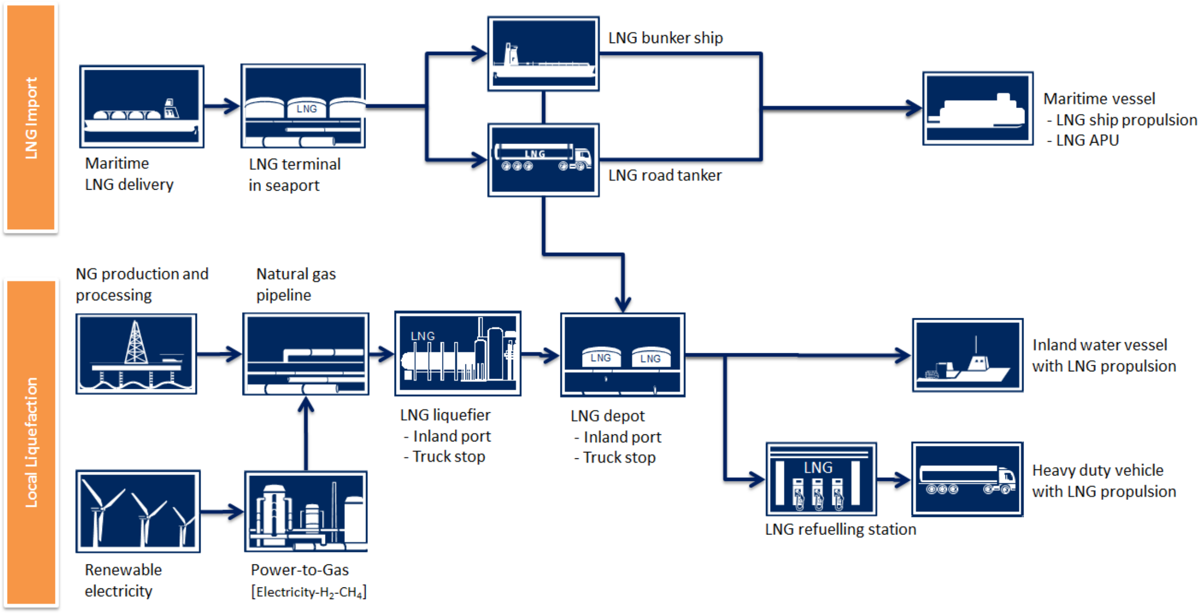

Figure 5: LNG supply chains in Germany

The advantages of maritime transport of LNG supply in comparison with pipeline delivery for natural gas producing countries may be found in the inaccessibility of markets without maritime transport (remote natural gas deposits), the relatively low costs of reaching markets (seller's market) and the increased flexibility of sales volumes (scalability). Recipient countries benefit from flexibility and diversification of supply, i.e. no dependency on a single supplier from a single main pipeline. In 1996, there were eight LNG producing countries on the market, in 2008 the number had risen to 15 and in 2020, 30 producers are expected. At present, about 25 countries maintain LNG import terminals [natgas 2013].

In 2012, about 37% of all LNG exports went to Japan, about 16% to South Korea, 5% to Taiwan, 6% to India and about 6% to China. Thus, a total of 69% went to those countries. Almost 19% of the total LNG was exported to the EU and less than 2% to the USA. About 40% of the total LNG were produced in the Middle East (Oman, Qatar, United Arabian Emirates, Yemen), whereas Russian LNG exports are primarily exported via pipeline [GIIGNL 2013].

Table 3: Production, consumption and import dependency for natural gas

Region	Production		Consumption		Import dependency
	Billion ft^3/d	Billion m^3/a	Billion ft^3/d	Billion m^3/a	
EU	6308	179	16,921	479	63%
USA	24,063	681	25,502	722	6%
Brazil	601	17	1031	29	42%
India	1426	40	2076	59	31%
China	3828	108	5152	146	26%

The import dependency for crude oil is immense. In 2012, approx. 85% of the EU consumption was imported. The inclusion of Norway lowers the import rate to approx. 70%. Please note that crude oil production in the United Kingdom and Norway has been in decline for a number of years. In consequence, the import dependency of the EU is expected to increase even with the inclusion of Norway, assuming a constant consumption.

In contrast, the import dependency for natural gas in Europe was lower than for crude oil with imports amounting to about 63% in 2012. However, for most European natural gas fields, output is in decline, in consequence leading to an increased import dependency under assumption of constant consumption. About 30% of the natural gas consumption was supplied by Russian imports in 2012, another 24% were imported from Norway. About 13% of the natural gas consumption was covered by LNG from Qatar, Algeria and Nigeria [BP 2013].

Demonstration tests with LNG fleets of HDVs in Europe

- 30 LNG HDVs for semi-trailer transport from Simon Loos in the Netherlands since 2012
- 10 LNG HDVs for semi-trailer transport from the logistics company Gebr. Huybregts in the Netherlands (fuelled with liquefied bio-methane)
- 15 LNG tractor-trailers from Vos Logistics in the Netherlands since 2012
- 14 LNG HDVs from Coca Cola in the United Kingdom since 2012
- LNG trailer HDVs from logistics company Hellmann in Osnabrück will be put into operation 2013 [Eurotrans 2013]
- 2 LNG heavy duty tractors (Scania/Otto EURO VI and Volvo/Dual-Fuel EURO V) from Transportes Monfort in Castellón since 2013
- Numerous sales of Volvo/Dual-Fuel EURO V in 2013 in the UK:
    - 35 LNG distribution HDVs at Tesco [Gasrec 2013a]
    - 50 LNG heavy duty tractors at ASDA Logistics [Volvo 2013a]
    - 101 LNG heavy duty tractors at DHL, another 51 are ordered [Transport Engineer 2013a]
    - 20 LNG heavy duty tractors at Eddie Stobart Logistics [Transport Engineer 2013b]

Diversification of the fuel demand includes debate on the utilisation of natural gas vehicles. There were at least 2866 CNG and 17 LNG fuelling stations in the EU as of June 2012 with about 1 million CNG and LPG vehicles in operation (approx. 0.4% of the vehicle stock for passenger cars, HDVs and buses in the EU) [NGVA 2012]. LNG as a fuel is virtually irrelevant to date, yet the application as a fuel option for maritime transport, inland navigation and HDVs is currently being considered. The scope of the national LNG platform of the Netherlands aims for 50 ocean-going and inland waterway vessels, respectively, and 500 HDVs with LNG engines by 2015. Completion of the targets is likely for heavy-duty vehicles in particular. Whether this is the initial step towards broad application or rather an extended demonstration project remains to be seen.

4.3 LNG supply

In the near future (to 2016), the Middle East is unlikely to invest in additional liquefaction capacity and the development of additional facilities in the Atlantic are not expected to exceed a moderate 18%. In case Qatar lifts the current moratorium, the development of liquefaction capacities could resume in the short-term period to 2016. Substantial capacity extension is currently under way around the Pacific Rim with increases of almost 50% in 2012, and 60% thereof in Australia alone. In consequence, Australia would surpass Qatar as the world leader in natural gas liquefaction (see Table 4). In contrast, Indonesia has already announced decreased exports and it remains questionable whether LNG demand in the coming half decade may be satisfied [IFPEN 2012]. Yet, the logistics centre Singapore is aiming to evolve into the LNG hub of commerce in Asia. LNG storage facilities with an annual capacity of 9 million t are under construction on Jurong Island, a separate island off the coast of Singapore. Singapore is striving to set prices as the principal spot market for LNG in Asia [FAZ 2013b].

World demand for LNG is expected to rise by more than 40%from a current 400 billion m³ to 566 billion m³ in 2020. In the period from 2010-2020, LNG consumption in Europe is expected to increase from about 85 billion m³ to 161 billion m³ by almost 90%, aiming to increase its LNG supply contribution from 19% to 24% (see Figure 6) [Cedigaz 2011]. Despite these growth projections, LNG is not expected to develop into a fully globalised market by 2020, and 50% of LNG production in 2020 is likely to remain in the hands of the three major producers (Australia, Malaysia, Qatar) [Cedigaz 2011]. Thus, increasing demand in Europe could add relevance to on-site liquefaction processing.

Table 4: Additional LNG liquefaction capacity 2011 to 2016

Country	End 2011	2012	2013	2014	2015	End 2016
Atlantic Basin	78.1	83.3	92.5	92.5	92.5	92.5
including						
Algeria	20.3		+9.2			29.5
Angola	0.0	+5.2				5.2
Middle East	100.4	100.4	100.4	100.4	100.4	100.4
Pacific Basin	101.3	105.6	105.6	110.6	137.8	150.8
including						
Australia	19.5	+4.3		+5.0	+11.1	48.4
Papua New-Guinea					+6.6	6.6
Canada					+5.0	5.0
USA					+4.5	9.0
World total	279.8	289.3	298.5	303.5	330.7	343.7

Source: [Cedigaz 2011]

4.4 LNG landing

The development of regasification capacities for LNG is highly dynamic. By the end 2011, about 90 regasification terminals with an annual capacity of 654 Mt were in operation world-wide. By 2016, extensions with an additional 125 Mt capacity are planned with about 80 Mt presently under construction. Most of these capacity extension projects are under way in Asia. Floating LNG gasification operations admit new players to the market of LNG regasification. Among the reasons are improved flexibility, lower investment, shorter construction lead times, rapid assembly, and potentially higher acceptance due to offshore implementation. About 12 floating facilities are currently operated with an additional 15 in the planning stage or under construction. There was a surplus of LNG tanker capacity after the recession in 2009 which has transformed into a scarcity in recent years, leading to short-term increases in charter fares. Only 20 LNG tankers are currently on order with only ten ready for delivery by 2020. However, a balance of supply and demand in expected by 2014. The current spread of natural gas prices between the USA, Europe and Asia/Latin America is distributed in a ratio of 4:10:16 (based on US$/MMBtu[2]), thus revealing certain opportunities for LNG-based natural gas trade [IFPEN 2012]. The natural gas wholesale prices realised in different markets may indicate the directions that LNG flows could take to reach markets with maximised selling prices

In principle, all LNG import terminals with their substantial associated LNG storage capacities are suitable for LNG transhipment and distribution. A number of them are already utilised for these purposes.

[2] BTU is the amount of energy needed to cool or heat one pound of water by one degree Fahrenheit. 1 MMBtu = 1.000.000 Btu = 1055,05585262 MJ ≈ 293,071 kWh

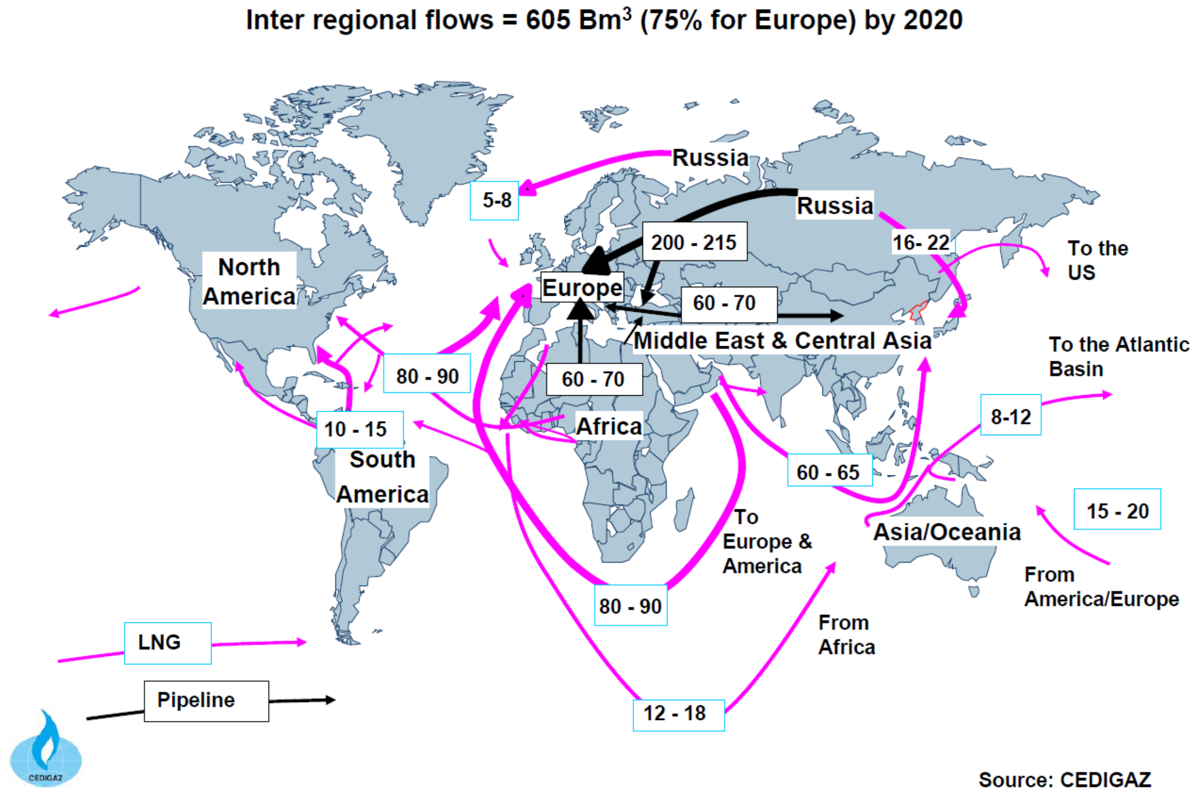

Figure 6: International trade flows for natural gas via pipeline and LNG transport by ship

Source: [Cedigaz 2011]

According to BP [BP 2011], Europe is required to double its import volumes for natural gas by 2030 due to depleted conventional natural gas fields. Statoil [Statoil 2013] estimates an ensuing supply gap (resulting from a decline in domestic production of approx. 140 billion m³ and simultaneously increasing demand by approx. 80 billion m³) of about 230 billion m³, a figure corresponding to almost 50% of the demand in 2012. Europe would have to cover this supply gap with imports from Russia, Central Asia, North Africa and with LNG imports. LNG imports to Europe would have to compete with prices on the Asian markets to successfully divert imports to Europe. At present, Asian natural gas prices exceed European prices by about 60% (which in turn exceed North American prices by 150%). BP estimates LNG imports for the year 2030 to amount to about 33% of global LNG trade, whereas Asia imports are expected to slightly exceed 52% [BP 2011].

4.5 Proposed regulations and infrastructure initiatives

4.5.1 EU infrastructure directive (AFID, draft)

The original directive draft COM (2013) 18 final [COM 2013] of the European Commission from 24 January 2013 on fuel infrastructure includes the following regulations for LNG according to the revised version of the EU Council of Transport [AFID 2013]:

- The member states are obliged to establish an LNG fuelling station infrastructure for seaports and inland ports allowing ship transport between the core network of seaports of the Trans-European Transport Network (TEN-T) by 31 December 2030. Member states may cooperate with their neighbours to ensure adequate coverage of the fuelling station network.
- The member states are obliged to establish adequate numbers of LNG fuelling stations in inland ports of the core network of the Trans-European Transport Network (TEN-T) (Figure 7) by 31 December 2030. Member states may cooperate with their neighbours to ensure adequate coverage of the fuelling station network.
- All member states join forces to ensure the establishment of an adequate number of public LNG fuelling stations along the TEN-T main corridors by 31 December 2030, thus enabling LNG-powered HDVs to refuel and operate across the entire European Union.

Figure 7: German ports within the TEN-T core network

Source: Figure: LBST, ports: http://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/main.jsp

4.5.2 LNG Blue Corridors Project

This project funded by stakeholders and subsidised by the EU is coordinated by the NGVA Europe (Natural & bio Gas Vehicle Association Europe). The LNG Blue Corridors Project aims for the implementation and demonstration of four pan-European transport corridors for long-distance transport (Figure 8), i.e. from Portugal/Spain to France, the UK and on to Ireland; from Portugal/Spain to France, Germany, Denmark and on to Sweden; from the Mediterranean to Italy and with one extension on to Croatia; and from Ireland/UK via Germany to Austria. The LNG Blue Corridors Project further aims to provide a connection with the Danube Inland Waters Blue Corridor that is projected to extend from Romania to Vienna. Thus, it integrates the AGRI (Azerbaijan-Georgia-Romania-Interconnection) Initiative that aims for an LNG supply relation from Azerbaijan via Georgia and Romania to Central Europe.

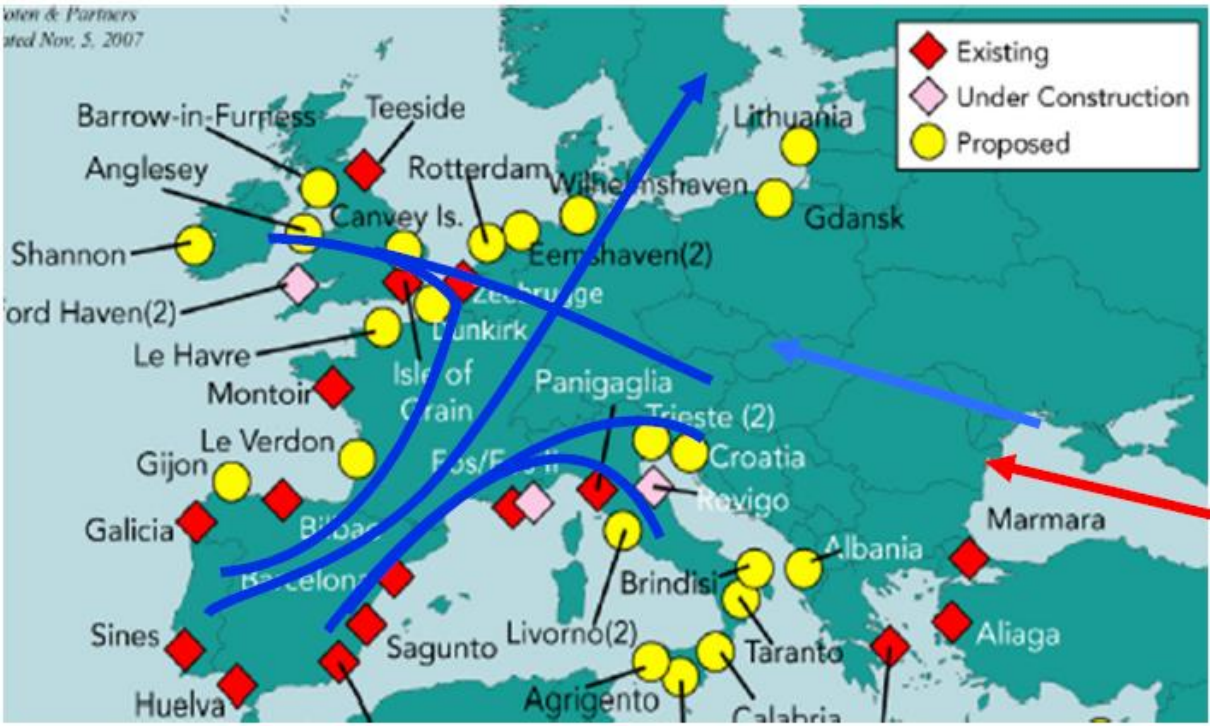

Figure 8: Proposed transport corridors and locations of LNG fuelling stations in Europe in context of the 'LNG Blue Corridors Project'

Source: [Lage 2012]

The EU project includes the construction of about 14 stationary or mobile LNG fuelling stations (LNG, LCNG) along critical long-distance hubs as well as a fleet development of about 100 LNG commercial vehicles along the corridors. Aims of the initiative include capacity building and raising public awareness for LNG as a fuel for medium- and long-distance road-based freight transport. The project is scheduled to run for four years, covers 12 EU member states and aims to synchronise with local LNG activities. The initiative integrates experience in LNG transport and infrastructure technology and fosters cooperation between commercial vehicle manufacturers, fuel suppliers, fuel distributors and fleet operators.

5 Status quo for engines and infrastructure technology

This chapter describes the status quo for the application of LNG with regard to propulsion technology, fuel supply and storage including safety aspects. For this purpose, advantages and disadvantages of existing technologies and the associated opportunities and limits for application are discussed. The individual characterisation is carried out separately for maritime transport, inland navigation and HDVs. The final Subchapter 5.3 concludes with an overall summary for each mode of transport.

5.1 Technological aspects of the application of LNG in maritime transport

In maritime transport, two different engine concepts for the application of LNG are currently available: mono-fuel engines exclusively powered by LNG and dual-fuel engines that either run on blends of diesel and natural gas, or switch between operation with diesel and gas. Engine technology for dual-fuel operation is further sub-divided into low-pressure and high-pressure concepts. High-pressure models are based on the principles of the Diesel Cycle. As such, they are associated with pressure levels between 300-350 bar for compression ignition. In consequence, compression ignition requires the proportion of gas in the blend to be raised gradually with increasing engine temperature during operation. The maximum gas proportion contained in the diesel-gas blend may be raised to approx. 80%. Dual-fuel engines with low-pressure technology employ the Otto Cycle with a proportion of gas of about 99%. A small amount of heavy fuel oil is required for fuel ignition via compression. Both dual-fuel engine concepts are suitable for the conversion of installed conventional engines. Mono-fuel ship engines exclusively powered by natural gas employ a spark plug for ignition in the Otto Cycle. Oil blends are thus obsolete during ignition or operation [IMO 2012, p. 49 ff., MARINTEK 2011, p. 11 ff., WÄRTSILÄ 2011, p. 13 ff., RR 2003, p. 13 ff.]. Relevant engine characteristics influencing operation, LNG supply and environmental impacts are illustrated in Table 5.

In sum, engine technology in maritime transport does not constitute a major obstacle for the application of LNG. This conclusion is confirmed by the results of the Magaloc Project [Magaloc 2008, p. 23]. Both options, dedicated LNG operation (e.g. more than 140 units sold by Rolls Royce/MTU) or dual-fuel (e.g. more than 140 units sold by Wärtsilä), are well-established [Wärtsilä 2011, p. 23, RR 2003, p. 8].

Major manufacturers of engine technology commonly focus on one concept for research and development. The coming years are expected to be a transition period that will see increasing utilisation of dual-fuel engines which are distinctly favourable due to their flexibility. Ship operators may elect to vary their utilisation of diesel and gas fuels depending on volatile demand and price development, available tank capacity (of the ship) and the area of operation [Gätjens 2013, Motorship 2013].

Table 5: Engine concepts for LNG application in ocean-going vessels

<table>
<tr><th colspan="3">Dual-fuel engine</th><th>Gas engine</th></tr>
<tr><th colspan="2">2-stroke engine</th><th colspan="2">4-stroke engine</th></tr>
<tr><th>High-pressure engines</th><th colspan="3">Low-pressure engines</th></tr>
<tr><td>Combustion process: Diesel</td><td colspan="2">Combustion process: Diesel (MGO/HFO) or Otto (methane)</td><td>Combustion process: Otto</td></tr>
<tr><td>Max. 80% methane, Min. 20% diesel or HFO under full load</td><td>99% methane, 1% diesel or/ HFO (Pilot Fuel) under full load</td><td>99% methane, 1% Diesel or HFO (Pilot Fuel) for the entire power output range</td><td>100% methane</td></tr>
<tr><td colspan="3">100% diesel/ HFO possible (e.g. outside the ECA Zone)</td><td>No operation with diesel/HFO</td></tr>
<tr><td colspan="2">Ignition via diesel-/HFO-injection into the combustion chamber</td><td>Ignition via diesel-/HFO-injection into a precombustion chamber (‘liquid spark plug’)</td><td>Ignition via spark plug</td></tr>
<tr><td>Exhaust gas after-treatment required to comply with IMO Tier III[3]</td><td colspan="3">Compliance with IMO Tier III[3]</td></tr>
<tr><td colspan="2">Minimal methane slip[4]</td><td>Methane slip[4] lower than 4-stroke gas Otto engine</td><td>Methane slip[4] presents a challenge</td></tr>
<tr><td>Robust to changes in gas quality</td><td colspan="2">Sensitive to changes in gas quality (No performance loss for methane number > 80)</td><td>Relatively robust to changes in gas quality (No performance loss for methane number > 70)</td></tr>
</table>

Sources: [Wärtsilä 2013a], [Wärtsilä 2013b], [Wärtsilä 2011], [Marintek 2011], [RR 2003]

Moreover, the potential for retrofitting of conventional engines with dual-fuel technology presents a distinct advantage. However, supporters of dedicated gas (or diesel) engines point out the superior efficiency and performance of engines optimised for a single fuel. Dual-fuel engines thus represent a compromise with associated losses [Motorship 2013]. In addition, ships with fixed routes may plan required bunkering in advance, thus rendering engine flexibility obsolete.

[3] The Tier Standard (I-III) defines NO_x quantities (g/kWh) acceptable for emission in Emission Control Areas. The Tier III Standard will enter into force in 2016 with a significant reduction of NO_x emissions relative to Tier I and II.

[4] Methane slip is the loss of uncombusted methane escaping from valves.

An important challenge for operators is the optimisation and reduction of energy consumption in ships. A fundamental innovation is the utilisation of boil-off gas escaping during transport. The proportion of gas thus lost, i.e. the boil-off rate (BOR), is dependent on tank volume and the ratio between volume and tank surface area [UDE 2011, p. 12, Sedlaczek 2008, p. 75]. Science assumes an approximated rate of 0.15% per day or per shipping unit [Sedlaczek 2008, p. 59, Moon 2007, p. 2].

The storage of LNG requires a cryogenic tank. A number of different constructions and models are feasible and currently available [CHAL 2010, p. 11, GL 2012, p. 35 ff.]. These tanks may be integrated into the ship body or installed outside. The stabling of LNG containers or trailers presents a mobile option (e.g. a 40-foot ISO container acting as a storage tank in a container depot). Despite the fact that one study criticises the lack of docking facilities in mobile refuelling facilities [GL 2013, p. 81 ff.], the German TÜV has already approved several container systems [MS 2012]. However, a standardised (European/global) solution for the maintenance of a universal standard is lacking. An associated hazard of LNG storage is the unrestricted escape of LNG and the flammability of the escaping gas in case of a damaged tank or bunker pipeline [SuS 2012, p. 22]. Refuelling facilities on vessels are already fitted with a number of available systems. Thus, these present no explicit barriers to the introduction of LNG as a fuel in maritime transport.

There are four different approaches to refuel a tank with LNG after [GL 2013, S. 13]:

❶ Refuelling with a small LNG tanker,

❷ Refuelling from an HDV via pipeline,

❸ Refuelling via pipeline connecting to a permanent refuelling station (terminal/pipeline) and

❹ Through the exchange of the mobile tank on-board the vessel.

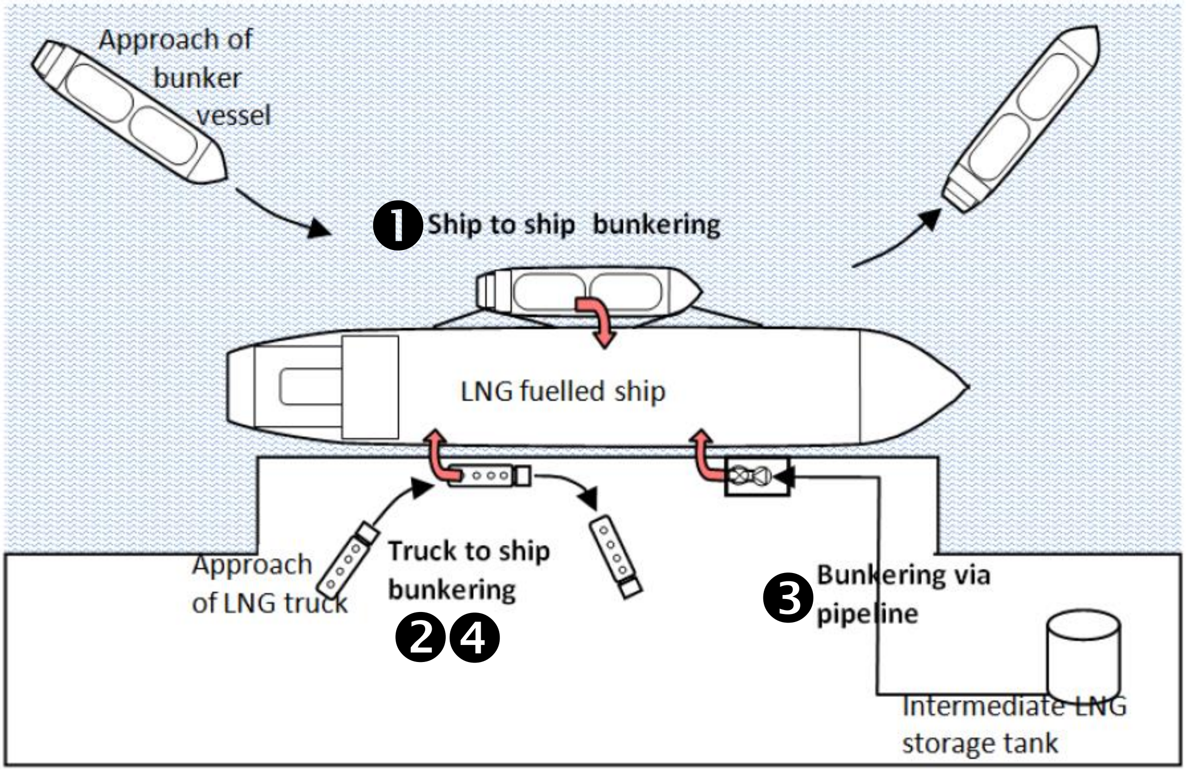

Figure 9: Options for bunkering of LNG in ocean-going vessels

Source: adapted from [GL 2012]

Technically, all four options are feasible. However, they are associated with specific advantages and disadvantages. The BMVI commissioned a study on the 'Bunkering of liquid gases in German ports' that summarises these pros and cons (see Table 6). Another study analysed 15 separate criteria and identified the bunker option ship-to-ship as superior to the alternatives, followed by application of mobile tanks (2nd place), truck-to-ship (3rd place) and finally terminal-to-ship [GL 2012, p. 40]. The EU-subsidised 'North European LNG Infrastructure Project' recommends the refuelling with the ship-to-ship approach after consideration of the LNG market. Consideration was further given to economic aspects of the ports, technological feasibility, logistics and safety and environmental concerns, as well as regulatory criteria [DMA 2012, p. 119-123, p. 187]. However, the utilisation of mobile tanks was excluded in this study. Refuelling with the ship-to-ship approach is currently viewed critically by port authorities due to hazards associated with port traffic restrictions caused by transversal vessels (short off-hire periods with rapid refuelling are less of a challenge). Furthermore, escape of LNG due to leakage and collisions and the ensuing fire hazards are controversial [GL 2012, p. 55].

Table 6: Advantages and disadvantages of LNG bunker options according to Figure 9

	Refuelling mode	Pro	Contra
❶	**Ship-to-ship**	Flexibility High bunker rates Large bunker volumes Bunkering in port possible	Costly infrastructure
❷	**Truck-to-ship**	Flexibility Low infrastructure cost	Low transfer volumes Low bunker rates
❸	**Terminal-to-ship**	Availability High bunker rates Large bunker volumes	Dedicated pier Blocking of port area Costly infrastructure Second mooring required
❹	**Mobile tanks**	Simple logistics (hazmat container) Regular transhipment Ready availability	Costly tanks Extended effort during loading/ unloading

Source: own representation after [GL 2012]

Two studies examined the legal situation regarding bunkering procedures. One arrived at the conclusion that in Germany, '(…) the bunkering of LNG in the general port area (outside tanker ports and excluding permanent refuelling structures) is currently not permitted.' [GL 2012, p. 54]. A second study commissioned by the European Maritime Safety Agency (EMSA) incorporated the detailed description of existing EU regulations for bunkering procedures into the project `Study on Standards and Rules for bunkering of gas-fuelled Ships' and identified the following challenges [GL 2013, p. 81 ff.]:

1. "The entire use of LNG as marine fuel and LNG bunkering procedures are not regulated by IMO requirements and standards as LNG is formally not fully recognised as fuel for the time being;
2. The future status of the ISO Technical Report on LNG bunkering within the international rule framework will have to be reinforced through references in other common Standards and/or legal texts;
3. The definition of the bunkering process and the division of responsibilities for bunkering LNG as fuel is not covered by the Technical Report of the ISO TC 67 WG 10. Responsibilities mentioned in the current Draft IGF Code are limited to the Ship to Ship transfer;
4. A conceptual delineation between transfer of LNG as cargo and bunkering of LNG as fuel is missing;
5. The connection and disconnection process of portable LNG fuel tanks is not defined in the current draft of the IGF Code and the Technical Report of the ISO TC 67 WG 10;
6. The absence of appropriate rules relating to the transportation of LNG on European inland waterways affects the lack of construction requirements for LNG inland tankers, bunker barges and gas-fuelled inland waterway vessels;
7. The use of LNG as fuel is not permitted on inland waterway vessels in general and is only possible by exemptions by the CCNR, which consequently does not stimulate the creation of larger LNG demand;

8. Despite the large range of national legislation, further guidance or Standards for small scale LNG bunkering stations could be developed using current best practices;
9. Despite various industry driven initiatives common guidelines for port rules on LNG bunkering procedures are not yet available;
    9.1. A common risk assessment approach and risk acceptance criteria for LNG bunker procedures are missing, which requires each port to develop its own standards with potential differences as a result;
    9.2. 9.2 Despite various applications of gas-fuelled cargo and passenger vessels the definition of detailed safety requirements for simultaneous LNG bunkering and loading / unloading or passenger embarking / disembarking processes are missing;
    9.3. Indicators for determining common safety distances and identification of LNG bunkering processes are currently missing;
    9.4. Common safety accreditation criteria for LNG bunker companies are missing;
    9.5. Additional measures for LNG bunker operations within emergency plans should be considered;
10. Crew training requirements for LNG carrying or fuelled inland vessels and barges not exist and have to be developed especially with a view on using inland barges as bunker barges;
11. No International Standards for the specification of LNG as marine fuel are available;
12. No requirements and guidelines are available for the measurement of the sulphur content of LNG as fuel;
13. A Standard for the safe sampling of LNG as fuel is missing;
14. No Standard is available for the Standardisation of the equipment for the connection of communication devices and process monitoring including Emergency Shut Down (ESD) between the LNG delivering facility and the receiving gas-fuelled vessel;
15. Procedures and equipment for gas measurement are missing;
16. Operational guidelines need to be developed to reduce potential negative environmental impacts related to the possible release of methane."

In sum, existing legislation and regulations on bunkering procedures are in need of revisions to permit the utilisation of LNG as fuel. Furthermore, a distinct lack of standards for technology and bunkering procedures was revealed in the studies, which urgently recommend the definition of a universal set of rules.

LNG-powered vessels may currently be serviced at nine LNG production facilities in northern Europe (5 in Norway, 3 in Russia and 1 in Finland). Furthermore, there are one or more LNG storage terminals located in Belgium, the Netherlands, the United Kingdom, in Sweden and in Norway [GL2012]. In addition to the existing facilities, a number of plans for infrastructure development are submitted or authorised, particularly in the Baltic Sea (see Figure 10).

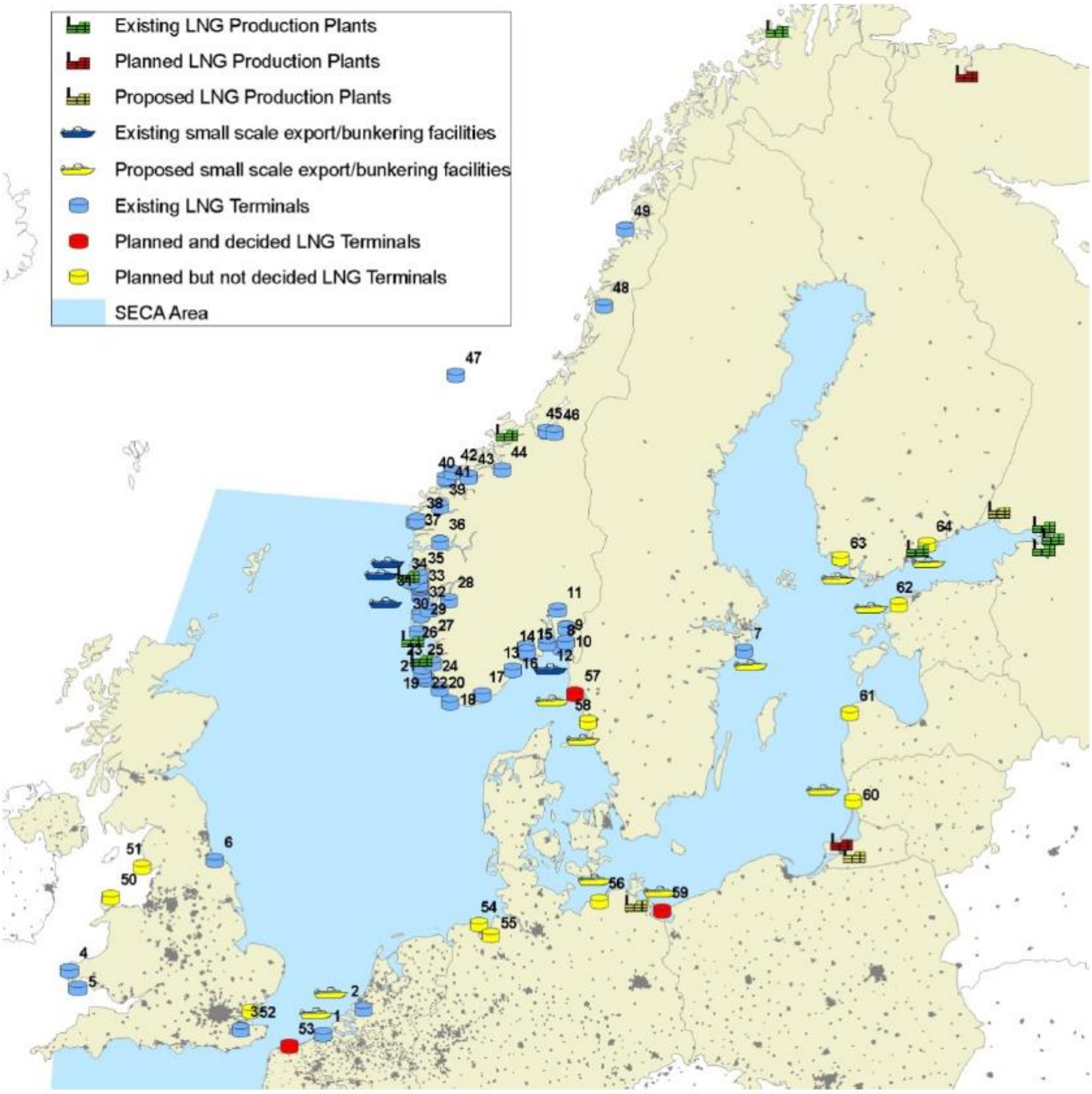

Figure 10: Planned development of LNG terminals in the North and Baltic Seas

Source: [GL 2012]

Development trajectories for LNG infrastructure are currently under investigation in two European projects. The first project focuses on the Baltic Sea (LNG in Baltic Sea Ports) whereas the second examines southern Europe (COSTA; CO_2 & Ship Transport emissions Abatement through LNG). Pre-requisite for these projects was an infrastructure analysis integrating the views of ship operators, ports and LNG supplies in the study `North European LNG Infrastructure Project‘ [DMA 2012]. The ship operator perspective revealed the following aspects [DMA 2012, p. 61]:

- For ship operators, the switch to alternative fuels/ exhaust after-treatment signifies an investment. There is no actual benefit, rather a comparison of the alternatives with respect to investment and operation costs to identify the most economic option.
- Many procedures are likely to change (e.g. the bunkering of LNG is notably slower than oil).

- Marine diesel oil presents an attractive holding pattern for ship operators until the structural challenges associated with LNG are resolved.

The following recommendations for infrastructure development in ports were issued [DMA 2012, p. 146 ff.]:

- A decisive factor for the construction of LNG terminals in addition to supply with conventional fuels is the structure of the respective port.
- In all likelihood, the initial demand for LNG will be from vessels with fixed and relatively short routes primarily in the Baltic Sea, or coastal shipping in the North Sea.
- The supply of vessels with an irregular schedule will only be possible with small/medium-size tanks or tanker vessels. Planning ahead, and anticipating supply and demand will be crucial in the introductory stage of LNG.
- Small and medium-size terminals are likely to break even only with additional shore-based demand. Cooperation with relevant stakeholders and their demands is vital for economic infrastructure development.

LNG suppliers are unlikely to develop additional infrastructure in absence of substantial increases in demand. At present, demand is too low to warrant major infrastructure development [DMA 2012]. Moreover, there is little common consensus or a universal set of regulations within the European Union pertaining the duration of legal authorisation procedures or the number of steps required in the proceedings for approval [DMA 2012]. National regulations may thus impede or desynchronise infrastructure development, which in turn may lead to competitive advantages or disadvantages.

The quality of the gas (methane number) represents another important factor influencing infrastructure development, because the available engines depend on the available methane number (see Chapter 5.1). The methane number (MN) is dependent on the natural gas composition of the respective country-specific resource (e.g. Trinidad MN 87.4 or Nigeria MN 69.5 [MARINTEK 2011, p. 17]).

In sum, ship and infrastructure technology are sufficiently available on the market to allow the utilisation of LNG as fuel. Impediments are presented in the lack of non-technical, formal instruments such as regulations and guidelines, standards etc. In some instances, these may be a distinct barrier and a serious obstacle for the application of LNG in maritime transport.

In addition to ship and infrastructure technology, bunkering procedures and LNG storage and their associated development potentials are discussed in the following.

LNG storage and handling for refuelling purposes are currently not carried out in a globally uniform manner. Thus, harmonisation is paramount to ensure (efficient) availability of LNG for diverse ship models in different ports. For this purpose, refuelling procedures and the associated equipment require standardisation. Furthermore, sea ports should seek to promote uniform levels of gas quality due to the fact that engine technology is dependent on gas quality [DNV 2012].

The need for universal regulation of gas as a ship fuel has recently prompted the IMO to engage in the drafting of the *International Code of Safety for Gas-fuelled Ships* (*IGF Code*). The code lays claim to be adopted as the internationally recognised instrument of regulation. It is expected to be completed in 2014, in time to be included in the revisions of the *International Convention for the Safety of Life at Sea* (*SOLAS*). After a period of two years, the regulations will enter into force in 2016. From this date, all vessels built in compliance with the IGF Code will reflect an international standard that aligns the safety standards of gas-powered vessels with those of conventional oil-powered vessels. The bunkering of liquid gas is also subject to the drafting of a universal standard which has been in progress since July 2011. A work group at the *International Organisation for Standardization* (*ISO*) is currently in the process of defining *Guidelines for systems and installations for supply of LNG as fuel to Ships* [GL 2012, S. 140 ff.].

In a recent study for the *European Maritime Safety Agency* (*EMSA)* published in February 2013, the *Germanischer Lloyd* illustrates 20 different conceivable activities within a port for the utilisation of LNG, thus indicating novel services and source of income associated with LNG.

To retain competitiveness with conventionally-powered vessels, refuelling with LNG requires streamlining to function without a hitch similar to the handling of conventional fuels. In consequence, refuelling, loading/unloading of cargo and the boarding of passengers should be carried out simultaneously [GL 2013].

Due to the as yet very slight demand for LNG as a ship fuel, delivery of the liquefied gas and refuelling of the vessel is currently carried out directly by truck [GL 2013]. One truck is able to supply 55 m^3 of fuel and the refuelling procedure takes about 90 min [MAGALOG 2008, p. 34]. Several truck loads are required depending on the size of the vessel. Sea-based refuelling ship-to-ship under current regulations is permitted only in tanker ports [GL 2012, p. 53], yet it presents the preferable bunkering option. Revision of the regulations is required in the near future to enable the operation of tankers in regular ports or at sea (close to the coast), thus extending the flexibility of LNG utilisation. The expected increasing demand is unlikely to be contained by truck-to-ship refuelling alone in sufficient scope and a cost-efficient manner. On the contrary, ports are expected to install large-volume storage facilities [MAGALOG 2008]. The intended construction of two dozen LNG terminals and bunker facilities in the coming years in the North and Baltic Seas alone illustrates this development (see Figure 10). The final report of the 2008 MAGALOG Project focuses on five ports in four coastal states of the North and Baltic Seas and attests Bergen (Norway), Gothenburg and Stockholm (Sweden), Lübeck/Travemünde (Germany) and Świnoujście (Poland) the potential for LNG bunkering in principle. Subsequent steps will depend on the respective port, the actual location and construction of the LNG terminal (in Bergen, a terminal already exits), agreements for long-term supply with shipping companies to provide planning security as well as the extended application of LNG particularly in regional shipping. In the Hanseatic City of Lübeck, the extensive and increasing fleet of RoRo and RoPax ferries connecting the port to a number of destinations in Northern Europe presents a promising outlet for the application of LNG. However, most vessels there are relatively new, thus a conversion to LNG technology will in all likelihood be gradual [MAGALOG 2008].

5.2 Technological aspects of the application of LNG in inland navigation

At present, most cargo vessels in inland navigation are equipped with diesel engines renowned for their reliability and energy efficiency. For the majority of inland vessels, the total engine power ranges between 100 and 4000 kW, which is generally rather modest compared to ocean-going vessels. The nominal capacity of engines may often be distinctly lower than the total engine power, e.g. due to operation with several small engines in sizes designed for HVDs.

At present, the number of LNG engines for inland vessels on the market is relatively small. Drive concepts available for operation today include:

- Mono-fuel engines, and
- Dual-fuel engines

Mono-fuel engines are dedicated for operation with natural gas und employ the Otto engine principle, which carries out combustion via external ignition. These engines are primarily utilised in stationary applications, e.g. generators, but also in motor vehicles (mostly CNG passenger cars or buses). The advantages of mono-fuel engines include distinctly lower pollutant emissions. They are characterised by very low particulate matter emissions and low nitrous oxide (NOx) emissions due to lower combustion temperatures compared with diesel engines. The energy efficiency of mono-fuel engines is high particularly in the high-performance range [Panteia 2013]. Additional efficiency improvements are expected through the operation of ship engines with LNG-Electric propulsion, i.e. in combination with a generator. This concept is realised in the first Dutch mono-fuel tanker vessels on the Rhine, the 'Greenstream' (launched in 03/20130 and the 'Green Rhine' (launched in 09/2013). In these vessels, two separate engine units with two gas engines provide power according to demand and allow optimal load management [Shell 2013]. The biggest disadvantage of mono-fuel engines in comparison with dual-fuel engines is the lack of fuel flexibility. Mono-fuel-powered vessels may only operate in waterway corridors equipped with an LNG refuelling infrastructure, or they require an additional diesel engine on board. Longer distances may only be travelled with an LNG tank of appropriate size. Moreover, the low pressure in the cylinder is associated with an increased risk of so-called methane slip, i.e. the escape of uncombusted methane (see GHG emissions in Chapter 7.2.1). Methane slip may be prevented with a methane slip catalytic converter [Panteia 2013].

In analogy to diesel engines, dual-fuel engines are operated with compression ignition. Ignition is always carried out with diesel fuel. High-pressure dual-fuel engines retain the characteristics of diesel engines. The LNG proportion may amount to a maximum of 80%. In low-pressure dual-fuel engines, ignition of the natural gas happens with diesel, yet in gas-powered mode, a gas-air blend is injected and combusted under low pressure in analogy to Otto engines. The biggest advantage of dual-fuel engines lies in their fuel flexibility allowing travel in corridors without LNG infrastructure. The efficiency in gas mode is comparable to a diesel engine, and the risk of methane slip is generally low in high-pressure dual-fuel engines. Disadvantages in comparison with mono-fuel engines may be found in the elevated NOx emissions due to high combustion temperatures. Moreover, all advantages are lost when operation is switched to diesel only. The first LNG vessel on the Rhine with dual-fuel engine was the MTS Argonon, a tanker vessel with a capacity of 6100 t [Argonon Shipping 2013].

In addition to the vessel's main engines, inland waterway vessels are frequently equipped with auxiliary power units or engines, e.g. for electricity generation on board. These are small engines designed for mobile machinery or equipment. In principle, gas engines could be utilised for these purposes as well if the vessel is fitted with an LNG tank. Thus, electricity supply via gas generator could help curb pollutant emissions relevant in port areas.

LNG on-board inland vessels is stored in so-called cryotanks. Despite the significantly higher density of LNG in comparison with e.g. CNG, the energy equivalent of LNG to diesel requires a storage volume that exceeds that of diesel by factor 1.8. The additional requirements for storage space present a major challenge for towboats and smaller vessels. The associated investment in cryotanks is also higher compared with diesel or methanol tanks [Panteia 2013; TNO 2011].

There are two options for LNG supply of inland vessels: natural gas may be delivered via the gas grid with on-site liquefaction in inland ports, or LNG could be supplied with tanker HDVs [GL 2012]. An alternative to pipeline refuelling is the utilisation of mobile tank containers, suitable in particular for container vessels. A trial LNG bunker station aimed to support the operation of the first LNG tanker vessels between Rotterdam and Basel is currently in operation in the Port of Rotterdam [Shell 2013b]. Bunker stations in Germany are further proposed for the ports of Hamburg and Rostock [Panteia 2013] with further extension into the hinterland discussed along the Rhine and the Danube [Seitz 2012]. The previous EU directive draft of the Council of Transport on the establishment of an infrastructure for alternative fuels demanded an LNG infrastructure for sea and inland ports by 2030 to allow ship transport along the TEN-T core network at least [AFID 2013]. Thus, in addition to Rhine and Danube, the Mitteland Canal and the Elbe would be navigable for LNG vessels. The consequences of an increased density of refuelling infrastructure would include the development of LNG supply along the inland waterway network. In addition, smaller tanks could be utilised to improve the application potential for smaller or existing vessels [Panteia 2013].

The central authority for inland navigation in Germany is the German Federal Waterways and Shipping Authority (*Wasser- und Schifffahrtsverwaltung des Bundes*, WSV). The German Federal States (*Länder*) are responsible for the administration of state inland waterways, state-owned ports, shipping in state-owned areas and monitoring of safety and feasibility of ship transport within the state territory. Thus, specific functions and responsibilities may be regulated in the framework of state legislation. Strictly speaking, the operation of inland vessels with liquefied natural is technically prohibited. However, dispensations are possible in certain cases based on the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways ('ADN') and the Regulations for Inspection of Ships on the Rhine (*Rheinschiffsuntersuchungsordnung*, RheinSchUO) [GL 2012].

Safety concerns primarily focus on the escape of LNG after tank or pipeline damage, e.g. in the form of so-called 'rapid phase transition' [DOE 2012] of LNG in combination with water or explosions of the highly flammable gas in combination with air. Potential hazards include:

- Human error, e.g. errors during ship manoeuvring and in communication between involved parties (bunker vessel, recipient vessel, harbour authority).
- Technical errors, e.g. system or machinery failure or operational faults

In emergencies, technical concepts for rapid cut-off of gas supply and disconnection of ships must be in place. For this purpose, gas sensors are employed for safety monitoring. Bunkering of LNG for inland vessels is subject to stricter safety regulations than for ocean-going vessels due to the close proximity of inland ports to densely populated areas with limited space for navigation and dense traffic.

Additional important regulations for the utilisation of LNG in inland navigation include:

- Construction and equipment regulated with Inland Navigation Ordinance (EU regulations)
- LNG as fuel not permitted (flashpoint below 55°C)
- Permit for bunkering and bunker site is issued by local port authority

5.3 Technological aspects of the application of LNG in heavy-duty vehicles

Overall, the technology for utilisation of LNG in HDVs is available, although at present there are only isolated models on the market. Compliance with pollutant standard EURO VI is already possible with dedicated natural gas engines [LO 2013]. For the dual-fuel engines, the target of compliance with EURO VI has not yet been accomplished. However, according to experts, there may not be a technical solution feasible for implementation.

The option to utilise biogas or RE methane in the form of LNG may yet pave the way for realising a CO_2 neutral drive technology for HDVs. Advantages, disadvantages and economic factors of LNG in combination with user requirements have to be weighed against alternatives such as renewable liquid fuels (e.g. biodiesel, power-to-liquids) or hydrogen and fuel cells in the framework of a long-term decarbonisation strategy. Every energy conversion step in addition to the generation of the primary storable medium (i.e. hydrogen) is associated with additional primary energy loss, e.g. for methanation, liquefaction or synthesis into liquid hydrocarbons. These losses increase when CO_2 for further synthesis is extracted from air. Further details may be found in the MFS study 'Renewable energies in transport'.

Technical components of both LNG refuelling infrastructure and LNG tanks and combustion engines are available. Natural gas is already utilised in a number of vehicles. For instance, IVECO offers a tractor unit of the model Stralis that is operated as a mono-fuel vehicle with dedicated a gas engine based on Otto engine principles [NGVA 2013]. With the Econic model, Mercedes also offers an HDV with gas engine specially designed for collection and distribution purposes in inner city areas. Emissions of CO_2, pollutants and noise are lower in the Econic [Mercedes 2013]. The Otto engine is able to process the gas supply with the aid of an additional compact heat exchanger heating the coolant of the ZF intarder that is standard in these gas engines. Thus, cold LNG is converted to reactive CNG feeding propulsion via injection [LO 2013].

Dual-fuel engines may currently be found in vehicles of the model Mercedes Actros [Erdgas Mobil 2013] and Volvo FM [Volvo 2013b]. MAN offers the technology, which is based on diesel engines, in vehicles in the bus sector in South America (Volksbus 17.280 OT with dual-fuel technology) [MAN 2012]. According to the company, the technology is currently in development for realisation in European HDVs [MAN 2013]. To date, dual-fuel engines are sold as Euro V (Volvo) and as vehicles of the emission class EEV (Mercedes).

Advantages or drivers for the utilisation of LNG are discussed in Chapter 3 (Drivers). However, disadvantages of the operation of HDVs with LNG have to be taken into consideration also:

- Based on dual-fuel technology in diesel engines, vehicles available to date only comply with the emission classes EURO V or EEV. Dedicated gas vehicles with Otto engines achieving compliance with EURO VI via 3-way catalytic converter are already available from one manufacturer [LO 2013].
- Dedicated gas engines achieve lower energy conversion efficiency than diesel engines with very few exceptions (e.g. Cummins Westport ISX G 12.0).
- To retain diesel compression ignition, dual-fuel engines may utilise a maximum of 70% methane in the best case scenario. Under consideration of actual drive cycles, the degree of substitution according to [CW 2013} typically ranges between 50 and 60%. [Gasrec 2013] report 64% substitution of diesel through methane in their LNG demonstration project with Kühne & Nagel Logistics. Depending on the practically realised ratio of fuel injected (parts diesel and gas, incl. the part of drive performance powered by diesel only), the environmental benefits over dedicated diesel engines are reduced. This is due to the fact that diesel combustion is inevitable in both concepts. Therefore, benefits of the utilisation of LNG have to be assessed depending on user plans for utilisation and opportunities for refuelling with LNG.
- LNG tanks in vehicles are heavier than diesel fuel tanks. The maximum permitted load for HDVs is thus reduced.
- LNG stored in the vehicle tank eventually warms up, thus increasing the pressure in the tank. If the pressure levels rise above a threshold, a valve automatically discharges natural gas (greenhouse gas) into the environment. Standing times of up to several days are possible without gas discharge depending on the temperature of LNG during refuelling. In case standing times of 2-3 days are expected, the tank should only be filled 50-70%. Longer standing times required adaptation of the filling level of the LNG tank [Indox 2013]. According to Daimler, the 5 days of holding time mandatory in the USA (time period until the safety valve opens for emergency discharge of methane) are realised [Daimler 2013].

The industry offers refuelling of LNG-HDVs at small to medium-size LNG facilities with an annual production capacity of 50,000-3,000,000 t. The required LNG is liquefied on-site with natural gas supplied by the gas grid [Linde 2013]. LNG tanks for HDVs are also available on the market, e.g. by the manufacturers Westport [Westport 2013] or Indox [Indox 2013]. However, the refuelling procedure requires specific training for drivers who are required to wear protective clothing. The refuelling procedure itself does not take significantly longer than the refuelling with diesel. Utilisation of dual-fuel technology prolongs the refuelling procedure due to two separate refuelling steps with different fuels.

In addition to the distribution of LNG in fuelling stations with on-site liquefaction facilities, there is the option of LNG distribution from seaports (and potentially inland ports at a later stage) via tanker truck. This option requires the development of associated infrastructure and logistics for exhaustive coverage. According to experts at the work shop of the BMVBS on 05.09.2013, the development of such an infrastructure has merit in combination with simultaneous development of inland port infrastructure.

5.4 Summary of the status quo for LNG application

The technological requirements for the utilisation of LNG in **maritime transport** are met. However, regulations and standards are not yet adapted for implementation. The fact that LNG does not qualify as an approved fuel for maritime transport presents a particular formal impediment, and currently acts as an immovable barrier. Moreover, both the current level of infrastructure and the uncertain prospects for development do not provide an encouraging base for ship operators aiming to plan ahead. On the other hand, uncertain levels of demand are at present discouraging LNG suppliers to expand their plans.

In **inland navigation**, the technology for LNG utilisation is already sufficiently mature for implementation. Required engine and fuel storage technologies are readily available, and refuelling concepts exist. Pilot projects have already seen the launch of the first LNG vessels on the Rhine. Furthermore, specific plans and proposals for the development of LNG bunker infrastructure have been submitted. A major impediment for the utilisation of LNG in inland navigation at present is the lack of consensus on the regulatory framework for registration and approval, e.g. approval of fuel and bunkering safety regulations.

The utilisation of LNG in **heavy-duty vehicles** is technologically feasible. However, for compliance with emission standard EURO VI and in the field of engine efficiency, innovation and development of combustion engines is needed. This includes both dedicated gas engines and dual-fuel concepts. The refuelling infrastructure in compliance with appropriate safety standards has to be raised from the ground up. However, suppliers ready to present relevant technological solutions already exist.

6 Scenarios for the development of energy demand for LNG

The following chapter explores potential scenarios for energy demand for LNG in the year 2030.

Maritime transport is analysed separately due to the fact that it is relevant on German territory and in international shipping alike. Potential trajectories for the North and Baltic Seas are discussed based on data from the literature (Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**).

In contrast, it is possible to explore inland navigation and road freight transport within Germany in light of the expected transport volume. For this purpose, the distribution of transport, the expected utilisation potentials for LNG and specific consumption factors for inland vessels and HDVs are considered (Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**). To illustrate the potential range of future LNG demand, both a moderate and an accelerated introduction model for LNG were investigated. Based on these findings, the demand for LNG in each respective transport sector is assessed under consideration of availability, supply security and integration of renewable energies (Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**). Moreover, the results indicate potential contributions to the relief of environmental burdens, especially the reduction of greenhouse gases (Chapter 7).

6.1 Maritime transport energy demand in the North and Baltic Seas

The assessment of maritime transport is restricted by lack of data for integration of national consumption levels into emission calculations. Thus, integration into the studied scenarios is incomplete. The limits are:

- Seagoing vessels are extremely variable in size, engine performance, drive mode and in consequence, consumption. Specific consumption across all ocean-going vessels could not be reliably determined.
- There is no statistical record of mileage and transport performance of seagoing vessels in German Waters.
- Data on fuel consumption in German Waters are not recorded. The following sources were consulted: official mineral oil data of the Federal Republic of Germany, energy balance of Germany, websites of ports, IEA Statistics. [IEA 2013] reports sales figures for the sale of bunker fuel oil in Germany (2,172,000 t in 2012). However, this figure does not reveal consumption in Germany or on German territory.

For the reasons above, the present short study characterises utilisation potentials for LNG in maritime transport in the entire North and Baltic Sea area based on published data to estimate LNG demand in 2030 independent of the country of origin of relevant transport.

In principle, all ships in maritime transport are suitable for operation with LNG due to readily available engine and bunker technology. However, the actual area of application is in all likelihood limited by the scarcity of refuelling infrastructure available at present or in the medium-term future. In this context, transport with fixed routes between ports with existing infrastructure appears particularly promising.

The most relevant types of ships for initial application in the North and Baltic Sea area are Ro-Ro/RoPax ferries and super-fast ships with a total of about 370 in operation in the North and Baltic Seas [Magalog 2008]. Only a substantial increase in demand is going to initiate development in addition to expansion measures already planned [DMA 2012]. An extended infrastructure would in turn promote LNG utilisation in additional ship types and on flexible routes, with the eventual result of global availability and utilisation.

At present, the conversion to LNG represents additional effort and expenses for ship operators. Direct comparison of costs currently favours conventional fuels. Besides LNG, the application of scrubber technology or marine diesel oil as an LNG alternative represent adequate measured to comply with regulations in Emission Control Areas. The decisive factor for the utilisation of LNG in maritime transport is the comparison of costs between alternatives.

The Magalog Project characterised the potential LNG market for the North and Baltic Sea area in the medium-term (approx. 15 years ahead of 2008) including evaluation of the most favourable ship categories, development of the fuel consumption and associated port infrastructure. The study reports a combined fuel consumption of RoRo/RoPax vessels and super-fast ships of 3,106,000 t in 2007, with 60% thereof utilised in the Baltic Sea. An itemisation depending on area of operation and ship type may be found in Table 7. Demand of the specified ship types is expected to remain relatively constant during the coming years. Furthermore, the study assumes an average annual stock turnover of 10 ships. In consequence, a complete switch of the fleet to LNG in the medium-term appears unlikely. Conversion of existing ships is considered unlikely due to financial constraints [Magalog 2008]. According to the study, the development trajectory for these ship traffics is likely to remain constant until 2023, thus the potential total LNG demand is expected to amount to 3.1 million t LNG maximum.

Table 7: Fuel consumption (HFO) in tonnes per year depending on ship type and area of operation in 2007

	North Sea	Baltic Sea	total
RoRo ships	557,000	645,000	1,202,000
RoPax and super fast ships	719,000	1,185,000	1,904,000
total	1,276,000	1,830,000	3,106,000

Source: own representation after [Magalog 2008]

The *North European LNG Infrastructure Project* [DMA 2012] considered of a number of different price scenarios and identified an LNG demand of 7 million t distributed evenly between new build and retrofitted vessels (Figure 11). In addition to RoRo/RoPax vessels and super-fast ships, this calculation for

LNG demand included all remaining ship types as relevant consumers. Consumption in this case is exclusively focused on SECA[5] zones in Northern Europe [DMA 2012].

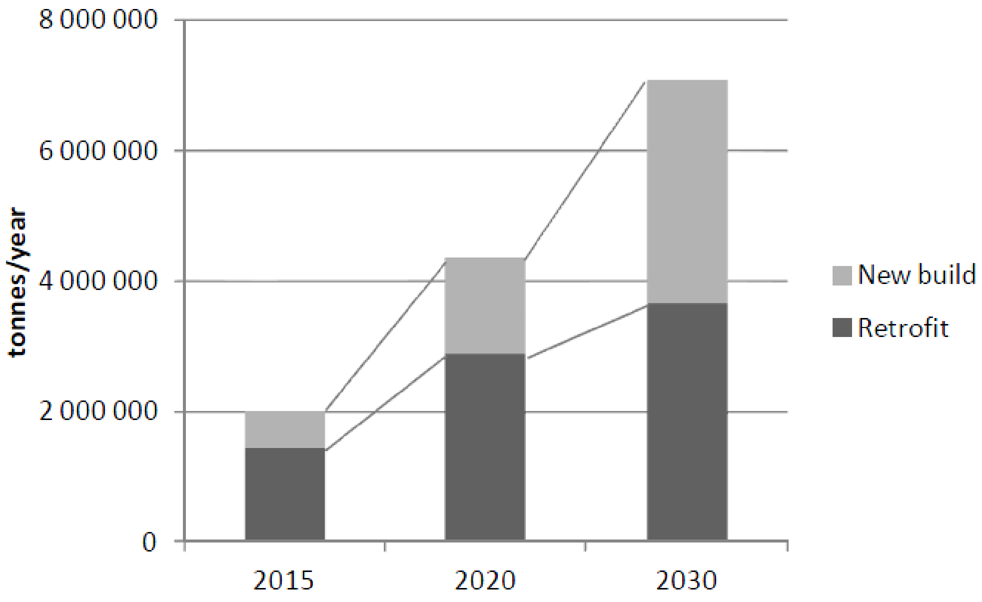

Figure 11: Expected development of LNG demand in the North and Baltic Sea area to 2030

Source: [DMA 2012]

The first study referenced here focused on the transition period between present-day fuel consumption and the situation in the medium-term in 2023. Effects of extended demand on additional ship types stimulated by a growing infrastructure for RoRo/RoPax vessels and super-fast ships in relevant ports are excluded from the analysis. Under thorough consideration of the potential demand segments including fuel price trajectories and life cycle costs for ships, a potential of 7 million t LNG in the northern European SECA zone is likely to be achieved. Passenger ferries in the Baltic Sea represent the largest demand segment with 50% in 2020 (the in-depth analysis concluded with the year 2020). In the North Sea, passenger ferries account for about one third of the demand for LNG in 2020 [DMA 2012]. However, the applied vessel classification does not allow direct comparison. The consequences of the outlined trajectories for Germany, and CO_2 emissions in particular, inevitably depend on a number of factors. For instance, the national strategy for infrastructure and demand development, in maritime transport and for LNG fuel in general, should be aligned with others; or rather a coordinated international approach is strongly recommended. This reflects important parameters for the distribution of the potential 7 million t in 2030 among specific ports and routes.

In sum, the expected demand for LNG in the maritime sector in the North and Baltic Sea area in 2030 may exceed the domestic demand in Germany multiple times (2-12-fold, depending on the scenario) (see Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**).The question arises whether Germany possesses sufficient political leverage to take up position in the LNG issue. In other words, how much effort should be dedicated to the promotion of LNG in Germany if the demand trajectory

5 SECA: Sulphur Emission Control Area.

could gain momentum in all or rather just a few specific coastal states of the North and Baltic Seas. The most attractive markets for LNG suppliers are likely to be in maritime transport, rather than in inland navigation and HDVs.

For meaningful comparisons, an extension of the system boundaries to include additional coastal states is required. Development of refuelling infrastructure in as many seaports as possible is a crucial prerequisite to establish LNG as a fuel option accepted by ship operators.

6.2 Scenario definition for inland vessels and heavy-duty vehicles

The calculations of domestic scenarios for road freight transport and inland navigation are based on the principle of analysing fuel consumption in correlation with mileage and transport performance including known specific consumption factors. The calculations are based on preliminary work with TREMOD (Transport Emission Model) that is utilised for national inventory reporting of greenhouse gas emissions in Germany [IFEU 2011, 2012].

The future expected transport performance in road freight transport is derived from projections of the German Federal Transport Plan (*Bundesverkehrswegeplanung*, BVWP). The revised Federal Transport Plan to 2030 was not available at the time of writing, and was thus excluded from the analyses. The development trajectory of freight transport performance was modelled based on the earlier Transport Projection 2025 (*Verkehrsprognose* 2025, VP 2025). The trends preceding 2025 are extended to the year 2030 (annual growth +2.2% in road freight transport, +0.5% in inland navigation; see [IFEU 2012]).

Considering the status quo, the projected trajectories of increasing road freight transport appear rather too optimistic. Thus arising uncertainties have to be taken into account for the evaluation of results on energy demand and greenhouse gas emissions in Germany. However, a general increase in mileage and transport performance in freight transport may be expected. The challenge of a medium- and long-term diversification of the energy supply in parallel with reduced dependency on fossil fuels remains. In consequence, the recommendations that conclude this study are not going to change in a fundamental way, regardless of anticipated changes in the sector development.

6.2.1 Application of LNG in inland navigation

At present, the utilisation of LNG in inland navigation appears feasible for part of the fleet only. Primary reasons include:

- High investment cost: the costs of investment for LNG (tank and engine) are currently about double the cost for diesel [TNO 2011a]. These costs are redeemed in light of lower costs of operation for LNG. Thus, vessels with high mileage and substantial fuel consumption may particularly benefit from operation with LNG. Examples include large vessels and push boats, as well as tankers and container ships.
- Additional space requirements for storage of LNG tanks: in all likelihood, the additional tank volume required may be factored into shipbuilding. However, in conversions or smaller vessels, freight capacity is likely to be lost. Storage of LNG tanks may be most convenient on-

board tankers and container ships. The former may be fitted with tanks on deck, whereas the latter may employ LNG container tanks.

As evident from the reasons above, technological and financial the implementation of LNG is feasible for large vessels in particular. The shipping business is also expecting to operate larger vessels with LNG in the future, whereas smaller vessels should be fitted with alternative drives [INE/EBU/ESO 2011]. Moreover, larger vessels are dependent on well-developed waterways such as the Rhine, which see frequent traffic and thus qualify for refuelling infrastructure development.

According to [Panteia 2013], LNG is suitable for application in newly built vessels exceeding 110 m in length with a capacity of 2750 t or more, and in push boats with an engine power exceeding 2000 kW. Conversion to LNG is further economical for vessels exceeding 135 m (or approx. 5000 t). The analysis is based on the assumption of a 20% advantage of LNG over diesel, which reflects a conservative price development for diesel. If the costs for LNG compare even more favourably, smaller or existing vessels may be operated economically with LNG.

Furthermore, the application of LNG could be favourable for tankers and container ships in particular due to ready storage space solutions and the promise of improved economy of operation. Freight vessels carrying dry cargo are associated with shorter operating hours and lower fuel costs. Within an operation time of 20 years, cost advantages for freight vessels are likely, thus even the conversion of existing motor vessels to LNG may be common [Panteia 2013].

The fundamental assumption of both scenarios in inland navigation in 2030 identifies the application potential in the inland vessel fleet (especially vessel size and age) as the limiting factor for the introduction of LNG, whereas the required refuelling infrastructure is assumed to be mostly in place. The latter is plausible due to the spatial distribution of inland navigation. At present, 80% of freight transport in inland navigation in Germany takes place on the Rhine [IFEU 2012]. Future projections expect that increasing overall transport is going to be associated with a steep increase of shipping transport on the Rhine [NEA 2011]. The Rhine, including its tributary rivers and canals, is thus a prime candidate for the establishment of the initial LNG corridor. In consequence, a number of recommendations of the EU commission on LNG infrastructure could be realised [COM 2013a]. Due to the fact that LNG is expected to be primarily utilised in larger vessels travelling on the well-developed Rhine, additional bunkering sites may be of lower priority for the establishment of LNG in inland navigation. In contrast, the application potential in the fleet is expected to be of great significance.

Both scenarios assume the application of LNG predominantly in larger vessels. Initial LNG vessels are newly built models (2010 or higher) with a capacity exceeding 2500 t. For a number of vessels, particularly very large freighters, tankers and container ships, conversion to LNG may be profitable. However, the factoring of these application potentials into LNG scenarios requires an analysis of the fleet development and the composition of overall transport volume in 2030. The next paragraph further illustrates the principles.

The consumption of inland vessel engines frequently ranges between 180 and 220 g diesel per kWh, with an average of 200 g/kWh frequently assumed for simplification [IFEU 2011]. However, the estimate of the total fuel consumption in correlation with vessel activity benefits from average consumption data dependent on transport performance (e.g. per tkm). The average assumed diesel consumption for inland navigation in Germany is currently 8.5 g/tkm or 0.365 MJ/tkm [IFEU 2011]. The order of magnitude of this value may be confirmed both with a bottom-up calculation for the total transport performance in combination with specific consumption values and with a top-down calculation computed from refuelling volumes [see IFEU 2011; ZKR 2013].

According to [TNO 2011a], consumption data of several manufacturers with different load points indicated a mean LNG energy conversion efficiency of 43%, whereas the energy conversion efficiency of a comparable diesel engine is 44%[6]. For simplification purposes, the same energy conversion efficiency is assumed for both engines.

The scenario for the year 2030 assumes reduced fuel consumption in inland vessels due to both technological and operational measures. Opportunities and potentials for reduced fuel consumption and CO_2 emissions were compiled in the activities of the Central Commission for the Navigation of the Rhine (CCNR). These include improved engines and propellers, optimised travel plans, smart steaming, etc. [CCNR 2012]. Based on the individual reduction potentials of all measures, the total sum amounted to a broad estimate for the period between 2010 and 2050 in the form of a conservative and an optimistic scenario. The scenarios in the present study adopted the CCNR scenarios and halved the potentials for the period up to 2030. The reduction potential was assumed to be higher due to the fact that the majority of technical measures apply to newly built vessels, and the fleet of potential LNG ships is likely to consist of such.

Table 8: Future fuel consumption reduction in inland navigation

	[CCNR 2012]*	**This study – total fleet**	**This study – new build**
Time horizon	2010 to 2050	2010 to 2030	
Technical measures	20%	10%	20%
Operational measures	10%	5%	5%
Total potential		15%	24%

* conservative scenario, excl. influence of increases in dead weight tonnage

NB: The total potential is derived from multiplication of the individual potentials

In contrast to [CCNR 2012], the reduction potential was not adapted to consider potential increases in dead weight tonnage (DWT). Although a separate investigation indicated an inversely proportional relationship between consumption and DWT [IFEU 2011], there is uncertainty whether the relative occupancy rate of larger vessels is lower. Lower relative occupancy would cancel out the advantage in consumption rate.

6 Analysis included data of a dedicated natural gas engine and dual-fuel engines in comparison with a conventional diesel engine with a respective nominal capacity of 1100-1200 kW.

The trend over the past years indicates that inland navigation is carried with continuously larger vessels. The average DWT in the German fleet between 1990 and 2010 rose from 1000 t to 1300 t or 1.5% annually [IFEU 2011]. The western European fleet in general, and Dutch vessels predominant in German inland navigation in particular, increased their tonnage by 1.6% to 1.8% annually [CCNR 2012].

The number of larger vessels in future inland navigation is expected to continue to rise, whereas the majority of smaller and older vessels are going to be dismantled for scrap [Panteia 2013, NEA 2011]. Thus, the overall DWT of the European fleet among vessels ≥2500 t is growing, whereas the DWT of smaller ships is in distinct decline (see Table 9). Transport in 2030 is assumed to reflect the increase in fleet tonnage in the proportion of transport performance performed in Germany.

Table 9: Data and assumptions on the trajectory of vessel size in inland navigation

	Year	<2500 t	≥2500 t	Source
Proportion of fleet capacity (EU)	2012	53%	47%	Own calculations after [Panteia 2013]
	2030	36%	64%	
Proportion of transport performance (DE)	2010	54%	46%	[IFEU 2012]
	2030	38%	62%	Own assumptions

Limitations of the utilisation potential based on vessel size (only >2500 t) are assumed in both scenarios. In consequence, the analysis primarily aims to differentiate between the proportion of LNG in newly built vessels and conversion of existing vessels. The following assumptions apply:

- **Moderate scenario**
  - 50% of new build >2500 t (between 2010 and 2030) with LNG
  - 10% of existing tankers and container ships >2500 t with LNG
- **Accelerated scenario**
  - 75% of new build >2500 t (between 2010 and 2030) with LNG
  - 50% of existing tankers and container ships >2500 t with LNG
  - 25% of existing freighters >2500 t with LNG

The new build of LNG-powered vessels is factored in assuming the following simplifications:

- The transport performance per vessel remains constant. In consequence, and increase in transport performance requires an expansion of the fleet with newly built vessels (2010 models or later).
- A 5% proportion of transport in tonne kilometres to date (status 2010) is already performed with newly built vessels, e.g. due to abandonment of older vessels thus exiting the fleet. The

assumption is based on the replacement of all larger vessels launched before 1960 for new build by 2030[7].

The resulting distribution of transport performance is illustrated in Figure 12. The steep increase in transport performance is mainly distributed among larger vessels. In consequence, newly built vessels launched in 2010 or later perform almost 30% of transport performances.

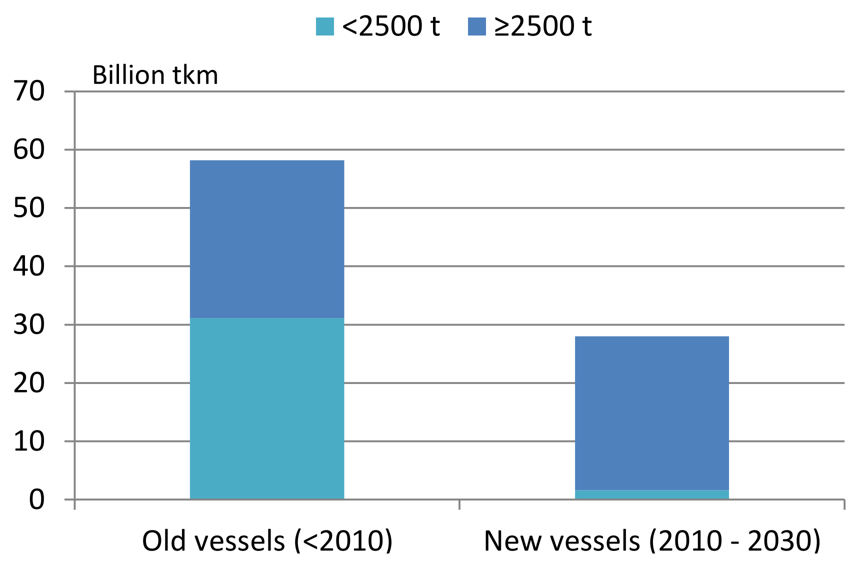

Figure 12: Distribution of transport performance in newly built and older vessels in 2030

Conversion to LNG of existing vessels is explored for individual vessel types (container ship, tankers, freighters). For simplification, the distribution of vessel types in assumed to remain constant between 2010 and 2030.

Table 10: Distribution of transport performance depending on vessel type (≥2500 t) in 2010

Vessel type	Proportion of transport performance
Containership	4%
Freighter	62%
Tanker	20%
Pushed convoys	14%

Source: [IFEU 2011]

The transport performance of diesel and LNG vessels resulting from the assumptions are illustrated in Figure 13.

[7] Based on fleet data from [NEA 2011] for vessels of the CEMT class V or higher (at least equal to a large Rhine vessel, i.e. approx. 2.750 t).

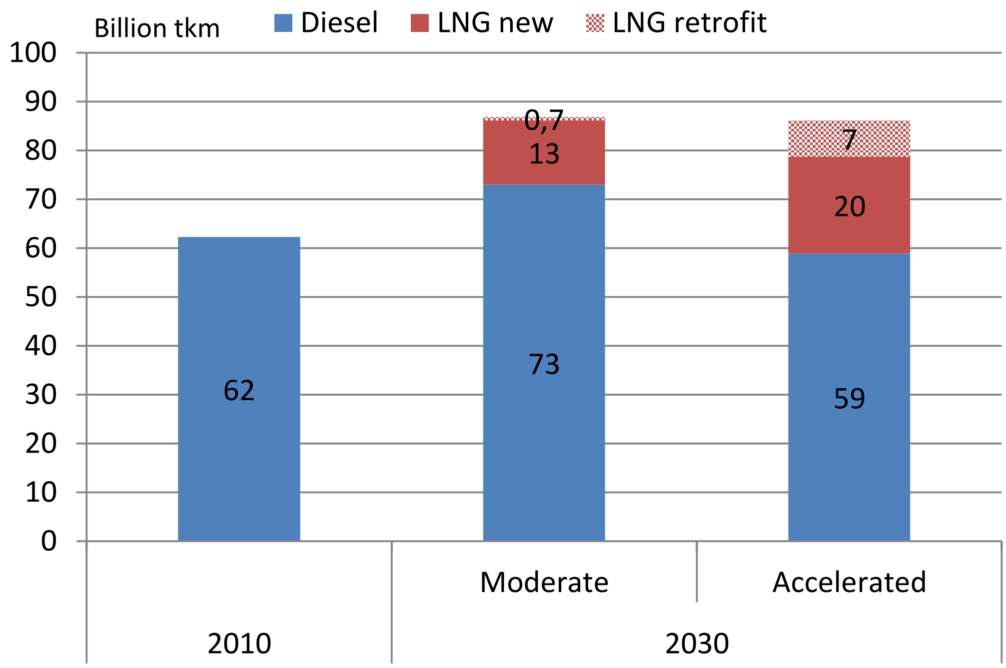

Figure 13: Inland vessel transport performance in the scenarios with LNG and diesel

6.2.2 Application of LNG in heavy-duty vehicles

The utilisation potential of LNG for HDVs is difficult to predict at present. The current situation presents a chicken-and-egg problem for this fuel option. It may only be solved with gradual development of the refuelling infrastructure in cooperation with vehicle manufacturers to signal fuel availability along the road network. Fulfilment of user requirements in their daily transport services is of vital importance. Infrastructure development should follow corridors with heavy traffic along Federal Motorways (*Bundesautobahnen*). Off-motorway service areas (*Autohöfe*) are particularly suitable as service points for refuelling with LNG since they are located in close proximity to the motorway but may be approached from both directions.

A technology supports the introduction of LNG could be found in dual-fuel engines that are able to operate on diesel when the gas supply is spent. If compliance with EURO VI standards can be achieved, this technology could enable the development of the LNG market and reduce the risks for users of LNG-HDVs and investors in infrastructure both.

In principle, long-distance HDV operators with high annual mileage may be open to adopt the new technology if it is associated with cost benefits and fuel availability is ensured. These vehicles are replaced every 4-5 years by their users. Thus, a substantial share of the market could be claimed within 10 to 15 years. At present, the specific future market share may only be estimated based on the scenarios introduced in the following paragraphs.

Scenario development was based on the following underlying assumptions. The maximum mileage of an LNG-fuelled HDV amounts to 600-1000 km per tank. Thus, a fuelling station network for LNG every 250 km would appear to be sufficient. Fuelling stations should be available in both directions wherever possible. An initial development scenario would include approx. 30 LNG fuelling stations preferably located at off-motorway service areas (*Autohöfen*). Thus, a substantial part of the motorway network could be covered and areas on both sides of the motorway would have access to service points for refuelling with LNG.

The proposed draft for a directive of the European Parliament and the Council on alternative fuels infrastructure [AFID 2013] is the foundation for member states to cooperate on realising fuel supply for LNG-fuelled HDVs operating along the TEN-T core network. For this purpose, an appropriate number of LNG refuelling station has to be supplied by 31.12.2030 at the latest. Thus, an essential prerequisite for the utilisation of LNG as fuel could be realised. A number of member states have voiced concern over the late deadline for introduction. These member states would be in favour of an introduction by 2020, and minimum distances between fuelling stations of 400 km as proposed in [COM 2013].

The assumed availability of an LNG fuelling station network could render LNG supply adequate to meet demand and persist in parallel with diesel by 2030. The following scenarios work with this assumption.

It is expected that an LNG utilisation potential is given particularly for HDVs of the vehicle category N3 including all HDVs exceeding 7.5 t gross vehicle weight and tractor units. These vehicles are frequently associated with high annual mileage. Thus, higher cost of purchase and potentially maintenance may be overcompensated with lower fuel expenses. The scenarios assume that transport performance by LNG-HDVs and tractor units in 2030 is performed with both dual-fuel diesel engines and dedicated methane Otto engines. These vehicles will be required to comply with future emissions standards. In consequence, the calculation of the precise mileage share of the respective vehicle was omitted. Instead, mileage was allocated according to the future achieved specific fuel mix, and thus assigned mileage to the respective fuel. Thus, the moderate scenario is derived (see Table 11). It assumes that the price increase for diesel fuel will only be sufficient to overcompensate additional costs of LNG vehicles in case of very high annual mileage.

Table 11: Moderate scenario: Assumptions on mileage or utilisation of different fuels in 2030

Mileage of vehicles with conventional and/or alternative drives	**N3 HDV > 7.5 t GVW**	**N3 tractor unit**
Proportion of mileage with combustion engines	100%	100%
part thereof diesel-powered	97%	95%
part thereof LNG-powered	3%	5%
part thereof dual-fuel engines	50%	50%

Source: own assumptions; GVW = gross vehicle weight

The second scenario (see Table 12) assumes an accelerated introduction of LNG to the market. Hence, a higher share based on quick overcompensation of additional purchase and maintenance costs is assumed. The accelerated scenario also expects a proportion of LNG-fuelled HDVs to be operated with dual-fuel technology.

Table 12: Accelerated scenario: Assumptions on mileage or utilisation of different fuels in 2030

Mileage of vehicles with conventional and/or alternative drives	N3 HDVs > 7.5 t GVW	N3 tractor unit
Proportion of mileage with combustion engines	100%	100%
part thereof diesel-powered	95%	80%
part thereof LNG-powered	5%	20%
part thereof dual-fuel engines	50%	50%

Source: own assumptions; GVW = gross vehicle weight

Additional assumptions for the assessment of the improvement potential of combustion engines for both diesel and gas engines were made. These were based on the analysis of efficiency potentials of specific combustion engines published by the TU Vienna [Nanupot 2011].

Table 13: Potentials for consumption reduction for the vehicle category N3 (diesel and LNG)

Vehicle category	N3 tractor unit or HDV > 7.5 t GVW
Potential diesel (moderate/accelerated)	20.6%
Potential LNG incl. dual-fuel engines (moderate/accelerated)	28%

Source: own assumptions (for LNG) and Nanupot study (for diesel) [Nanupot 2011]

It is expected that these efficiency potentials may be achieved by the year 2020 and will be realised in vehicles sold then, or introduced from 2020 in the case of LNG.

Both diesel and LNG may be blended with renewable feedstocks. Moreover, synthetically produced gas from renewable electricity may be liquefied to LNG and blended into the fuel supply. Blending of renewable energies reduces the CO_2 emissions in the overall balance (well to tank). This was factored in for the year 2030 under the following assumptions, although it is expected that the biofuel portion of diesel may be increased through technological advancement in biofuel production. In consequence, biofuel supply costs would approach fossil diesel costs and the required biomass or waste materials could be generated without competition from food/feed production.

Table 14: Scenario for application of blends for diesel and LNG in 2030

Blending quota alternative fuels	N3 HDVs > 7.5 t GVW	N3 tractor unit
Biodiesel share combustion engine diesel	13%	13%
Biomethane share combustion engine LNG	-	-

Source: own assumptions

6.3 Energy demand of inland navigation and road freight transport in Germany

The overall energy consumption of inland navigation of about 27 PJ accounts for only about 3-4% of the energy consumed in road freight transport. The expected overall increase in transport performance will be associated with an increase in overall fuel consumption. In the moderate scenario, LNG consumption amounts to 4 PJ or approx. 13% of the inland navigation total. In contrast, the accelerated scenario predicts an LNG consumption of 8 PJ or approx. 28% of the total consumption in inland navigation. Thus, diesel consumption is slightly reduced in comparison with 2010.

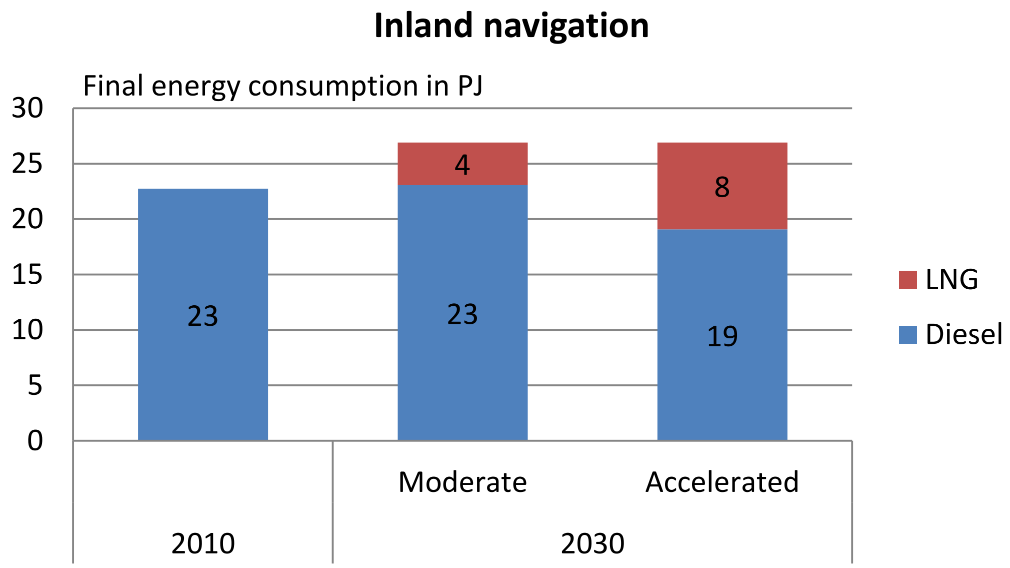

Figure 14: LNG demand for inland navigation in the scenarios

In case of the expected steep increase of demand for freight transport, the energy demand in road freight transport until 2030 is going to rise despite advances in drive efficiency. The LNG demand based on LNG utilisation potentials in 2030 is projected to amount to LNG fuel volumes of 30 PJ with moderate introduction and 97 PJ with accelerated introduction. This is equal to 4-12% of the total fuel consumption in road freight transport. The demand for diesel is going to increase in both scenarios unless alternative fuels, e.g. hydrogen in fuel cell propulsion, are simultaneously established on the market.

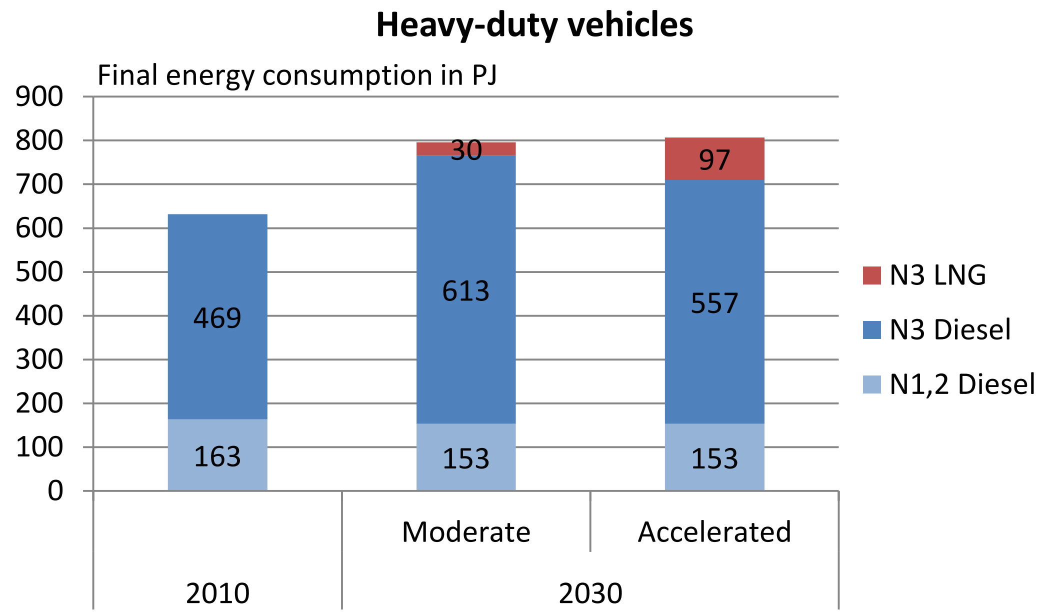

Figure 15: **LNG demand for road freight transport in two scenarios**

The two scenarios project an LNG demand of the freight transport sector in 2030 between 34 PJ and 105 PJ. To put this in perspective, in 2012, the German transport sector consumed 8.9 PJ natural gas, whereas the total natural gas consumption across all sectors was 2123 PJ [BMWi 2013, Table 17]. The lion's share of the LNG demand would arise in road freight transport, although the percentage of LNG compared with diesel in inland navigation is expected to be higher than in road freight transport in both scenarios.

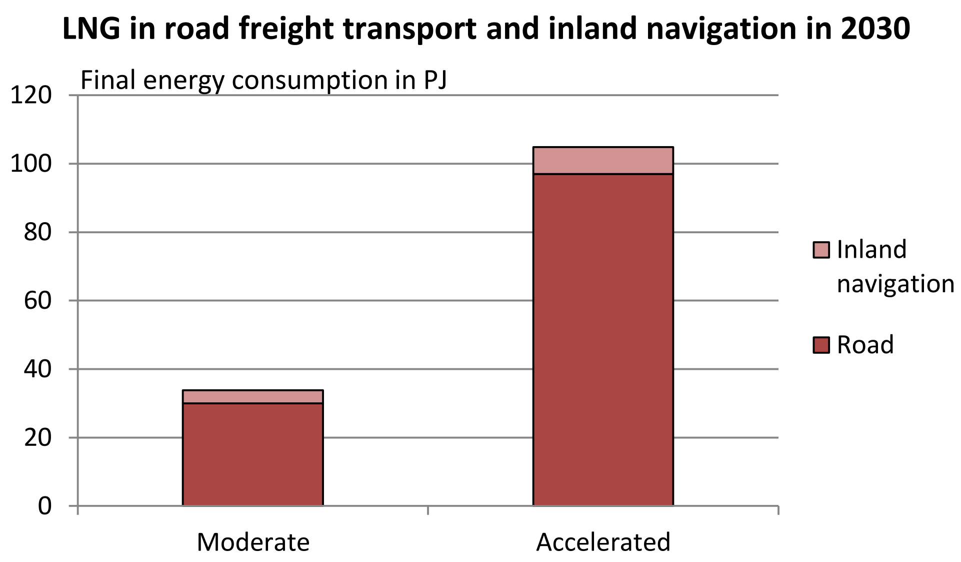

Figure 16: **LNG demand in 2030 by scenario and sector in Germany**

6.4 Comparison of demand to RE methane potential

Due to the considerable potentials for renewable electricity (and theoretically limited CO_2 supply), a substantial proportion of LNG demand could be substituted with RE methane (with CO_2 from air about 1469 PJ – see Table 2). Liquefied RE methane produced with CO_2 from biogas upgrading only is insufficient for both scenarios. CO_2 from the flue gas of wood-fired CHP plants would be able to cover domestic LNG demand in Germany.

With CO_2 from air, the moderate development scenario for inland waterway vessels and HDVs and also for maritime navigation in the North and Baltic Seas may be realised with reduced energy conversion efficiency using liquefied RE methane from Germany. The accelerated development scenario for Germany in combination with maritime navigation will not be possible with RE methane from Germany alone.

In this context, other potential consumers of electricity and RE methane (e.g. in the stationary sector and passenger services) as well as a potential increase of demand after 2050 have to considered. For further details, please see the MFS study 'Renewable energies in transport: potentials and development perspectives of assorted renewable energy carriers and energy consumption of the transport modes'.

7 Potential contributions to the reduction of emissions

The following chapter explores the environmental benefit potentials of LNG. Due to the pressing concerns of climate change mitigation, the principal focus of the chapter is on potential greenhouse gas savings. The potential reduction of pollutant emissions is another vital aspect under investigation due to the fact that air pollution is a common problem in Germany[8]. Both types of emissions are modelled in scenarios comparing the status quo with projection for the year 2030. However, although a technology evaluation for maritime transport is carried out, interpretation of the findings in reference to Germany was not feasible (allocation).

7.1 Methodology and input data on greenhouse gas emissions

7.1.1 General emission factors

Modelling of greenhouse gas emissions includes CO_2, nitrous oxide (N_2O) and methane (CH_4). These are reported in sum as CO_2 equivalents based on a GWP100 after [IPCC 2007]:

- CO_2: 1 g CO_2 equivalents/g
- CH_4: 25 g CO_2 equivalents/g
- N_2O: 298 g CO_2 equivalents/g

Soot emissions ('black carbon') influence climate change both as aerosols in the atmosphere and as deposits at the polar ice caps. This is particularly relevant in maritime transport along polar routes. The IPCC has yet to publish a greenhouse gas factor for black carbon. The greenhouse gas impact of soot is strongly dependent on the location of the emission (geography) and the prevailing weather patterns (meteorology). Current debate among experts proposes GWP100 factors between 1500-2240 g/g [Jacobson 2007], with special reference to Europe 374 g/g [Boucher und Reddy 2008].The greenhouse gas impact of soot emissions was omitted from the present study due to the lack of internationally established standards for this emission factor. The relevance of soot emissions decreases according to fuel type and exhaust aftertreatment measures:

- Heavy fuel oil (HFO) without exhaust aftertreatment
- Marine diesel oil (MDO)
- Methane diesel mix
- Methane

The immission of soot emissions is particularly relevant for the greenhouse effect on bright surfaces and under stable meteorological conditions, e.g. on snow and ice fields or desert areas. Soot deposits

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[8] Soot particle emissions also influence climate change as aerosols and deposits. These effects have not been sufficiently quantified in science to date, i.e. no IPCC factor has been assigned to define greenhouse gas impacts of soot particle emissions.

lower the reflexion capacity of these surfaces. In consequence, the Earth retains more thermal radiation. In addition, glacier retreat is exacerbated.

Due to the fact that the impacts of greenhouse gases are felt globally, emissions arising along the entire causal chain are considered, i.e. from well to tank (WTT) and further from tank to wheel or propeller (TTW/TTP).

The supply of fuel from well to tank (WTT) consists of a number of processes like extraction, conditioning and transport. Thus, fuel supply has to be modelled for specific pathways or routes. The result reports the sum of all greenhouse gases in reference to fuel consumption (e.g. g/MJ).

The CO_2 emissions from the operation phase (TTW/TTP) are derived directly from the respective fuel consumption based on carbon content under the assumption that all carbon is fully combusted. The value for diesel in this context is 73.2 g CO_2/MJ, whereas LNG is assigned the value for natural gas of 55 g CO_2/MJ (pure methane) [JEC 2013]. Direct CO_2 emission are not assigned to renewable fuels from biomass or renewable electricity due to the fact that the individual carbon content had been previously 'removed' from the atmosphere during cultivation (or extraction in case of CO_2 directly derived from air for methanation). CH_4 and N_2O emissions arising during combustion depend on engine and emission reduction technology.

Details on the emissions factors influencing the GHG emissions of the supply pathways and means of transport under investigation may be found in the following chapters.

7.1.2 Supply of LNG (WTT)

Supply of LNG is commonly focused on imports with maritime transport, in some cases supplemented by biomethane, e.g. [PwC 2013]. The German Energy Transition (German: *Energiewende*) presents specific opportunities and challenges. In consequence, the present study includes additional relevant LNG supply options, e.g. liquefaction in Germany or in a location of choice as well as the production of LNG from renewable electricity (liquefied RE methane).

The following pathways or routes were explored for LNG supply:

- Natural gas liquefaction in close proximity to natural gas fields (e.g. Qatar), transport of the liquefied natural gas (LNG) to the EU, transport of the LNG via bunker vessel to recipient ship in need of refuelling over a distance of 5 km, and discharge to recipient ship
- Natural gas liquefaction in close proximity to natural gas fields (e.g. Qatar), transport of the liquefied natural gas (LNG) to the EU, transport of the LNG via tanker truck to a fuelling station in port over a distance of 5 km, and discharge to recipient ship in need of refuelling
- Natural gas liquefaction in close proximity to natural gas fields (e.g. Qatar), transport of the liquefied natural gas (LNG) to the EU, transport of the LNG via inland vessel to a fuelling station over a distance of 500 km, and discharge to recipient ship in need of refuelling
- Natural gas liquefaction in close proximity to natural gas fields (e.g. Qatar), transport of the liquefied natural gas (LNG) to the EU, transport of the LNG via tanker truck to a fuelling station

in port or a HDV depot over a distance of 500 km, and discharge to recipient ship or the recipient HDV in need of refuelling

- Natural gas field outside the EU, natural gas transport via pipeline over a distance of 4000 km, distribution of the natural gas to local natural gas liquefaction operation in fuelling stations at inland ports
- Natural gas field outside the EU, natural gas transport via pipeline over a distance of 4000 km, distribution of the natural gas to local natural gas liquefaction operation in fuelling stations at HDV depots
- Production of hydrogen via water electrolysis with subsequent catalytic methanation and in-feed into the natural gas grid, local natural gas liquefaction in fuelling stations at inland ports
- Production of hydrogen via water electrolysis with subsequent catalytic methanation and in-feed into the natural gas grid, local natural gas liquefaction in fuelling stations at HDV depots

Three options were considered for the supply of CO_2 for catalytic methanation:

- CO_2 from air
- CO_2 from flue gas
- CO_2 from biogas conditioning

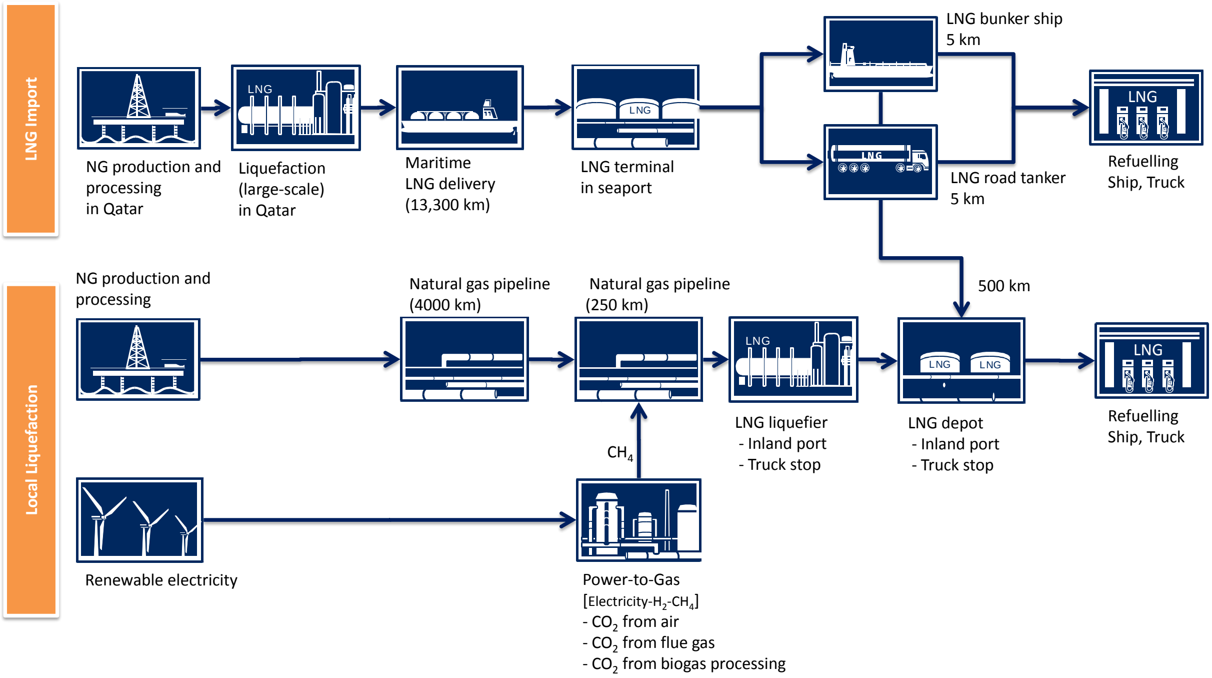

Figure 17: Pathways or routes for LNG supply Well-to-Tank

The energy input and the associated emissions from extraction and conditioning of natural gas and from commercial liquefaction of natural gas in close proximity to natural gas field were adopted from [JEC 2013]. The electricity consumption of large-scale natural gas liquefaction operations amounts to approx. 0.036 MJ per MJ LNG. It was further assumed that the electricity demand of the liquefaction operation is supplied by a natural gas-powered combined cycle gas turbine (CCGT) power plant with an energy conversion efficiency of 58% in analogy to [JEC 2013]

The fuel consumption of the ocean-going LNG tanker (approx. 0.089 MJ per MJ LNG delivered including return trip) is partly supplied in the form of boil-off gas (approx. 54%) and partly with HFO (approx. 46%). The transport distance from Qatar to Zeebrugge is about 13,000 km (one-way).

The bunker vessel and the LNG inland waterway tanker are operated with diesel fuel. The energy and associated greenhouse gas emissions for the supply of diesel fuel were adopted from [JEC 2013].

On-site liquefaction in the fuelling station at the inland port was modelled with data from a plant manufacturer (Galileo). According to [Galileo 2013], the electricity consumption of the liquefaction plant, model 'CRYOBOX', amounts to 420 kWh per 500 kg LNG or approx. 0.060 MJ per MJ LNG. Furthermore, minor quantities of LPG and lubricants are required. For on-site liquefaction in an LNG fuelling station at a depot, data from Stirling Cryogenics was applied. The electricity consumption amounts to approx. 0.064 MJ per MJ LNG. Electricity for the liquefaction process is supplied by the grid.

The electricity consumption for water electrolysis is assumed to amount to 4.5 kWh per Nm³ hydrogen. The pressure of the applied hydrogen is 3 MPa (pressure electrolysis). The operation is connected to the medium-voltage grid.

The next step involves methanation under application of CO_2. The conversion of hydrogen into methane proceeds in the following reaction:

$$4\ H_2 + CO_2 \Rightarrow CH_4 + 2\ H_2O\ \text{(gaseous)} \qquad \Delta H = -165\ kJ$$

The reaction is exothermic. Catalytic methanation is carried out at temperatures between 200 to 400°C in the presence of a catalysts based on Ni or Ru, Rh, Pt, Fe, and Co [Lehner 2012]. Catalytic methanation takes place at a pressure of 0.5 MPa.

CO_2 capture from air is carried out via absorption by an alkaline lye (KOH) solution and regeneration of the scrubbing agent via electrodialysis. The electricity consumption amounts to 8.2 MJ per kg CO_2 [Sterner 2009]. In a subsequent step, CO_2 is compressed from ambient pressure to 0.5 MPa.

CO_2 separation from flue gas is carried out via amine scrubbing with monoethanolamine (MEA). Both the regeneration of the scrubbing agent and the separation of CO_2 require heat, which amounts to 4.3 MJ [Specht et al. 1995]. An additional 0.0334 kWh of electricity are required for pumps and fans [Socolow et al. 2011]. In a subsequent step, CO_2 is compressed from ambient pressure to 0.5 MPa. The heat demand is partly supplied by heat generated during methanation.

For the case that the CO_2 required for methanation is produced in a biogas plant, it was assumed that the biogas plant was equipped with facilities for the conditioning of biogas into pure methane for infeed into the gas grid. The electricity demand of the CO_2 supply is derived from the compression of CO_2 from ambient pressure to the pressure level of the methanation plant (0.5 MPa).

Table 15 illustrates the energy and material flows for the production of methane from H_2 and CO_2.

Table 15: Energy and material flows for methane production from H_2 and CO_2

	I/O	Unit	CO_2 from air	CO_2 from flue gas	CO_2 from BG upgr.
H_2	Input	MJ/MJ	1.200	1.200	1.200
CO_2	Input	kg/MJ	0.055	0.055	0.055
Electricity for CO_2 supply	Input	MJ/MJ	0.4590	0.0098	0.0080
Heat for CO_2 supply	Input	MJ/MJ	-	0.2365	-
CH_4	Output	MJ	1.000	1.000	1.000
Heat	Output	MJ/MJ	0.200	0.200	0.200

BG upgr.: biogas upgrading

The produced methane is transferred to the liquefaction operation at the inland port or the HDV depot via the natural gas grid.

Figure 18 illustrates energy input for the well-to-tank supply of CNG and LNG fuel itemised by fossil and renewable energy input.

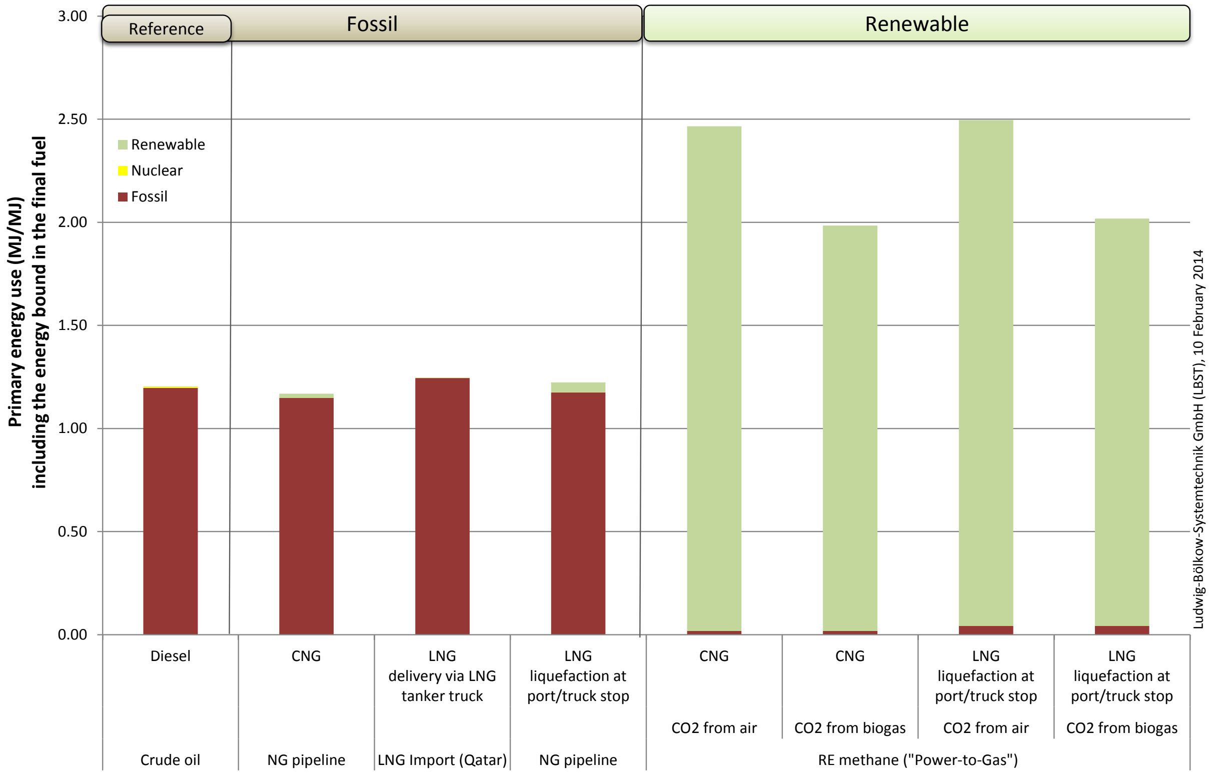

Figure 18: **Energy costs of selected CNG and LPG supply pathways (incl. energy content of the fuel)**

Figure 18 demonstrates that the total energy input for fossil pathways is the lowest overall. In this case, nature has completed the labour over millions of years. The energy input for the conditioning of methane (densification, liquefaction) is not a crucial factor. The densification and liquefaction of methane is carried out with the German electricity mix 2030.

Figure 19 illustrates greenhouse gas emissions associated with LNG supply broken down into the respective process stage. The fossil proportion of carbon in fuel in this well-to-tank calculation is also reported.

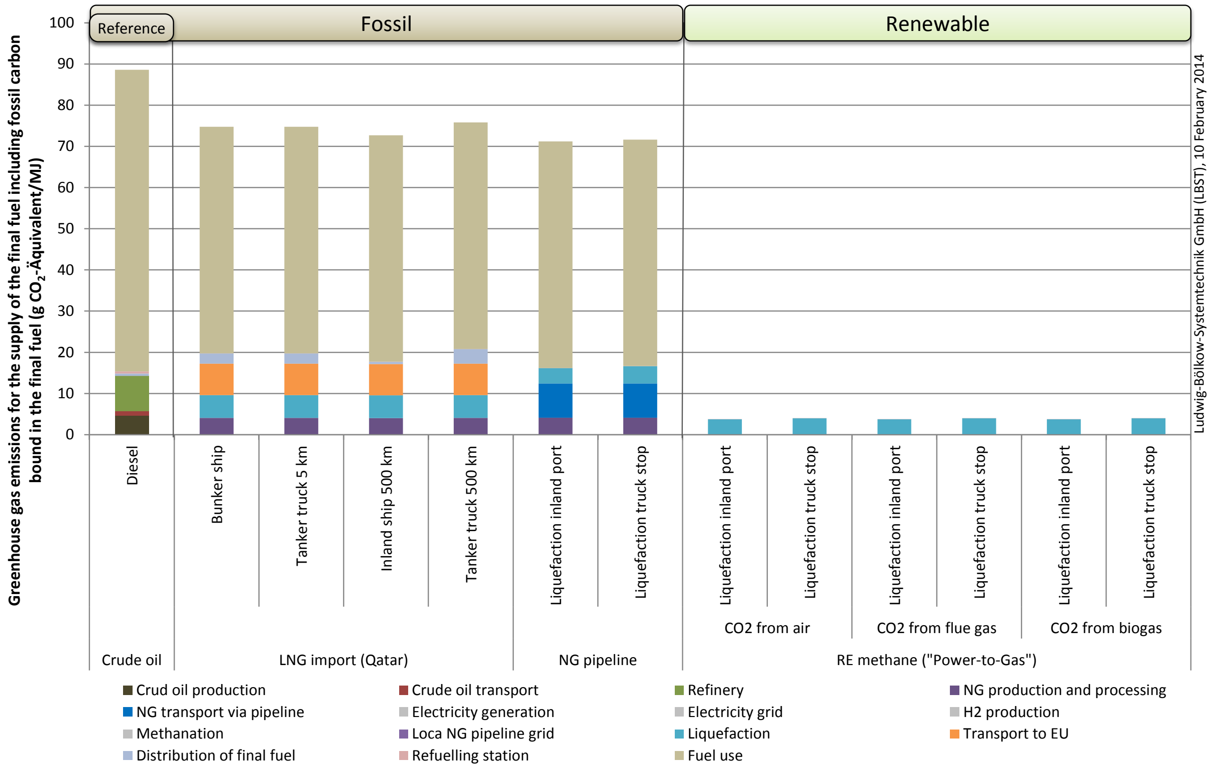

Figure 19: Greenhouse gas emissions from LNG supply (incl. fossil carbon content of the fuel)

Well-to-tank greenhouse gas emissions for the supply and utilisation of LNG from natural gas range between 72 and 76 g CO_2 equivalent per MJ LNG depending on the supply pathway, under application of the electricity mix 2030 for the electricity demand of the liquefaction plants. Differences between the individual supply pathways are thus minor. If the current electricity mix is applied for the liquefaction step, greenhouse gas emissions amount to 73 to 79 g CO_2 equivalents per MJ LNG. The application of renewable electricity for the production of synthetic methane via electrolysis and subsequent methanation including CO_2 supply substantially reduces greenhouse gas emissions to approx. 4 g CO_2 equivalents per MJ LNG. This amount is generated in the operation of the on-site liquefaction plant at the inland port with electricity from the electricity mix 2030. The differences in energy input for the supply of CO_2 do not alter emissions due to the fact that the electricity demand is covered by re-newable electricity.

The total emissions (WTW/WTP) are overall very similar, thus the comparison may be simplified to evaluate the means. For this reason, Chapter **Fehler! Verweisquelle konnte nicht gefunden wer-den.** addresses the following three supply pathways only:

- HFO from crude oil
- Diesel from crude oil
- LNG from natural gas (mean)
- LNG from renewable methane (mean)

Diesel greenhouse gas emissions are assumed to amount to 15.35 g CO_2 eq. per MJ[9]. HFO emissions after [TNO 2011] are 9.8 g CO_2 eq. per MJ.

7.1.3 Emission factors for inland vessels (TTP)

The direct CO_2 emissions of LNG (55 g/MJ) per energy content are about 25% lower in comparison with those of diesel (73.3 g/MJ). Due to the fact that drive efficiency in LNG and diesel engines is about equal, the CO_2 reduction may be applied per distance travelled or transport performance performed.

CH_4 emissions from diesel engines are assumed to amount to 2.4% of HC emissions following the rule for HDVs (based on HBEFA 3.1). Thus, the result is 0.001 g CH_4/MJ diesel. LNG engines after [TNO 2011] are associated with the much higher value of 0.53 g/MJ based on empirical data from gas engines in stationary operation as well as data on engine performance. Even higher methane emissions may occasionally arise during low load operation [TNO 2011]. A detailed analysis is outside the scope of the present study, yet the relevance of methane as a greenhouse gas demands future consideration of the issue.

Based on past experience with diesel and gas engines, N_2O emissions may be considered negligible for the total of GHG emissions in road transport. Following the TNO study, a value of 0.4 g CO_2 equivalents/MJ (equals 1.34 mg N_2O/MJ) is assumed for both LNG and Diesel [TNO 2011].

In addition to fuel quality (e.g. methane content) and share of renewable energies, future (2030) specific greenhouse gas emissions (per MJ fuel) are primarily going to depend on engine technology. CH_4 emissions in LNG engines are currently contributing almost 20% of the total of direct greenhouse gas emissions. However, it may be expected that methane emissions are going to be restricted to 0.5 g/kWh in context of the implementation of stricter emission standards such as the EURO VI standard for HDVs [Panteia 2013]. Thus, a considerable reduction of greenhouse gases assuming constant energy consumption in comparison with diesel could be achieved. The trajectory for N_2O emissions is difficult to project due to the fact that there are currently no N_2O emissions standards applied or in preparation. For simplification, N_2O emissions are thus assumed to remain constant up to the year 2030.

9 Value used for all MFS studies. Detailed description may be found in MFS study ‘On the road to sustainable energy supply in road transport – potentials of CNG and LPG as transportation fuels’

Table 16: Emission factors for greenhouse gases from inland vessel engines (TTP)

	Diesel (class IIIA)	LNG (2013)	LNG (2030)
CO_2 [g/MJ]	73.2	55	
CH_4 [g/MJ]	0.001	0.53	0.06
in CO_2 eq. [g/MJ]	0.02	13.25	1.57
N_2O [g/MJ]	0.001	0.001	
in CO_2 eq. [g/MJ]	0.4	0.4	
CO_2 eq. total [g/MJ]	73.6	69.9	56.9

Source: [TNO 2011] and own assumptions; Conversion of standards per kWh to MJ with a specific consumption of 8.6 MJ/kWh (equals 200 g diesel/kWh)

7.1.4 Emission factors for heavy-duty vehicles (TTW)

Similar to the situation for inland vessels, CO_2 emissions per energy content are about 25% reduced in comparison with those of diesel. However, due to the considerably reduced engine efficiency of LNG versus diesel in HDVs, this advantage per kilometre travelled may be compensated (see greenhouse gas balance in Chapter 7.2.1).

Methane emissions of diesel engines may be considered negligible. The emissions standard EURO VI merely stipulates a limit for total hydrocarbons (THC) of 0.16 g/kWh. Under assumption of compliance with this standard including a CH_4 emission content of 2.4% (assumption HBEFA), the CO_2 equivalents arising from methane would amount to a mere 0.01 g/MJ diesel fuel. From 2013, the specific CH_4 limit for new HDV gas engines entering the market is 0.5 g/kWh. This is equal to methane emissions of 0.06 g/MJ, or 1.6 g CO_2 eq./MJ. Assuming compliance with the standards, methane emissions are going to be a minor part of overall GHG emissions.

N_2O emissions of diesel cars with EURO VI are simplified to 5% of the NOx standard, whereas the estimate for CNG engines is 3%. These assumptions may be applicable to HDVs for simplification purposes. Assuming compliance with the NOx standard of 0.46 g/kWh, the resulting emissions amount to 0.064 g N_2O or 1.5 g CO_2 equivalents per MJ, respectively. N_2O emissions are thus of minor importance in the greenhouse gas equivalent total.

At present, the European Union has no official intentions of introducing revised emission standards for HDVs. The targets stipulated in EURO VI may already be considered advanced. For these reasons, an investigation of future emission factors for HDVs is omitted from the present study.

Table 17: Emission factors for greenhouse gases from HDVs (TTW)

	Diesel (EURO VI)	LNG (EURO VI)
CO_2 [g/MJ]	73.2	55
CH_4 [g/MJ]	0.0005	0.06
in CO_2 eq. [g/MJ]	0.01	1.57
N_2O [g/MJ]	0.001	0.001
in CO_2 eq. [g/MJ]	0.34	0.34
CO_2 eq. total [g/MJ]	73.6	56.9

Source: own assumptions; Conversion of standards per kWh to MJ with a specific consumption of 7,95 MJ/kWh (equals 185 g diesel/kWh)

7.2 Contribution to greenhouse gas reduction

The potential reduction of greenhouse gases is illustrated along the entire supply chain from well to wheel or propeller (WTW/WTP). For this purpose, a current benchmark comparison of specific emissions of LNG versus diesel is carried out and an outlook on future development regarding vehicle efficiency and supply is provided.

Furthermore, the overall contribution of LNG to greenhouse gas reductions by 2030 for the respective transport modes is explored based on the scenarios developed in Chapter 6 with particular attention to existing political targets. The overall reduction of GHG emissions represents a compulsory measure to mitigate climate change. The energy concept of the German Federal Government stipulates an overall GHG reduction target of 55% by 2030 and 80-95% by 2050 in reference to the year 1990 [BMU 2011]. There are currently no binding targets for the transport sector. However, for the transport sector, the EU White Paper proposes a reduction of 20% by 2030 or 60% by 2050 [EU White Paper 2011]. The European inland navigation associations on their part have proposed GHG reductions of 30% by 2020 or 50/70% by 2050 [INE/EBU/ESO 2011].

7.2.1 Maritime transport

The utilisation of LNG in combustion (TTP) is associated with lower CO_2 emissions (TTP) compared with HFO or marine diesel oil [IMO 2009, Magalog 2008]. These are about equal to the chemical CO_2 advantage of LNG versus diesel or HFO[10], which may only be achieved under similar conditions for engine efficiency and energy consumption.

Methane slip in LNG engines may reduce greenhouse gas benefits. According to [Marintek 2011], methane slip in high-pressure dual-fuel engines may be considered negligible. In contrast, it is currently a major challenge for low-pressure dual-fuel engines and dedicated gas engines. After factoring in of methane emissions, the GHG emission of LNG are still between 15% and 30% lower than to those of HFO [Marintek 2007, 2011]. Despite methane slip being a common phenomenon, it is seldom referenced and thus remains an uncertain factor in the evaluation of LNG contributions to climate change mitigation.

The supply of LNG is associated with distinctly higher greenhouse gas emissions relative to HFO. However, the WTT proportion of LNG accounts for only approx. 25% of total GHG emissions (16% for diesel). The greenhouse gas emissions per tonne kilometre across the entire supply chain (WTP) are exemplified for a container vessel in Figure 20. In total, greenhouse gas reductions achieved with the utilisation of LNG are minor in comparison with HFO. More substantial greenhouse gas reductions are possible if fossil LNG is substituted with renewable methane (see next paragraph). The extent to which this may be adopted as common practice in future international maritime transport is difficult to estimate in the present study.

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[10] Diesel and HFO have a higher carbon content per MJ an thus higher CO_2 emissions than LNG or methane

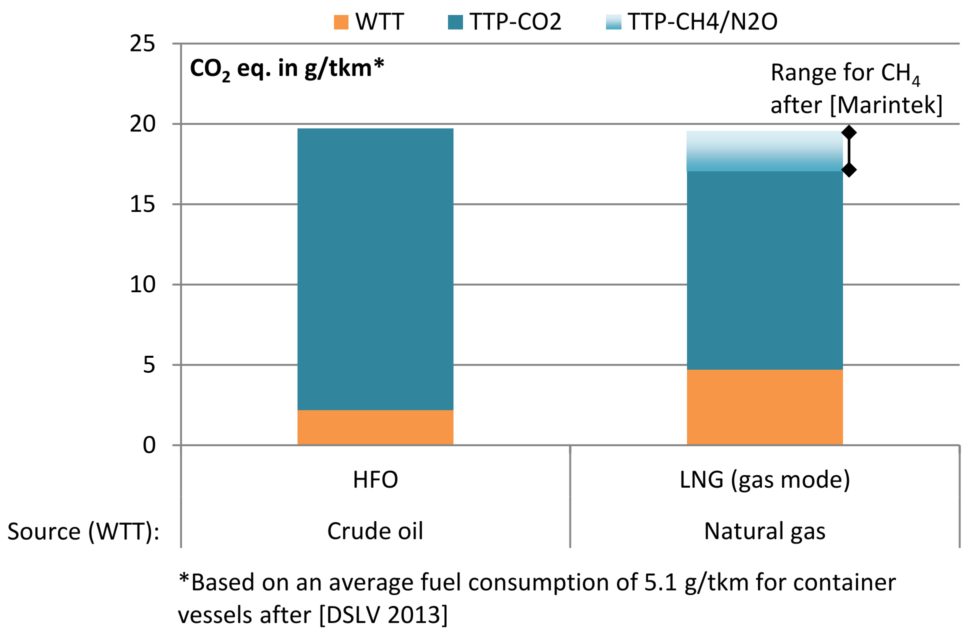

Figure 20: **Specific GHG emissions of ocean-going vessels in 2013**

7.2.2 Inland navigation

Combustion of natural gas in inland vessels (TTP) may reduce CO_2 emissions per MJ fuel in comparison with diesel by 25%. However, due to methane slip prevalent in current engines, this advantage for the GHG emissions total (in CO_2 equivalents) is considerably reduced. An additional contribution to GHG emissions in comparison with diesel arises during LNG supply from gas field to tank (WTT). In sum, there a no specific GHG emissions advantages of LNG over diesel at present.

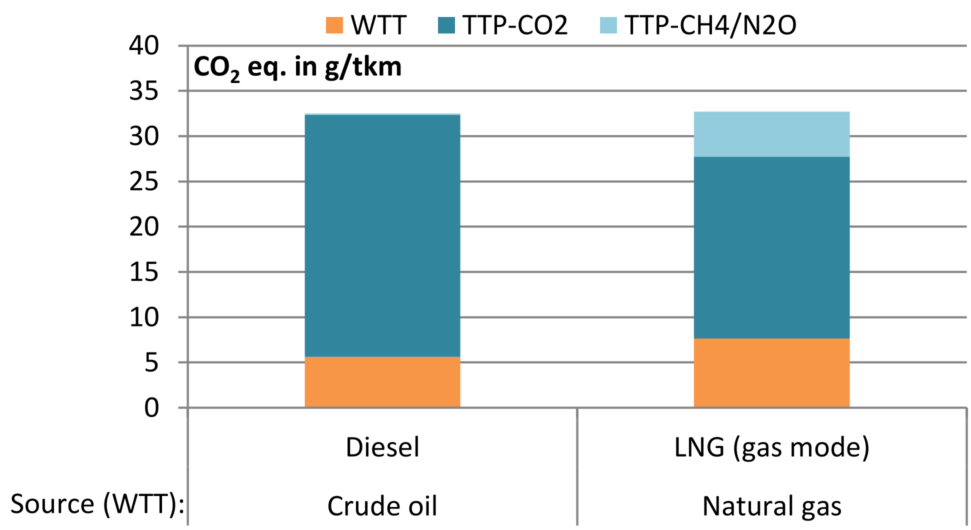

Figure 21: **Specific GHG emissions of inland vessels in 2013**

Future LNG engines are still associated with notably greater potentials for GHG reduction. Stricter emissions standards analogous to the EURO VI standard proposed for HDVs could mitigate methane slip. Moreover, the application of renewable LNG from RE methane would allow virtually CO_2-neutral combustion. The application of fossil LNG (natural gas) would reduce GHG emissions by 15%. However, utilisation of RE methane results in a reduction of over 90% in comparison with fossil diesel.

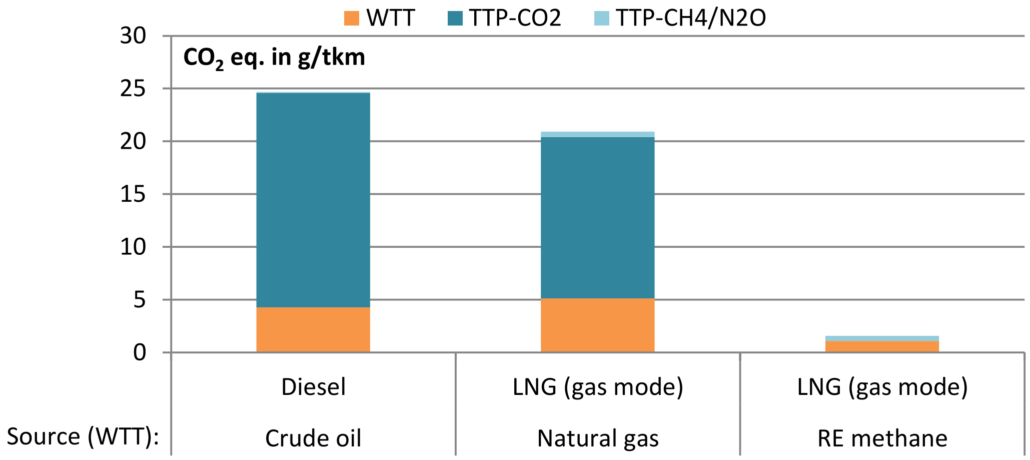

Figure 22: Specific GHG emissions of inland vessels (WTP) in 2030

The potential future contribution of LNG vessels to the overall reduction of GHG emissions factors considers the energy demands calculated in Chapter 6. Furthermore, the mean specific GHG emissions in the year 2030 are calculated under the assumption that 75% of the LNG fleet in 2030 are operating in compliance with a methane standard of 0.5 g CH_4/kWh, similar to the EURO VI standard in HDVs. This would follow [Panteia 2013] proposing the introduction of a standard in 2020 under the assumption that ship engines are replaced every 15 years on average [Planco 2007]. Another assumption specifies a 13%[11] biodiesel quota for diesel fuel in compliance with the Germany Biofuels Sustainability Ordinance (*Biokraftstoffnachhaltigkeitsverordnung*, Biokraft-NachV) to achieve -60% GHG emissions by 2020. In context of the targets of the German Federal Government (-55% across all sectors) and the EU White Paper (-20% in transport), the contribution to the reduction of greenhouse gases by 2030 is referenced to the year 1990.

Figure 23 illustrates the resulting contribution of LNG to greenhouse gas reduction in inland navigation. If renewable methane is ignored, GHG emissions may only be reduced by about 2.5% in reference to 1990. Substitution of fossil LNG with renewable methane results in a reduction of 14% maximum in the moderate scenario and 27% maximum in the accelerated scenario. The results reveal that LNG engines in shipping may be instrumental in reaching the target of the EU White Paper for 2030 (in reference to the entire transport sector), at least in the accelerated scenario and with a renewable methane share of >75%.

[11] The biodiesel quota is set at 13% (MJ/MJ) to comply with criteria stipulated in the decarbonisation strategy from 2020 (minimum 7% in comparison with conventional fuel) (see [IFEU 2012]).

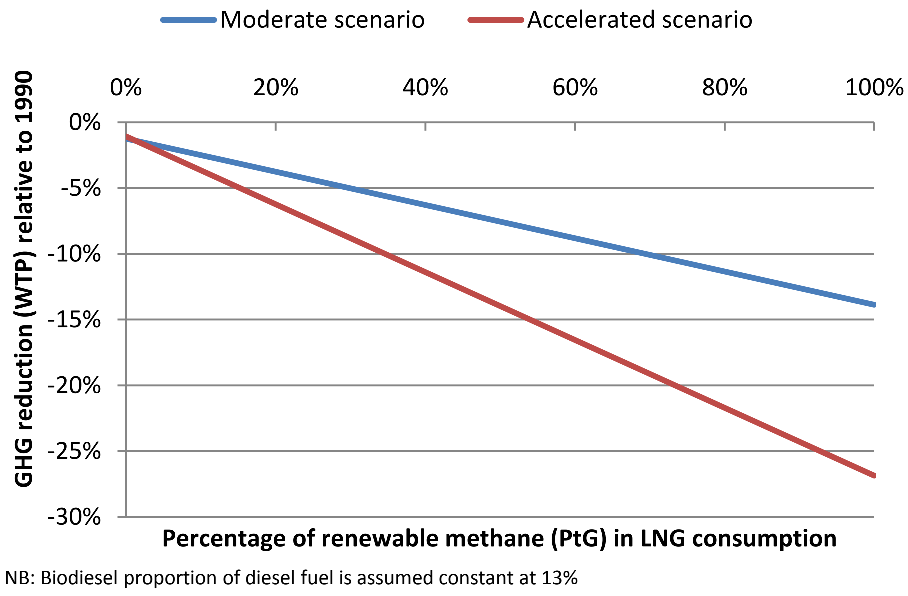

Figure 23: Potential GHG reduction with LNG in inland navigation depending on the percentage of renewable methane

To achieve more substantial GHG reductions, the utilisation of LNG among the fleet would have to be expanded even more (more conversions and application in small vessels). Moreover, sufficient substitution with renewable methane would have to be realised. Alternatively, an increased percentage of the biodiesel could considerably reduce GHG emissions. However, in contrast to RE methane, biodiesel is in direct competition with feed/food production. Similar to methane, renewable diesel fuel may in principle be produced from electricity (so-called Power-to-Liquid, PtL). Substantial GHG savings may thus be realised.

The results presented above indicate potential contributions to the saving of greenhouse gases only in reference to the LNG share of energy demand. Furthermore, reductions of the specific fuel consumption could considerably reduce GHG emissions. The baseline assumptions of the present study expect rather conservative advances in efficiency in comparison with potentials previously published [CCNR 2012].

7.2.3 Heavy-duty vehicles

In the entire supply chain (WTW), the greenhouse gas emissions of a current LNG HDV with approx. 1100 g CO_2 eq./km exceed those of a diesel HDV by about 10%. The CO_2 advantage during combustion of approx. 25% is thus compensated with higher GHG emissions during LNG supply and distinctly higher fuel consumption. Direct CH_4 and N_2O emissions (TTP) may be considered negligible due to strict EURO VI standards (Figure 24).

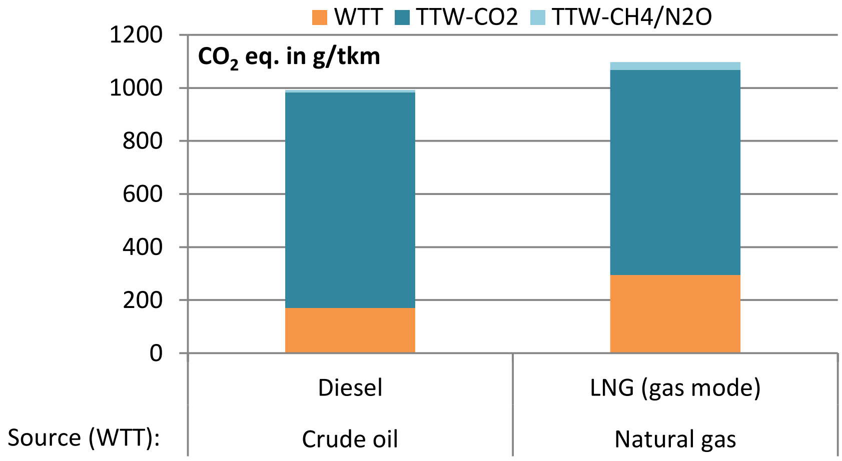

Figure 24: Specific GHG emissions of HDVs (N3) in 2013

Future greenhouse gas emissions per km are expected to decrease by more than 20% compared to the current status quo, mostly due to improved vehicle efficiency. The efficiency improvement is even more pronounced for LNG HDVs, resulting in a decrease of approx. 14% in GHG emissions relative to diesel. Thus, the GHG advantage of LNG is much improved in comparison with 2010. However, major greenhouse gas savings may only be achieved with the utilisation of dedicated renewable methane in LNG vehicles (Figure 25).

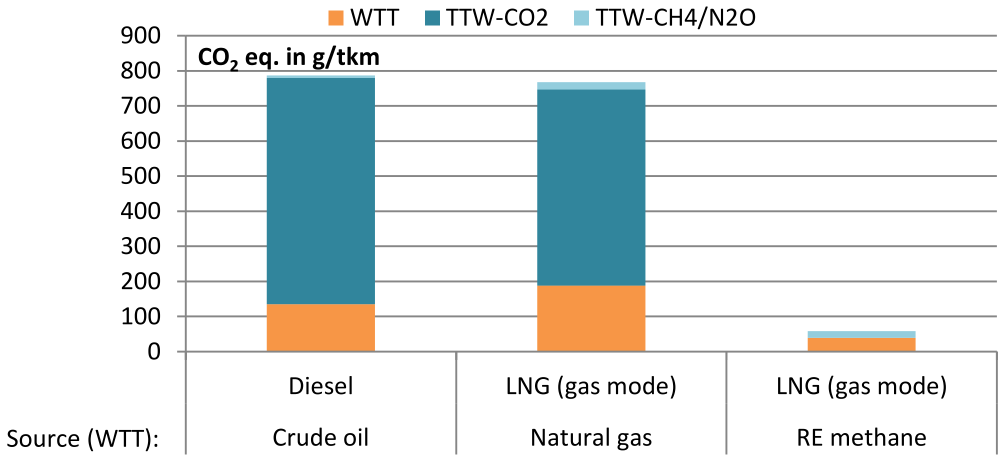

Figure 25: Specific GHG emissions of HDVs (N3) in 2030

LNG could make vital contributions to the future reduction of greenhouse gas emissions in road freight transport. In this context, it is expected that transport provided by HDVs in 2030 is performed entirely with vehicles complying with the EURO VI standard. In analogy to inland navigation, diesel fuel contains 13% biodiesel to comply with the Biofuels Sustainability Ordinance (-60% GHG emissions).

Figure 26 illustrates that greenhouse gas emissions from road freight transport across the entire supply chain are expected to increase rather than decrease in reference to 1990 (between 54-78%). Due to the minor share of fuel consumption in 2030, application of LNG may only partly reduce GHG emissions. Without renewable methane, the moderate and the accelerated LNG scenario project similar greenhouse gas emissions due to the fact that emissions from diesel with 13% biodiesel content are similar to LNG from fossil natural gas. Substitution of natural gas with RE methane may distinctly reduce greenhouse gas emissions, particularly in the accelerated scenario.

The overall substantial greenhouse gas emissions in reference to 1990 are primarily due to steep increases in freight transport (see Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**). A more moderate increase in transport performance would result in an overall greater reduction of greenhouse gas emissions. Quantitative assessment should be approached within the framework of the German Federal Transport Plan (*Bundesverkehrswegeplanung*, BVWP 2030) which was unavailable at the time of writing.

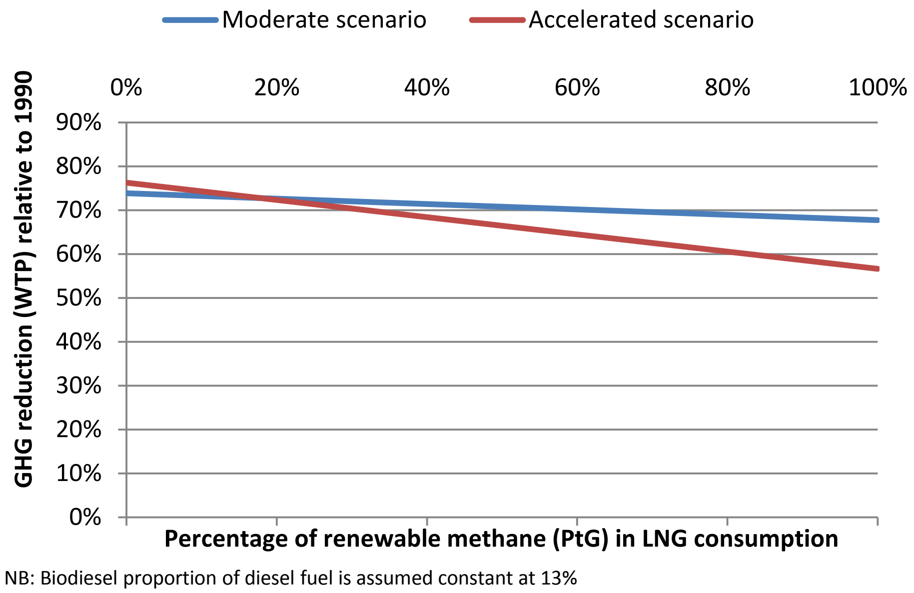

Figure 26: Potential GHG reduction with LNG in road freight transport depending on the percentage of renewable methane

7.3 Contribution to the reduction of pollutant emissions

In addition to the potential contribution for the saving of GHG emissions, a separate driver for the promotion of LNG utilisation may be the reduction of air pollutant emissions. Emissions of nitrous oxides (NOx), particulate matter (PM) and sulphur dioxide (SO_2) are responsible for air pollution in inner-city areas, acidification and eutrophication. In contrast to greenhouse gasses, pollutant emissions mostly act as local to regional environmental hazards. For these reasons, the following chapter explores direct pollutant emissions from engine exhaust gases (i.e. TTW/TTP) only.

7.3.1 Maritime transport

Potential reductions of air pollutant emissions from ocean-going vessels have to be considered in correlation with the different petroleum-based fuels and current emission standard legislation. The latter is regulated in the framework of the MARPOL Annex VI by the IMO (International Maritime Organisation). The IMO defined so-called Emissions Control Areas (ECAs) as well as areas outside ECAs. To date, SOx and NOx emissions are regulated, whereas additional pollutants, e.g. soot, are not subject to limitation.

Regulation of SOx emission through the IMO is carried out via the sulphur content of the fuel and staggered in time (Chapter 3). Starting in 2015, the sulphur content within ECAs may not exceed 0.1% (weight-to-weight), which still exceeds the sulphur limit for diesel fuel in road transport by factor 100. To comply with regulations, Marine Diesel (0.5% S) or gasoil (0.1% S) may be utilised. Utilisation of HFO is permitted in combination with scrubber technologies for SOx aftertreatment. However, thus arising environmental burdens from acidic or polluted waste water remain a challenge. This challenge is intensified with the additional requirement for NOx aftertreatment [IMO 2009]. In contrast, LNG with 3.5 ppm qualifies as virtually sulphur-free [TNO 2011]. In consequence, SOx emissions could be reduced by nearly 100% relative to HFO or Marine Diesel with LNG.

NOx emissions are regulated globally since the introduction of Standard Tier 2 since 2011. This standard may be achieved with inner-engine adjustments without specific exhaust aftertreatment measures. Within ECAs, a tightening of regulations for NOx emissions with Standard Tier 3 is scheduled for 2016. At present, there is debate on a postponed implementation by the year 2021 [MEPC 2013]. According to [Magalog 2008], utilisation of LNG would allow compliance with NOx limits stipulated in Tier 3 today. This would equal NOx emission reductions of 70% relative to Tier 2. In the time period until Tier 3 is formally adopted, LNG may already be instrumental in the reduction of NOx emissions. After implementation of Tier 3, LNG would still hold a distinct advantage if it was utilised outside of ECAs. Calculations by [Wärtsilä 2011] suggest that the LNG option may be more cost-efficient than operation with HFO in combination with scrubber technology and NOx exhaust gas after-treatment. Thus, LNG could be profitable for vessels spending at least part of their time in ECAs.

Particulate matter emissions (PM) in maritime transport are not regulated with emission standards. However, these emissions are strongly correlated with the sulphur content of the fuel. According to [Magalog 2008], engines of vessels operated with HFO are associated with PM emissions of 1.5 g/kWh, whereas the emissions for Marine Diesel (0.5% S) are approx. 65-80% lower. Gasoil emissions (0.1% S) are reduced by up to 90%. With a minimum of 0.15 g/kWh, the PM emissions of ocean-going vessels still exceed those of passenger cars to a considerable extent. Reasons include no mandatory requirement for particle filters, which may be unfeasible due to high sulphur contents. However, according to [Marintek 2007], LNG is virtually free of PM emissions. Additional reductions are thus definitely possible.

In sum, LNG presents a viable option for the reduction of air pollutants in maritime transport. LNG not only complies with all common standards regulating pollutant emissions, it over-accomplishes all existing targets. Moreover, technological challenges of exhaust gas aftertreatment are much simpler than those associated with a combined application of NOx aftertreatment measures and scrubbers. In addition to compliance with prevailing regulations at sea, the minor pollutant emissions of LNG vessels present a distinct advantage in ports and inner-city areas in close proximity to port facilities.

7.3.2 Inland navigation

To date, very few publication have addressed the issue of air pollutant emissions for LNG engines in inland waterway vessels. The benchmark originates from a study conducted by [TNO 2011], which analysed empirical manufacturer data of initial LNG engines (mono-fuel and dual-fuel).

Table 18 illustrates the emission factors thus derived. According to [TNO 2011], the NOx and PM emissions of LNG-fuelled inland vessels are subject to uncertainties reflected in emission ranges as opposed to discrete levels. However, the following data include only values within ranges that appear plausible based on additional information.

SO_2 emissions are calculated directly from consumption and sulphur content of the fuel under the assumption of complete oxidisation of sulphur to SO_2. Diesel fuel for utilisation in inland vessels has to comply with an upper limit of 10 ppm sulphur since 2011. In practice, this translates into a sulphur content of 8 ppm [IFEU 2012]. The sulphur concentration in LNG from upgraded natural gas is negligible. According to Shell, the average sulphur content of LNG is 3.5 ppm [TNO 2011].

At present, inland vessel engines are type-approved based on emission standard regulations of the EU directive 97/68/EC with Stage IIIA in combination with the Regulations for Inspection of Ships on the Rhine (RheinSchUO) with Stage CCNR II[12]. A tightening of emission standards for future engines is currently explored within the scope of the revision of the directive 97/68/EC [COM 2013b]. The final emission standards are decisive for the environmental comparison between LNG and diesel engines. To cover the potential range of emissions standards in inland navigation, two separate emission standard scenarios for 2030 are explored:

- Stage IIIB with a rather conservative revision via harmonisation with IMO/EPA Tier III-Standards. This measure alone would result in the reduction of NOx emissions by approx. 65-75%.
- Stage V with an ambitious revision for harmonisation with EURO VI standards for HDVs. This would be associated with a drastic reduction of both PM and NOx emissions (exceeding 95%).

Table 18: Pollutant emissions TTP for new inland vessel engines in 2010

	2010		**2030**			
	Diesel (Stage IIIA)	LNG	Diesel (Stage IIIB)	LNG	Diesel (Stage V)	LNG (Stage V)
NOx [g/kWh]	8.8	2.0	1.81		0.4	
PM [g/kWh]	0.12	0.02	0.12	0.02	0.01	

Source: [TNO 2011, Panteia 2013] and own assumptions

12 Type-approving is only applicable to new engines, the stages IIIA and CCNR II entered into force in 2007.

The pollutant emissions of different emission standards are compared in Figure 27. At present, pollutant emissions of LNG engines are distinctly lower than those of modern diesel engines for inland vessels. Due to the relatively moderate requirements of Tier IIIA, an LNG engine (dual-fuel in gas mode) produces approx. 1/5 of the NOx and PM emissions associated with a diesel engine. These emissions distinctly influence local air quality, primarily in ports an along waterways with heavy traffic. Thus, LNG is at a distinct advantage. Despite the mandatory utilisation of essentially sulphur-free fuel in inland vessels (since 2011), LNG may reduce SO_2 emissions by more than half relative to diesel.

However, future diesel engines for inland vessels could operate with distinctly reduced pollutant emissions. Moderate tightening of standards via Stage IIIB would still favour LNG over diesel with respect to PM emissions, whereas NOx emissions would draw level. In the case of stricter emissions standards such as Stage V adopted from HDVs, emissions would be equal with the exception of SO_2. Moreover, even LNG engines are expected to require exhaust gas aftertreatment measures such as SCR (Selective Catalytic Reduction) and diesel particulate filters to comply with the emissions standards [Panteia 2013].

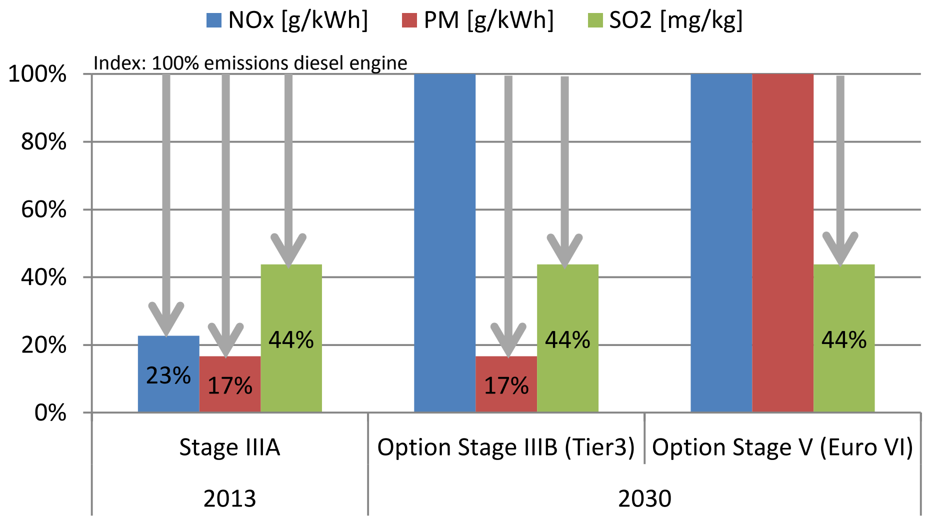

Figure 27: Comparison of specific pollutant emissions of LNG versus diesel in inland vessels

Source: [TNO 2011] and own assumptions

Future growth of the LNG fleet as introduced in Chapter 6.1 could still reduce pollutant emission in inland navigation in the medium-term. The scenarios demonstrate that transport performance and energy consumption of inland vessels in the year 2030 will mostly continue to rely on diesel engines. This is unlikely to change unless cost-efficient alternative drive concepts may be found for smaller and older vessels. Emission savings through LNG in inland navigation in general are thus limited, particularly if stricter emissions standards in the framework of Directive 97/69/EC come into effect in the short-term. Conversion of older diesel engines is generally not economical since these are often installed in smaller or older vessels. Replacement with new diesel engines could present the more cost-efficient solution.

However, it may be expected that stricter emission standards could be achieved with dedicated gas engines with lower exhaust gas aftertreatment expenses compared with diesel engines, e.g. in the case that a particulate filter is not necessary. The savings could compensate the higher investment costs for LNG engines and tanks, thus accelerating the amortisation of LNG vessels and promoting them on the market (see [Panteia 2013]).

7.3.3 Heavy-duty vehicles

From 1.1.2013, type-approving of HDVs is required to comply with EURO VI standards. From 1.1.2014, all newly registered HDVs are required to comply with EURO VI standards. All relevant manufactures are already offering models with EURO VI standard, and the development for EURO VI is complete with the exception of dual-fuel engines. EURO VI may only be achieved with the aid of exhaust gas aftertreatment measures such as diesel particulate filters (DPF) in combination with SCR, with the exception of very few engine models specifically optimised for SCR.

It is expected that dedicated gas engines will not hold any major advantages over EURO VI diesel engines with respect to pollutant emissions. For CNG city buses, HBEFA 3.1 assumes slightly lower PM emissions, yet slightly elevated NOx emissions in comparison with diesel buses[13]. Compliance with the EURO VI standard could thus be associated with exhaust gas aftertreatment measures for LNG that remain to be developed, particularly for dual-fuel engines. Furthermore, combustion of methane in HDV engines requires compliance with a CH_4 emission standard. Fundamental reductions of pollutant emissions through LNG thus appear unlikely at present or in the foreseeable future.

7.4 Summary on the reduction of greenhouse gas and pollutant emissions

LNG offers perspectives to reduce specific GHG emissions in comparison with petroleum-based fuels. The lower carbon content of fossil natural gas with an approximately equal engine efficiency of LNG engines has the potential to save about 25% of direct CO_2 emissions in comparison with diesel or up to 30% relative to HFO. However, considerable methane emissions currently associated with ship engines in particular, as well as higher emissions arising during fuel supply (WTT), could substantially diminish this potential. For HDVs with EURO VI, these constraints do not apply if compliance with the methane standard is achieved. However, the surplus in fuel consumption in total (WTW) prevents distinct greenhouse gas advantages in comparison with diesel. The implementation of strict methane emission standards for LNG engines in vessels and increased efficiency in HDVs in the near future could result in GHG advantages for both transport modes. If the utilisation of renewable electricity in the form of RE methane can be permanently integrated into transport, the utilisation of fossil natural gas and the associated greenhouse gas emissions could be reduced.

High substitution rates of natural gas with RE methane could contribute to future overall reductions of greenhouse gas emissions of the steeply increasing freight transport sector [VP 2025] and support political aims particularly in inland navigation. Thus, LNG should be considered as an alternative to

[13] Please see MFS short study ‘On the road to sustainable energy supply in road transport – potentials of CNG and LPG as transportation fuels’

CNG from renewable sources, renewable liquid fuels (e.g. biodiesel or power-to-liquid), and renewable hydrogen for fuel cell drives or direct utilisation of electricity.

In maritime transport, application of LNG allows compliance with all common pollutant emission standards with a distinct reduction of emissions in comparison with HFO or diesel. Moreover, LNG may reduce pollutant emissions from inland vessels as long as new standards do not call for much stricter emissions standards for diesel engines, such as the regulations already in place for HDVs. Revised emission standard legislation is going to require considerable lead time. Therefore, it is unlikely to enter into force before 2020, whereas 'clean' LNG engines could be in operation today. To improve air quality in ports and along waterways with regular heavy traffic, increased utilisation of LNG-fuelled vessels could be accelerated.

8 Recommendations for action

The utilisation of LNG for the operation of ocean-going and inland vessels and HDVs presents an attractive alternative fuel in comparison with established fuel options in these segments. Some crucial technological components have been in use for a number of years. Remaining open technological questions are regarded as solved (e.g. methane slip in ship engines), or the motor vehicle industry has announced novel solutions (e.g. dual-fuel HDVs complying with Euro VI). For the successful introduction of LNG and the associated infrastructure, the development of a 'National development agenda for LNG as an alternative fuel for maritime transport and inland navigation' is recommended, a joint project for industry and policy makers. In case of successful implementation of such an agenda, a separate agenda for LNG-powered heavy-duty vehicles could be approached.

In the following, recommendations for the three means of transport are compiled from the present study. These recommendations focus on LNG. Additional fuel options such as compressed methane (CNG) or compressed hydrogen (CGH_2) are evaluated in the MFS study 'Renewable energies in transport: potentials and development perspectives of different renewable energy carriers and energy consumption of the transport modes.

First, a number of **general aspects** equally applicable to maritime transport and inland navigation as well as road freight transport with HDVs:

- In any case, orientation towards or introduction of LNG should be prepared thoroughly and all relevant technological and economic risks should be identified and carefully assessed. The required investment is immense, thus relevant stakeholders along the value chain should be included.
- Coordination of plans at the European level is required to incorporate international freight transport flows and ensure utilisation beyond Germany (e.g. in ports, along the TEN-T networks).
- The perspective of LNG should extend beyond LNG imports via ship transport and the debate of shale gas resources. An integration of regional and on-site liquefaction of methane and the application of renewable methane (e.g. from biogas or RE methane) should be pursued.
- The integration of renewable energies should be promoted, particularly through so-called power-to-gas methane and possibly through biomethane in the context of an integrated resource and fuel strategy.
- The applicability of renewable methane credits towards the EU target of 10% renewable fuels by the year 2020 is supported in principle. Coordination with European Commission is required to define default values for different renewable LNG pathways for record in the EU Renewables Directive (RED), thus standardising the crediting methodology and providing transparency.

Recommendations for **maritime transport:**

- In the early stages of the introduction of LNG in maritime transport, German ports may be able to establish themselves as hubs for transhipment and application. This extends to additional modes of transport that are faced with stricter emission standards. Stakeholders could be supported in pilot applications (e.g. matters of authorisation/ permits)
- Maritime transport markets, with the exception of holiday cruises, have been characterised by sinking freight rates and surplus capacities in small and medium vessels for a number of years [Schiff & Hafen 2013]. In addition, there is a financing bubble of ship funds that influences financing banks in light of decreased freight rates [Spiegel 2013]. The resulting reduction of the German fleet manifests itself in fewer new vessels and reduced follow-up financing for existing ships. Before financial support for the fitting out of new vessels and the conversion of existing ocean-going vessels is granted, criteria assessing the merit of the planned expenses need to be defined. These criteria should be based on the current and foreseeable market trajectory in the various freight segments (freight type, vessel size).
- Extended services around the application of LNG should be promoted with research and demonstration projects to accelerate the transition of LNG from a niche product in maritime transport to a relevant energy carrier. Positive side effects would include increased development of the market environment and easy access to the developing market for German enterprises.
- Synergies in the establishment of an LNG infrastructure (bunkering) for maritime transport and inland navigation should be identified.
- RoRo, RoPax and high-speed RoPax vessels are potential candidates for early LNG markets due to the regularity at which they frequent ports and routes over medium distances. Starting from this transport market, LNG may be expanded to additional markets such as international container transport. These types of ships are associated with the lowest barriers for the application of LNG from a user perspective, and should in consequence be the focus of political subsidisation.
- International cooperation is an essential pre-requisite for the development of an integrated and user-friendly infrastructure in the individual ports.

Recommendations for **inland navigation**:

- Establishment of a legal framework for the operation of LNG vessels in Germany. A central role for freight transport on inland vessels in Germany is played by the Central Commission for the Navigation of the Rhine (CCNR).
- Already a part of the inland vessel fleet may reap economic benefits from the application of LNG instead of diesel. Due to the often small scale of inland navigation operations, designated finance concepts could help shoulder the burden of required investment.

- Extension and improvement of available data regarding the emission of methane along the entire pathway well-to-tank with a special focus on methane emissions of the engine (under real conditions where applicable) and loss during refuelling.
- Greenhouse gas emissions of LNG engines in inland vessels in the form of methane could be regulated with mandatory standards in analogy to HDVs. The authorities responsible include the European Commission and the Central Commission for the Navigation of the Rhine.
- Stricter pollutant emissions standards for inland vessels could favour the utilisation of LNG over diesel for the sake of cost-efficiency. Thus, a contribution to the saving of greenhouse gases would be promoted.
- Development of a baseline infrastructure of LNG fuelling stations for vessels along the Rhine in the immediate future.
- Where appropriate, subsidisation of 'clean vessels' to promote LNG with reduced harbour dues, as exemplified in the Rotterdam 'Green Deal'.

The introduction of LNG as a fuel for **heavy-duty vehicles** may be aided by the implementation of a number of major development milestones that require support from both policy makers (e.g. establishment of framework and funding) and industry (e.g. technology development and pilot projects):

- Initial steps should include: risk assessment related to very minor greenhouse gas savings potentials, in particular for LNG from fossil sources, and in case the establishment of dual-fuel engine technology fails. In those cases, the justification of government funding for infrastructure development may be questionable. Furthermore, critical assessment of greenhouse gas savings associated with the energy-intensive supply of LNG from RE methane in comparison with available alternatives is required.
- Follow-up measures should include: support of the motor vehicle industry to strive for rapid implementation of the emission standard EURO VI for dual-fuel engines, promoting availability of these engines on the new vehicle market. Consultation with HDV engine manufacturers is recommended to learn if and how EURO VI dual-fuel engines may be realised, including projections of the entailed effort and the timeframe for realisation. These facts are vital to encourage user acceptance.
- Extended follow-up measures: establishment of LNG fuelling stations for commuter fleets. These fuelling stations should be open to all users.
- Furthermore, exchanges with the motor vehicle industry and operators of infrastructure are recommended to promote debate on long-term framework requirements for the implementation of LNG as a fuel for heavy-duty vehicles.

The stages of development listed above should be advanced simultaneously, although additional prerequisites may be required. Policy makers and industry should interact to identify common interests and define specific targets for efficient realisation, e.g. in the context of an MFS process:

- Confirmation, e.g. via empirical analyses with users, that LNG is developing into a favoured option for heavy-duty vehicles.
- Identification of applications and circumstances that may render diesel or CNG equal or favourable as a fuel.
- Proof of user acceptance of alternatives such as dual-fuel technology in diesel engines, dedicated methane application in the form of LNG, or as CNG in Otto engines based on a comparison of user costs with conventional HDVs with diesel-powered combustion engines. Key question to explore: Which users may expect future benefits from LNG under which precise conditions (e.g. minimum average annual mileage, depending on the difference in price between LNG and diesel)?
- Comparison of infrastructure costs associated with the different options for the supply of HDVs with LNG or CNG, in particular with reference to regional and local concepts.
- Draft of an agenda scheduling the development of the refuelling station infrastructure, the required approval and authorisation procedures and the establishment of additional necessary framework for planning and construction, such as:
    - Establishment of an infrastructure for the distribution of LNG from seaports, to be extended to inland ports.
    - Development of refuelling stations carrying out liquefaction on-site with natural gas delivered via the public gas grid.

These recommendations for action aim to encourage and support an in-depth examination of the application of the energy carrier LNG in Germany. Thus, the way may be paved for the extended application of LNG in ship transport and operation of HDVs.

The recommendations may be utilised as important building blocks for the national development agenda for LNG as an alternative fuel for ship transport and heavy-duty vehicles. Thus, EU targets for LNG stipulated in the proposed EU infrastructure directive [COM 2013] may be addressed in Germany for the different means of transport in a comprehensive and coherent manner.

Abbreviations

BTU	British Thermal Unit
CCGT	Combined Cycle Gas Turbine
CCNR	Central Commission for the Navigation of the Rhine
CH_4	Methane
CNG	Compressed Natural Gas
DPF	diesel particulate filter
ECA	Emission Control Areas
ft^3/d	Cubic feet per day
GHG	Greenhouse gas emissions
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HBEFA	Handbook Emission Factors for Road Transport
HDV	Heavy Duty Vehicle
HFO	Heavy Fuel Oil
ICE	Internal combustion engine
LCNG	Compressed Natural Gas from Liquefied Natural Gas
LNG	Liquefied Natural Gas
MEA	Monoethanolamine
MPa	Megapascal (1 MPa = 10 bar)
Nm^3	Standard cubic meter
NO_x	Nitrogen oxide
PtG	Power-to-Gas (Electricity to hydrogen and via methanation to synth. methane = RE methane)
PtL	Power-to-Liquid (Electricity to hydrogen and via synthesis to synth.liquid fuel)
RE	Renewable Energies
SCR	Selective catalytic reduction
SECA	Sulphur Emission Control Areas
SO_x	Sulphur oxide
TEN-T	Trans-European Network –Transport
tkm	Tonne kilometre

TTP	Tank-to-Propeller
TTW	Tank-to-Wheel
WSV	Wasser- und Schifffahrtsverwaltung (Waterways and Shipping Administration)
WTP	Well-to-Propeller
WTT	Well-to-Tank
WTW	Well-to-Wheel

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Appendix

Gases are reported in different units depending on the literature source. Table 19 illustrates the conversion factors for the different units.

Table 19: Units for natural gas or methane

	Nm³	Scf	t CH_4 at 0°C
1 Nm³ =	1	35.32	0.0007162
1 Scf =	0.02832	1	0.00002028
1 t CH_4 at 0°C =	1.396	49.300	1

Table 20 reports the lower heating values (LHV) of different fuels.

Table 20: Lower heating values of fuels

	MJ/kg (kWh/kg)	MJ/l (kWh/l)	MJ/Nm³ (kWh/Nm³)
Otto fuel (petrol)	43.20 (12.00)	32.18 (8.94)	-
Diesel fuel	43.13 (11.98)	35.88 (9.97)	-
fatty acid methyl ester (‘biodiesel’)	37.2 (10.33)	33.11 (9.20)	-
LNG (methane)	50.00 (13.98)	18-21 (5.03-5.87)[14]	35.82 (9.95)

Source: [JEC 2013]

[14] Density and resulting volume specific lower heating value are dependent on pressure and temperature