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## Revision History

<table>
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<tr>
<th>Author</th>
<th>Organization</th>
<th>Description</th>
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<tr>
<td>Milagros Rey Porto</td>
<td>GNF</td>
<td>January 2014. Suggested additional content</td>
</tr>
<tr>
<td>Judith Domínguez</td>
<td>IDIADA</td>
<td>February 2014. Suggested additional content</td>
</tr>
<tr>
<td>Xavier Ribas</td>
<td>IDIADA</td>
<td>March 2014. Suggested additional content</td>
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Executive Summary

The LNG Blue Corridor project is focused on demonstrating the use of LNG as truck fuel and to define a road map for future large scale development of the market. This report is the second deliverable of the Work Package 3.

Work Package 3 LNG Logistics which includes aspects to supply the market with fuel filling stations and up-stream. The report covers aspects of LNG and LBG.

LNG is a dynamic, cryogenic fuel which means that specific considerations must be taken to secure fuel properties from terminal up to the time of delivery to the truck.

This report – 3.2 Gas Quality - is written to highlight the aspects of gas quality for LNG and LBG to be used as fuel in trucks. Additional reports regarding gas quality issues will be written based on experiences gained as the project develops. Examples of future deliverables with relevance to this report are D3.6 Liquefied Biomethane experiences and D3.11 Studies regarding ageing of fuel.

Discussions on how to find marked- and technology solutions to handle varying gas qualities should be done in the initial phase of the project covering the following topics (examples):

- Sourcing of gas
- Fuel management solutions throughout the delivery chain.
- Solutions to secure gas quality are kept within agreed specification.
- Measuring of gas quality in small scale LNG facilities
- Evaluation regarding design criteria and possibilities for different engine technologies to be optimized toward different gas qualities in terms of robustness, engine efficiency and emission control. The project consortium is recommended to monitor and report accordingly during the demonstration period, at what extent gas quality will effectively influence engine performance, setting through substantiated observations the range of quality indicators and parameters jointly with target range values to be met to ensure proper functioning of engines.
Introduction

1.1 LNG Blue Corridors project

The LNG Blue Corridors project’s aim is to establish LNG as a real alternative for medium- and long-distance transport—first as a complementary fuel and later as an adequate substitute for diesel. Up to now the common use of gas as fuel has been for heavy vehicles running on natural gas (NG) only for municipal use, such as urban buses and garbage collection trucks. In both types of application, engine performance and autonomy are good with present technologies, as they are well adapted to this alternative cleaner fuel.

However, analyzing the consumption data, the equivalence in autonomy of 1 liter of diesel oil is 5 liters of CNG (Compressed Natural Gas), compressed to 200 bar. Five times more volume of fuel prevents the use of CNG in heavy road transport, because its volume and weight would be too great for a long-distance truck. This opens the way for LNG (Liquefied Natural Gas), which is the way natural gas is transported by ship to any point of the globe. NG liquefies at 162º C below zero, and the cost in energy is only 5% of the original gas. This state of NG gives LNG the advantage of very high energy content. Only 1.8 liters of LNG are needed to meet the equivalent autonomy of using 1 liter of diesel oil. A 40-ton road tractor in Europe needs a tank of 400 to 500 liters for a 1,000 km trip; its equivalent volume with liquid gas would be 700 to 900 liters of LNG, a tank dimension that could easily be fitted to the side of the truck chassis. LNG therefore opens the way to the use of NG for medium- and long-distance road transport.

LNG has huge potential for contributing to achieving Europe’s policy objectives, such as the Commission’s targets for greenhouse gas reduction, air quality targets, while at the same time reducing dependency on crude oil and guaranteeing supply security. Natural gas heavy-duty vehicles already comply with Euro V emission standards and have enormous potential to reach future Euro VI emission standards, some without complex exhaust gas after-treatment technologies, which have increased procurement and maintenance costs.

To meet the objectives, a series of LNG refueling points have been defined along the four corridors covering the Atlantic area (green line), the Mediterranean region (red line) and connecting Europe’s South with the North (blue line) and its West and East (yellow line) accordingly. In order to implement a sustainable transport network for Europe, the project has set the goal to build approximately 14 new LNG stations, both permanent and mobile, on critical locations along the Blue Corridors whilst building up a fleet of approximately 100 Heavy-Duty Vehicles powered by LNG.

This European project is financed by the Seventh Framework Programme (FP7), with the amount of 7.96 M€ (total investments amounting to 14.33 M€), involving 27 partners from 11 countries.

This document corresponds to the 2nd deliverable within work package 3. It is a document describing the aspects of gas quality for LNG and LBG to be used as fuel in trucks. This document will be available at the project website: http://www.lngbluecorridors.eu/.
1.2 Aim of this deliverable

The LNG Blue Corridor project is focused on demonstrating the use of LNG as truck fuel and to define a road map for future large scale development of the market. This report is written as part of the Work Package 3 LNG Logistics which includes aspects to supply the market with fuel filling stations and up-stream. The report covers aspects of LNG and LBG.

LNG is a dynamic, cryogenic fuel which means that specific considerations must be taken to secure fuel properties from terminal up to the time of delivery to the truck.

This report – 3.2 Gas Quality - is written to highlight the aspects of gas quality for LNG and LBG to be used as fuel in trucks. Additional reports regarding gas quality issues will be written based on experiences gained as the project develops.
2 Gas quality – Compressed vs. Liquefied

When describing the issues of gas quality for liquefied gas there are significant aspects to handle in terms of pressure/temperature and how to store the liquefied gas up to it is delivered from the refueling station to the truck and how it is handled at the truck. However, except from fuel pressure to the engine there are from an engine design perspective no significant difference between compressed or liquefied as the gas during combustion always is injected in gaseous form. Therefore, gas quality aspects for LNG and LBG is mainly focused on how to secure same quality level as compressed gas with additional parameters due to liquefaction.

2.1 Differences between CNG and LNG

The use of the natural gas means a reduction of the contaminants in the combustion process, in addition, the natural gas liquefaction process have a particular advantage in terms of storage and transport. This is the one of the differences in the use of LNG as a fuel of Heavy duty vehicles. But in order to know better the difference between CNG and LNG about the gas quality below are detailed the composition of the both gases and some differences that affect to the gas quality. CNG is different from LNG in that it is a gas that is compressed to nominal pressures as high as 3,600 pounds per square inch (psi). (Pressures can be even higher when taking temperature compensation effects into account).

LNG has a higher energy density than CNG and many other alternative fuels. This means that LNG has most energy per volume than CNG.

It is also important to talk about the LCNG (Liquefied to compressed natural gas), it is produced by pumping LNG up to a selected pressure level and then vaporizing the liquid through a heat exchanger (vaporizer). It is more efficient and faster to pressurize natural gas in liquid form. LCNG can be pressurized via a relatively small cryogenic pump (e.g., basketball size). LCNG can be used for light- and heavy-duty vehicles and its fueling stations and operations are similar to those for LNG.

The liquefaction process, of the LNG; requires the removal of the non-methane components like carbon dioxide, water, butane, pentane and heavier components from the produced natural gas. When vaporized it burns only in concentrations of 5% to 15% when mixed with air. For this reason, and others which are explained in the following chapters of this deliverable, CNG and LNG varies in composition. In this way are explained some differences between CNG and LNG, which we discuss this further in following chapters.

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2.2 LNG specifications

Per definition LNG is natural gas which has been cooled down so much that it is converted into a liquid. The base natural gas from which it is made not only contains methane, although this is by far the most abundant component, but also ethane, propane and even some butane, and, a contain amount of, nitrogen will be present as well.

Since, after nitrogen, the methane requires the lowest temperature for liquefaction, the other hydrocarbons, which may present in the natural gas, will all become liquids before the methane during the cooling-down process. Therefore, the standard situation is to take out most of these in a process called fractioning and which can be explained by the boiling temperatures and liquid densities.

<table>
<thead>
<tr>
<th></th>
<th>Boiling temperature at atmospheric pressure (°C)</th>
<th>Liquid density (kg/dm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>-195.8</td>
<td>0.810</td>
</tr>
<tr>
<td>Methane</td>
<td>-161.5</td>
<td>0.421</td>
</tr>
<tr>
<td>Ethane</td>
<td>-88.6</td>
<td>0.546</td>
</tr>
<tr>
<td>Propane</td>
<td>-42.0</td>
<td>0.585</td>
</tr>
<tr>
<td>N-Butane</td>
<td>-0.5</td>
<td>0.600</td>
</tr>
</tbody>
</table>

Depending on the liquefaction process, storage capacity, other practical and economical considerations at the terminal, there might be an incentive to keep some of the higher hydrocarbons in the LNG.

2 http://www.beg.utexas.edu/energyecon/lng/LNG_introduction_07.php

3 http://www.gie.eu/ “GIE position paper on gas quality”
A limited amount of heavy hydrocarbons will always be present in the LNG, but the actual content may depend on its origin. This also means that there will be a certain spread in the knocking resistance (methane number) of gas made from LNG depending on its origin. As we will see in the following chapter: Gas quality by source market.

Liquefaction plans have strict requirements on gas purity to prevent freeze out (carbon dioxide—CO2, water and heavy hydrocarbons), corrosion and erosion. Some components must be removed to meet the LNG product specifications, such as hydrogen Sulfide—H2S, corrosive and erosion components (mercury), inert components (helium and nitrogen) and oil. Consequently, LNG contains no CO2 and no corrosive substances. Anyways the composition is still variable.

1. During the LNG transportation the “Boil off” appears, and this affects the LNG composition (gas quality). These differences in the LNG composition show up in the engines operation: Natural boil-off gas, which is taken of the top of the LNG tanks above the liquid will have a high methane content and some nitrogen and thus have a high knocking resistance. Analysis show values typically around Methane Number (MN) 100 and LCV between 33-35 MJ/Nm3. (Initial gas extraction after up-loading may have reduced calorific value because of the high nitrogen content at the top of the tanks). This is a somewhat special application typical for fuelling of LNG tanker propulsion plants.

2. Forced boil-off gas, i.e. LNG extracted from down in the tanks and evaporated separately. This gas will contain a mixture of all hydrocarbons in the liquid and its resistance to knocking may differ from origin to origin and even from load to load, with the MN typically in the range between 70 and 80. The calorific value will be higher than natural boil-off gas and quite stable at around 38-39 MJ/Nm3.¹

2.2.1 Methane number

The motor octane number and the methane number are topics of interest on describing a fuel for use in an engine. These numbers describe the tendency for a fuel to knock (early or pre-ignition) in a spark-ignited engine.

The motor octane number is most familiar on ratings used for gasoline and the methane number has been developed to better describe knock tendency of gaseous fuels. “The methane number scale is based on the molar percents of methane and hydrogen, with neat methane equal to 100 methane number.”²

The selection of a limit to methane number is very important because if the range to methane number is between 80 and 100 this would exclude the majority of available LNG from coming to Europe. Below you can see a figure that visualizes the methane number versus Wobbe index for LNG qualities. Recently, there has been a push to reduce the methane content requirement for LNG to one that is more similar to the CNG so that more suppliers can be used in transportation. But currently, most LNG

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vehicle users require very high methane content (>98%). This higher methane content for LNG is intended to reduce the effects of weathering of the fuel.

The lower methane content can also lower the price of the LNG. Your LNG supplier can provide the methane number for LNG fuel that they can supply. Note that the lower the methane content, the more vigilant the users will need to be in understanding weathering of LNG and minimizing the effect. LNG weathering is discussed in more detail later in this subsection.7

The topic of the methane number is explained in further details in the Chapter 6 "Sensitivity to varying gas quality".

2.2.2 LNG saturation

Unlike gases, which increase in density under higher pressures, saturated liquid-vapor mixtures are less dense at higher pressures. Understanding saturation is critical to assess the use of LNG and the amount of LNG stored on a vehicle or in a storage tank.

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6 http://www.iea-amf.org/content/fuel_information/methane

7 http://www.afdc.energy.gov/pdfs/lng_resource_guide.pdf
LNG is stored on-board a vehicle as a saturated liquid-vapour mixture. This means that the mixture is in between the liquid and vapour phases, so it will boil when heat is added and condense when heat is removed.

To understand LNG saturation, it is helpful to briefly consider the process of refrigerating natural gas to make LNG. As heat is removed from the gas, its temperature decreases. This continues until the gas becomes so cold that it begins to condense to a liquid. The temperature and pressure at which this occurs is called the saturation point. Both the gas (which is usually referred to as a vapour in this state) and the liquid that starts to form are said to be saturated. At this point, removing heat will cause more vapour to condense to liquid, but will not reduce the temperature as long as the pressure is held constant and the natural gas is not completely condensed, or liquefied. The temperature at which this transition from vapour to liquid takes place is called the saturation temperature. In commercially available LNG fuel systems, fuel is stored on-board vehicles under saturated conditions, because it reaches an equilibrium of liquid and vapour through boiling and condensation. As stated earlier, a saturated liquid-vapour mixture typically boils when heat is added and condenses when heat is removed.

The saturation temperature for condensation or boiling depends on the pressure. Conversely, the saturation pressure for boiling or condensation depends on the temperature. The relation between saturation temperature and saturation pressure is shown in Figure 2-3. This is known as the saturation curve or saturation line.

\[\text{Figure 2-3 the saturation curve for natural gas (100\% methane), defines the conditions where the liquid and vapour phases can coexist \((^\circ F = 1.8 \times ^\circ C + 32 \text{ and } 1\text{psi}=6.90 \text{ kPa})\).}\]
Figure 2-3 applies if the natural gas (and LNG) is 100% methane. When natural gas contains other constituents, the saturation temperature (or pressure) changes slightly as more vapor is condensed to liquid, or liquid is boiled to vapor. Also, the concentration of non-methane constituents is different in the liquid and vapor phases. If the non-methane constituents have a higher boiling temperature than methane, they may be more concentrated in the liquid phase. This phenomenon is called “weathering” or “enrichment” in some situations. When natural gas is saturated, the liquid phase usually has a much higher density than the vapor phase. The dependence of this density on the pressure and temperature is indicated in Figures 2-4 and 2-5, by the difference in density between the triangle to the far right of the figures and the circle to the left of the figures. It should be noted that these points lie on the broken-line curves labeled “saturation line.”

In Figures 2-4 and 2-5, the triangles to the right denote the state of the liquid in the LNG fuel tank, which is assumed to be saturated at a typical pressure of 100 psig (690 kPa). The corresponding saturation temperature is -200°F (-93°C). Note that the liquid density at this state is 23.0 lbm/ft³ (368 kg/m³), which is nearly twice the density of a full CNG fuel tank. The higher density of LNG relative to CNG is the main reason that LNG is preferred for many heavy-duty vehicles with high fuel consumption and limited space for fuel tanks. On the other hand, CNG is more convenient for light-duty vehicles and many medium-duty vehicles, because fueling is simpler and there are no issues associated with cryogenic materials, fuel vaporization, and venting. The circles on the left side of Figures 2-4 and 2-5 denote the state of the vapor in the LNG fuel tank ullage, which is saturated at the same temperature and pressure as the liquid.
The path shown from the triangle to the circle to the diamond in Figures 2-4 and 2-5 denotes the change experienced by the LNG as it warms in the vaporizer. Its temperature and pressure remain constant at saturation conditions until all the liquid is boiled to vapor. As more heat is added in the "vaporizer," the gas temperature increases (Figure 4-5), and the density decreases slightly. Figures 2-2 and 2-4 illustrate an additional issue pertaining to LNG fuel system design. Note that if the LNG could be stored at a lower saturation temperature and pressure, its density would be greater and so more fuel could be stored in a given-size fuel tank. However, for current generation LNG fuel systems, it is convenient to store LNG at a saturation pressure slightly more than the engine fuel pressure requirement. This simplifies the system because no fuel pump is required, but it also involves compromises including the quantity of fuel that can be contained in the fuel tank.

2.2.3 Wathering of LNG fuel*

The Dedicated natural gas engines are typically designed for a minimum methane content in the fuel. When the LNG is stored for long periods, there is a tendency for the lighter gases (specifically methane) to boil off and vent, leaving the heavier components. Consequently, the methane content of fuel that is stored for long periods of time can diminish. This process is known as weathering.

This fuel, with the reduction of the methane, can cause reduced engine performance and even engine failure when used on a vehicle. In order to reduce weathering, LNG fuel should be treated as a perishable product.

Proper fleet management is crucial to preventing excessive weathering. The best weapon against weathering is to prevent the fuel being stored long enough for significant boil off. By using the vehicles regularly, the pressure within the fuel containers stays at reasonable levels, preventing excessive vaporization of the fuel within the container, thus preventing weathering. Any techniques that prevent heat gains will also prevent weathering, as well as fuel venting. This is true of both the vehicle fuel system as well as the fueling station. By using the fuel stored on the vehicle and in on-site fuel storage tanks in a timely manner, heat gains are prevented which will reduce both weathering and loss of fuel through venting.

The susceptibility of a vehicle fuel system to weathering will depend on how the fuel system is designed to remove fuel from the fuel tanks. Some systems are designed to remove vapor from the fuel tank before removing liquid. These systems are highly susceptible to weathering because the vapor removed from the tank will be mostly methane. Higher hydrocarbons will become concentrated in the liquid that remains in the fuel tank. As the tank approaches empty, the methane content of the fuel delivered to the engine will decrease. If the tank is not emptied before each refueling, the methane content of the fuel in the tank will progressively decrease with each refueling. Another system design removes primarily liquid fuel from the fuel tank. While this system will not prevent all weathering, it will prevent progressive weathering of fuel from successive fuelings. With a liquid draw fuel system, there should not be significant on-board weathering issues as long as the vehicles are used regularly. Understanding how the vehicle fuel system used on your vehicles removes fuel from the fuel tanks will help you to properly manage your fleet to prevent excessive weathering. For these same reasons, it is important for you to understand how vapor is managed in stationary fuel storage tanks as well.

2.3 LNG fuel quality standarization

There are ongoing projects within the standardization organization CEN to handle gas quality aspects with focus on compressed gas. Traditionally standardization of gas has been strongly focused on safety aspects but not so much on engine design aspects drivability, efficiency, etc

Gas infrastructure is dealt with within CEN/TC 234, in which WG 11 is handling the functional requirements of gas quality. For petroleum products the vehicle fuel quality aspects are normally handled by TC019. These two groups have commonly formed the PC408 with main focus to define the quality aspects of biomethane for injection and use as vehicle fuel which is also relevant for the use of natural gas as vehicle fuel. A general position is that TC 234 Gas Infrastructure is focusing to preserve present status while the actors within TC019 is working for tight specification of gas quality with reference to fulfillment of emission lever EURO 6 and fuel efficiency.

The only present international standard for CNG is “ISO 15403:2006 Natural gas for use as a compressed fuel for vehicles”. In this standard no limits are given in the normative part 1 (Designation

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9 Source: Mattias Svensson, Swedish Gas technology Center, Presentation at NGV 2013 Gothenburg.
of the quality). However, part 2 includes an informative technical report (Specification of the quality) on certain trace elements which to a high degree is based on US national standard SAE J1616 from 1994.

Criteria handled in ISO15403:2006 are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>&lt; 0.03</td>
<td>Volume fraction</td>
</tr>
<tr>
<td>O₂</td>
<td>&lt; 0.03</td>
<td>Volume fraction</td>
</tr>
<tr>
<td>S</td>
<td>&lt; 120</td>
<td>mg/m³</td>
</tr>
<tr>
<td>H₂S</td>
<td>&lt; 5mg</td>
<td>S/m³</td>
</tr>
<tr>
<td>Mercaptans</td>
<td>&lt; 15mg</td>
<td>S/m³</td>
</tr>
<tr>
<td>Water</td>
<td>&lt; 30</td>
<td>mg/m³</td>
</tr>
</tbody>
</table>

Also the European Association for the Streamlining of Energy Exchange – gas, EASEE-gas, has identified a number of gas properties and parameters for harmonization across the European Union. Based on specific reference conditions the parameters are described in the table below.

Another standard dealing with qualitative criteria is Swedish Standard SS 155438:1999. This standard covers the scope of direct utilization of biomethane as vehicle fuel. The standard is under revision and will be updated during spring 2014. Examples of covered parameters in present standard for biomethane to vehicles with catalyst (Type B) are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Recommended implementation date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wobbe index lower</td>
<td>43.9 – 47 MJ/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane content</td>
<td>97+/- 2 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MON</td>
<td>130</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dew point</td>
<td>t-5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The aspects of harmonization and standardization of LNG will be developed during the project and reported in later deliverables, e.g. D3.5 and D3.11.

The LNG Blue Corridor-project will increase the experiences from using methane as vehicle fuel and will develop knowledge that will support the development of the standards especially with additional data regarding experiences of liquefied gas. As the work to develop the standards is ongoing all aspects regarding specific quantitative with relevance also to compressed gas is referred to TC234 and PC408. In the LNG Blue Corridor project it is recommended to harmonize the actors view of which are the important parameters that are to be considered as important design criteria for future efficient and clean technologies and possibilities to provide the gas to the market on a cost efficient level for all actors within the market chain. This is primary recommended to be done in working groups with open dialogue including open dialogue regarding LNG-engine systems and fuel logistics/upgrading aspects with actors participating in WP2 and WP3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content</td>
<td>max. 32 mg/m³</td>
</tr>
<tr>
<td>CO₂+O₂+N₂</td>
<td>max. 5 % (vol)</td>
</tr>
<tr>
<td></td>
<td>where of O₂ max 1 % (vol)</td>
</tr>
<tr>
<td>Total sulphur</td>
<td>max 23 mg/m³</td>
</tr>
</tbody>
</table>
LNG delivery chain

LNG is commonly used globally to supply the market with natural gas. The supply chain is traditionally based on large scale production of LNG by condensation of natural gas close to the gas field. The gas is stored in a LNG export terminal built for export from which large deep sea LNG carriers transport LNG to import terminals. Japan and South Korea are countries importing LNG. Also in Europe LNG is imported though terminals in Portugal, Spain, UK, Belgium, the Netherlands, Italy, etc. The absolute majority of the imported LNG is re-gasified and injected to the European gas grid and distributed in gaseous form to end-customers for heat and power generation.

By using LNG as truck fuel the delivery chain is added with more steps as this requires small scale LNG delivery to the refueling station. For LBG the distribution chain involves different steps and the chain as a whole is to consider as small scale compared to LNG distribution chain, see illustration below.

Liquefied natural gas is stored and transported in tanks as a cryogenic liquid, i.e. as a liquid at a temperature below its boiling point. Just like any liquid, LNG evaporates at temperatures above its boiling point and generates Boil-off gas (BOG). BOG is caused by the heat ingress into the LNG during storage, shipping and loading/unloading operations. The amount of BOG depends on the design and operating conditions of LNG tanks and ships. The increase in BOG increases the pressure in the LNG tank. In order to maintain the tank pressure within the safe range, BOG should be continuously eliminated. In the LNG supply chain, BOG can be used as fuel, re-liquefied or burned in a gasification.
plant. Furthermore, the more volatile components (nitrogen and methane) boil-off first, changing LNG composition and quality over time.11

The US and European markets have to some extent developed differently with respect to gas quality, with the US being the leanest one. One of the reasons for this is the use of LNG peak shaving facilities for seasonal swing, and the fact that the domestic sources have been leaner in the US, than the supplies from the north, east and south to Europe. In Europe large pipelines along with underground storage has been used to meet the peak demand.

11 http://hrcak.srce.hr/ “Problem of Boil-off in LNG Supply Chain”
4 Gas quality by market: source, import and export

Due to the liquefaction of methane the fuel is to a large extent already upgraded. This means in theory less variations in gas quality compared to markets offering different qualities of compressed gas, i.e. L-GAS vs. H-GAS or different levels of upgraded biogas. However, the content of LNG from different sources still varies depending on the source and this is important to take notice of when designing engines.

Table 4-1 Worldwide average LNG compositions

<table>
<thead>
<tr>
<th>Source; NGVA Europe Position Paper: LNG, a Sustainable Fuel for all Transport Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>The table above is an example based on average composition per source. The qualities defined in the tables might change over time. Other variations of gas might occur if the cryogenic fuel is stored too long in the storage tank or in the fuel tanks of the vehicle. Small scale mixing of LNG qualities, i.e. refueling of storage tanks at filling stations will also lead to small variation in gas quality delivered to the truck.</td>
</tr>
</tbody>
</table>

Information about LBG gas quality have been found from Lidköping Biogas (Sweden) and Gasrec (UK) which are the two leading actors in EU producing LBG. Depending on the producer the qualities are as presented in table below:

Table 4-2 LBG gas quality in UK and Sweden

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lidköping Biogas (SE)</th>
<th>Gasrec (UK)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>98,5</td>
<td>97</td>
<td>% Vol.</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1,2</td>
<td>3</td>
<td>% Vol.</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0,3</td>
<td>-</td>
<td>% Vol.</td>
</tr>
<tr>
<td>Energy content</td>
<td>13,5</td>
<td>N/D</td>
<td>kWh/kg</td>
</tr>
</tbody>
</table>
The LBG produced by Gasrec is physically blended into LNG and sold as “bio-LNG” with a standard blend of 25% LBG. The LBG in Sweden is typically sold by the fuel distribution company FordonsGas under the name of “BiGreen” which means the LBG is normally sold without blending but with carbon footprint based on 50% renewable content. This system is certified by the third party “Svanen” which is a Nordic Eco Labelling organization.

4.1 Import of LNG

The performance and consumption of the vehicle depends directly on the gas quality. We saw that the gas characteristic differs in accordance with the market. LNG coming from two different sources will have high variation on the principal gas key parameters. Variations of Methane Number, Wobbe Index or Heating value will affect the customer buy changing the engines performance or even affect the engine reliability (Knocking, Misfire). For this reason, a gas harmonization is needed in order to avoid performance disparities due to a different source of importation.

![Figure 4-1 worldwide overseas LNG importation](image)

Imports represent three key markets: Asia, Western Europe and America.

4.1.1 Asia

Five importing countries: Japan (as the world’s leading importer, Japan purchases 39% of global production), South Korea (15.2% of imports), Taiwan (5%), India (4.6%) and China.

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12 Svanen’s criteria for third party certification of vehicle fuel is found [here](http://www.gie.eu).

13 [www.gie.eu](http://www.gie.eu) (20130606 GLE presentation, LNG Shipping Forum, by Pierre Cotin)

Since 2006, these countries have imported LNG from seven producer countries: Qatar (the world’s leading exporter, with 17% of global production), Malaysia (13.1%), Indonesia (12%), Australia (8.7%), Brunei (4.1%), Oman (5.4%) and Abu Dhabi (3.3%).

In 2007, Asian countries also imported LNG produced in Alaska, Egypt, Algeria, Nigeria and Equatorial Guinea (plant commissioned in 2007).

4.1.2 Western Europe

Most trade in LNG is from Algeria (10.4% of global production), Nigeria (9.7%) and Egypt (6.2%). This LNG goes to Spain (11% of global imports), France (5.6%), Turkey, Belgium, Italy, Portugal, the United Kingdom and Greece.

In 2007, cargoes also came from Qatar, Trinidad-and-Tobago, Libya and, to a lesser degree, Oman.

The first two deliveries were also received from the Snøhvit plant in Norway, which came on stream in 2007.

4.1.3 America

The USA is both an exporter—shipping LNG to Japan from Alaska (0.6%)—and an importer (9.5% of the world total), receiving LNG on the East Coast and in the Gulf of Mexico, mainly from Trinidad-and-Tobago (8.3%), Egypt and Nigeria, as well as from Equatorial Guinea.

Porto-Rico, the Dominican Republic and Mexico (since 2006) also import LNG.

4.2 Differences between the markets

The three most important markets are supplied with different LNG composition.

The Asian market (Mostly Japan) is oriented to the Rich LNG due to its historically originated LNG supplies from Indonesia, Malaysia, Brunei, Australia, and Abu Dhabi (i.e. mostly sourced from rich gas fields). So Japanese specifications typically require LNG with a higher Heating Value and Wobbe Index that is than the gas which can be produced. In these cases, the imported LNG needs to be enriched with LPG. Korea follows the same pattern as Japan standard quality without LPG addition.

The American market represented by the USA, which uses mostly lean LNG coming from Alaska production plants. The range of acceptable Heating Values varies between pipelines, but is lower than that of most LNG that is currently available. Exceptions to this are LNG from Trinidad, Egypt, Equatorial Guinea and some Algerian LNG; historically most of the LNG imports to the USA have come from these countries.

The various European gas quality specifications are different but broadly similar. Three groups of natural gases have been defined by EN 437 which specifies the test gases and pressures to be used when testing domestic gas appliances for compliance with the Gas Appliance Directive. These categories are defined according to their Wobbe Index as follows:

- Group L: $39.1 < W < 44.8 \text{ MJ/m}^3$
- Group H: $45.7 < W < 54.7 \text{ MJ/m}^3$
- Group E: $40.9 < W < 54.7 \text{ MJ/m}^3$
Group L and H refer to low-calorific value and high calorific value gases available in countries in the Continental Europe. Specifically defined and used only in Germany and Luxembourg, Group E covers all of the Wobbe Index range of Group H and part of that of Group L. Each EU country has then defined their own limits within these categories for their different gas transmission systems. The Netherlands, UK and Italy are likely to need to process the import LNG to the national specifications. 

<table>
<thead>
<tr>
<th>Country</th>
<th>Proposed CBP Gas Quality</th>
<th>± Percentage Wobbe</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>White Paper3</td>
<td>± 4.0% Wobbe</td>
</tr>
<tr>
<td>UK</td>
<td>GS(M)R</td>
<td>± 4.3% Wobbe</td>
</tr>
<tr>
<td>EASEE-gas</td>
<td>Proposed CBP Gas Quality</td>
<td>± 5.6% Wobbe</td>
</tr>
<tr>
<td>France</td>
<td>Transmission Entry Spec.</td>
<td>± 7.0% Wobbe</td>
</tr>
<tr>
<td>Germany</td>
<td>National Standards</td>
<td>± 10.1% Wobbe</td>
</tr>
<tr>
<td>Italy</td>
<td>National Standards</td>
<td>± 5.0% Wobbe</td>
</tr>
<tr>
<td>Korea</td>
<td>National Standards</td>
<td>± 4.6% Wobbe</td>
</tr>
<tr>
<td>New Zealand</td>
<td>National Standards</td>
<td>± 6.1% Wobbe</td>
</tr>
<tr>
<td>UAE</td>
<td>Abu Dhabi Spec.</td>
<td>± 3.0% Wobbe</td>
</tr>
</tbody>
</table>

The European LNG imported has strong differences on their composition which results on Wobbe index and Heating values disparities. As show in the table 5-1, the Wobbe index ranges changes form a country to another (example UK ± 4.3% / Germany ± 10.1% Wobbe Index). These fluctuations affect every stages of the LNG supply chain, from the import production plant to the customer. In order to keep the same vehicle performance, the LNG available through Europe should meet standards in order to obtain a constant LNG quality.

### 4.3 Gas Quality Management

Quality adjustment of gas or liquefied natural gas (LNG) can be carried out at various stages in the chain of natural gas production and use, to meet contractual specifications.

Techniques listed below are widely used for quality adjustment at point of production, as well as at import terminal prior to send-out point, with the exception of blending which is mainly carried out in the transmission network:

- Ballasting with inert gas.
- Propane/butane removal/injection.
- Carbon dioxide or nitrogen removal.
- Blending of different streams.

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Control of combustion process (air-to-fuel ratio) is often preferred at the point of use to cope with the variation in gas quality.

### 4.3.1 Ballasting

Ballasting is a technique to lower the Wobbe Index and Heating Value of rich natural gas by the addition of a readily available gas (e.g. nitrogen, carbon dioxide, air, hydrogen) such that the quality of send-out gas from a terminal meets customer requirements. The degree of adjustment is often limited by the allowable concentration of a specific component.

- Ballasting with nitrogen is widely used for its strong effect on Wobbe Index.
- Air ballasting is very similar to nitrogen ballasting albeit with the disadvantage of introducing oxygen into the natural gas.
- High levels of hydrogen induce high flame speed and high diffusivity; therefore, hydrogen ballasting is limited to small changes.

### 4.3.2 Propane/butane removal/injection

Propane/butane removal or injection will allow modifying the gas original Wobbe index to Rich or Lean levels in order to meet the expect specifications.

LPG and NGL removal from LNG are standard fractionation processes, except that the operating temperatures involved for LNG are substantially lower than most other fractionation processes. For rich feed gas streams, it is standard practice for the LNG plant to remove NGLs (LPGs and/or condensate).

LPG (in both its liquid and gasified forms) can be injected into a natural gas or LNG stream to increase its Wobbe Index. One major issue with LPG injection is the increased hydrocarbon dewpoint which could result in condensation into local distribution systems after pressure letdown. Therefore, this is only practical for small corrections.

### 4.3.3 Carbon dioxide or nitrogen removal

Carbon dioxide removal is only applicable to pipeline gas as LNG contains no carbon dioxide. Removal could be based on amine absorption, solid bed adsorption or membrane separation. It is economical and efficient for small adjustment of Wobbe Index. The process of nitrogen removal by cryogenic distillation is more complex, as it requires upstream elimination of carbon dioxide and water which have lower boiling points. This technique is used to adjust gas quality which is beyond the capacity of carbon dioxide removal.

Since LNG has virtually zero carbon dioxide content, the carbon dioxide or nitrogen removal method is only applicable for adjustment of pipeline gas quality prior to entry into a transmission system.

### 4.3.4 Blending

Blending is typically a low cost option and can be used for both derichment and enrichment depending on the quality of the blending gas available. At an LNG export/import terminal, blending of LNG between tanks in its cryogenic liquid form can be done for quality management. This is a routine operation for many import terminals receiving LNG from diverse suppliers and where storage is limited.
Another upstream adjustment option is blending of LNG in the send out section prior to entering transmission pipeline, to eliminate the need for an extra blending tank. Blending in the network deals with transient changes of gas quality and is not always possible.

For LNG, in-tank blending is likely to be the cheapest option provided no additional storage tank is required and stratification problems can be avoided.

### 4.4 Interchangeability

Interchangeability: “The ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, performance or materially increasing air pollutant emissions”.

This topic is a relevant issue to talk about the differences qualities of LNG in the market. The issue of the LNG interchangeability is therefore how to ensure security of gas supply at reasonable cost, knowing that gas quality parameters of much imported gas may be at the extremes of, or outside, existing gas-specification limits.

Below you can see the major categories of gas quality and their objectives for best interchangeability. Some of these topics already have been discussed before, in order to talk about the composition and its characteristics of the LNG.

<table>
<thead>
<tr>
<th>Energy content</th>
<th>Gross Calorific Value</th>
<th>Billing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy load</td>
<td>Wobbe Index</td>
<td>Burner control</td>
</tr>
<tr>
<td>Combustion characteristics</td>
<td>European Standards EN 437</td>
<td>Health &amp; Safety</td>
</tr>
<tr>
<td>Impurities</td>
<td>S compounds, O2, CO2, water &amp; HC dew points</td>
<td>Damage avoidance</td>
</tr>
</tbody>
</table>

### 4.4.1 Country Gas Quality Programmes

Different countries have come to describe their interchangeability issues in a number of different ways. This section gives several examples and describes the national/regional initiatives developed to achieve harmonised gas quality standards.

- **UK Gas Quality Programme** – The completed test programme led by the UK government, leading to the recent decision on the UK strategy for dealing with new gas imports.
- **Europe Follows UK Programme** – The development of EASEE-gas standard for cross-border trading across EU member states, and work by CEN, the European Standardisation Department.
- **United States** – The recognition of Wobbe Index and initiatives to converge towards harmonised standards through the National Gas Council.

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16 MVV consultant “Study on Interoperability of LNG Facilities and Interchangeability of Gas and Advice on the Opportunity to Set-up an Action Plan for the Promotion of LNG Chain Investments”

17 A useful definition of interchangeability could be the one provided by the NGC+ group
• Far East – The Far East occupies a unique position in gas quality standardisation, with Japan being a mature LNG based market and Korea and China as emerging gas users. Their respective efforts in gas quality standardisation are discussed.

4.4.2 Interchangeability parameters

The most critical measure to interchangeability is the **Wobbe Index**. Below we show the range of variation of this parameter by LNG source.

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18 [www.gie.eu](http://www.gie.eu) (20130606 GLE presentation, LNG Shipping Forum, by Pierre Cotin)

19 ec.europa.eu "Fjrc_reference_report_200907_liquefied_natural_gas.pdf"
Different interchangeability measures have been specified by countries.

- In the Continental Europe, limitations on Wobbe Index and inert gases are considered to be sufficient for wholesale gas.
- The UK looked further into parameters related to appliance non-optimum performance such as the Lift Index, Incomplete Combustion Factor and Soot Index.

In the report “Liquefied Natural Gas for Europe - Some Important Issues for Consideration” discuss this topic, the two illustrations following are taken from this report.

![Figure 4-3 Composition of European pipeline gas and LNG (the relative size of the bubbles indicates the methane content); Source Report EUR 23818 EN](image1)

![Figure 4-4 Physical properties of European pipeline gas and LNG (the relative size of bubbles indicates the density of gas relative to air) Report EUR 23818 EN](image2)

[20] The report EUR 23818 EN is found [here](#).
In the figure above shows average Wobbe Index for most sources of LNG supply to Europe.

How you can see the average values from all selected sources are within the limits of Wobbe index values that EASEE-gas recommended for the gas to be accepted at all entry and interconnection point in the European Union.

In the figure above shows the maximum and minimum Wobbe Index values set by the seven importers of LNG into Europe. These values are also compared to EASEE-gas recommendation.

This parameter is not a completely accurate way to predict the behavior of burners using alternate gases, but it is convenient and accurate enough for most purposes. Generally speaking, a gas in the preferred ranges of HHV and Wobbe Index will burn without combustion problems such as flame
lifting, flashback, excessive NOx and CO, or yellow tipping. Figure below shows the preferred Wobbe Index region and the consequences of operating in objectionable ranges.

Early LNG trade was primarily to Japan from Pacific Rim and Middle East export plants and to Europe from Northern Africa. The Japanese specifications vary depending on the importing utility company, but typically have a **high heating value** between 39.7 and 43.3 MJ/Sm. This relatively high range permits maximum use of infrastructure by moving greater combustion heat capacity for a given volume. European countries typically allow wider ranges. Spain, for example, allows a range between 35.0 and 44.9 MJ/Sm.

In one example a gas with HHV = 42.6 MJ/Sm3 is suitable for the Japanese and Korean markets, but is too high for the US or UK. In the second example a gas with HHV = 37.2 MJ/Sm3 meets US/UK specs but has an HHV too low for Korea or Japan. Both examples however are within the ranges allowed for France and Spain.
For base load LNG production the feed gas pre-treatment will be similar for a wide range of feeds. CO2, water and mercury will have to be removed completely (to 50 ppm CO2 and 1 ppm water). This is generally done in the same way for all base load LNG plants around the world.

N2 is always reduced to a level below the limit for roll over, generally 1 mol%. During design, the 1% limit is normally used, but in operation this can be somewhat increased, since rollover is a minor problem for the upstream production due to the short storage time. Setting the Gross Calorific Value (GCV) for the LNG is an issue for the process engineer when doing the design. The pressure and temperature in the heavy hydrocarbon (HHC) column will decide the split between the part going to cool down, and the rest going to fractionation. How this is integrated in the liquefaction process will depend both on the design philosophy and on the technology used, but this is in general straightforward for all of the available LNG technologies.

New and stricter environmental regulations will affect the design for LNG liquefaction plant. Traditionally, all technologies have used end flash as fuel gas, along with boil off gas (BOG) from the storage tanks. Normally the BOG is returned from the ships during loading has been flared. This design has generally been independent of LNG liquefaction technology.21

5 Sensitivity to varying gas quality

The truck engines are based on different technologies. Depending on the technology the engine is more or less sensitive to different fuel qualities or specific parameters. The engine technologies have different critical design criteria and can be optimized for a larger or smaller window. Typically, dual-fuel technology is more sensitive to varying gas qualities compared to spark ignited engines in terms of knocking. However, also spark ignited engines are optimized based on specific gas properties. An example is Methane Number [MN] as design criteria. Methane Number is a way to calculate the fuel sensitivity for knocking and is calculated based on the content of the fuel. The higher value the more resistant the fuel is to knocking thereby allowing increased engine compression ratio in a spark ignited engine or higher diesel substitution factor in a dual-fuel engine. A spark ignited engine can use gas with low Methane Number, but the higher value that is possible to optimize the engine towards, the higher efficiency the spark ignited engine can reach as this will give possibility to increase compression ratio etc. Minimum methane number for a spark ignited EURO 6 engine is MN70\(^\text{22}\) while there are examples that specific technology platforms of dual-fuel engines for EURO 5 require at least MN85 or even MN90 to be able to optimize the efficiency of the engine.

EURO 6 and the stricter regulation increases the need to either develop technologies with high possibility to adapt to different gas qualities or to use gas with less varying quality, thereby making the engine fulfillment of EURO 6 technically less advanced. From an engine development perspective gas as fuel is still to be considered as a new type of fuel for trucks compared to diesel. From a gas provider point of view the vehicle market is still small compared to heat and electricity. In combination with competition between different technology providers willing to support the truck OEM it has until know been difficult to openly evaluate relevant design criteria that influence efficiency and robustness for different technology platforms. The experience of gas engine demonstration for EURO 6 for truck OEMs and technology providers within LNG-BC will be the platform for conclusion of relevant design criteria to quantify how gas quality affects the efficiency and costs to fulfill EURO 6.

A parameter that has been discussed for biomethane and LBG, especially when produced from landfill is potential contamination by siloxanes. Based on studies in Sweden\(^\text{23}\) the conclusion is that the amount of siloxanes in the raw gas is taken care of during the upgrading of the gas. Therefore, siloxanes should not be considered as a show-stopper but as a parameter to keep a close eye upon during the upgrading of biogas to biomethane where the key factor is that the filtering systems are running properly at all times.

Based on input from engine manufacturers developing EURO 6 engines the LNG-BC project has to report more quantitative figures for the relevant parameters when the data is available and processed by the actors in the project.

As we have seen the chapter of gas quality in function on how LNG is extracted there are two distinct type of gas, Natural boil-off and Forced boil-off, in the following paragraphs is explained how affect these difference in fuel to the engine operation. and his sensivity against these changes.

\(^{22}\) Source: Folke Fritzon, Scania

Natural "boil off" gas from the top of the tanks for propulsion is very high in methane and has good knocking stability. It is therefore particularly well suited as an engine fuel. However, when a propulsion system is specially designed for this use, it is important, to ensure, that there is always enough natural boil-off gas with high methane content available, so that any need for mixing in forced boil-off gas from the bottom of the tanks in order to maintain the power is limited. If this is nevertheless required, the operators must be aware that the knocking stability of the gas will be reduced and that appropriate precautions concerning engine power or ignition timing will have to be taken in order to avoid knocking.

Engine installation specially designed to be fuelled by LNG should preferable be of the type forced boil off with the LNG taken from deep down in the tanks and well mixer before extraction into the evaporator. This will ensure good homogeneity of the LNG taken out and so constant gas quality. One must be aware that this type of LNG-based fuel gas will be different from the natural boil off gas from a tank top and the rating of the engine will have to be based on somewhat lower MN in this case, in order to ensure knocking-free operation. Evaporator sizing must be sufficiently large in order to ensure that no gas droplets are entering the engine even under severe transient operation. LNG is the preferred fuel for long haul truck since it has significantly higher energy density. LNG is also the preferred fuel to use for DDF technology since LNG normally has higher knock resistance (due to higher content of methane) than CNG and also allow for extra cooling from the evaporation which is beneficial in DDF engines.24

Some key parameters discussed regarding LNG and EURO 6 engines are:

- Methane Number: The higher MN the better possibility to optimize engine
- Wobbe Index: Narrow interval helps to fulfil EURO 6 in terms of specified power and torque.
- Temp./Pressure: Technology road path indicates need of two pressure intervals:
  - Spark ignited: minimum ~10 bars
  - HPDI and similar technologies: “As cold as possible”
- Siloxanes: Limit needed to secure engine durability (risk of abrasion and increased probability for knocking)

And also there are some aspects to be considered, related to gas quality, which affect to the engine and gas infrastructure.

- Hydrogen: risk of embrittlement for the metallic materials
- Water: risk of corrosion and driveability problems.
- Hydrogen sulfide, H2S: corrosive in the presence of water, could affect after-treatment devices, combustion products could create problems by sticking the engine valves.

When talking about methane fuel for automotive applications, the main engine technology always has been the Otto engine, either under stoichiometric or learn-burn conditions of the air-fuel mixture. That has been thus until the appearance of the dual-fuel engines which are compression-ignition based engines. The difference in the functioning principle causes also relevant differences in the pollutant emissions derived from these engines, and thus also significant differences to the after-treatment strategies. Some of the main differences:

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• Stoichiometric spark-ignition natural gas engines: characterized by a homogeneous air-fuel mixture, the air-fuel ratio being controlled via an oxygen sensor (or lambda sensor) installed in the exhaust stream.

• Lean-burn spark-ignition NG engines: characterized by a stratified air-fuel mixture. These engines usually require indirect fuel injection or a direct fuel injection with induced turbulence. The indirect fuel injection requires the fuel to be injected in a pre-chamber designed, to keep the air-fuel mixture at stoichiometric conditions until it is suctioned into the combustion chamber. Excess of oxygen concentration in the exhaust is controlled via a linear oxygen sensor.

• Dual-fuel compression-ignition NG/Diesel engines: dual-fuel engines differ from dedicated engines in their capability to burn two fuels at the same time. Dual fuel engines use diesel as the main ignition source for the natural gas-air mixture. Diesel substitution ratios can vary depending on the dual fuel engine technology and also depending on the operation of the engine itself.

Theoretically, energy efficiency is higher and engine-out emissions are lower for lean-burn engines than for stoichiometric engines. However, the stoichiometric engine is able to control emissions efficiently via a three way catalyst (TWC), which oxidizes CO and HC while reducing NOx. Due to the excess oxygen, TWCs can’t be used for lean-burn engines. Instead, oxidation catalysts are used to oxidize CO and HC, but without an effect on NOx. For the dual-fuel engine, the current and future emission legislations (EURO V and EURO VI) require that the engine is equipped with similar after-treatment technology as diesel engines, which means installation of a selective catalytic reduction (SCR), an oxidation catalyst and a diesel particulate filter (DPF). NGVs equipped with TWCs meet even EURO VI NOx emission requirements.

5.1 Methane number

The MN of a fuel gas is the main factor to determine risks of knocking and misfiring. However the importance of the MN on the knocking depends on the engine architecture (direct injection, indirect injection) and its technology (gas engine or dual fuel engine, etc.).

Some Engines manufacturers claim that when the MN is below of 80 the concentration of heavy components (Butane, Pentanes, etc.) is high, premature auto-ignition of these components causes vibrations and knocking (shocks).

When the MN is higher than 110, the concentration of non explosive components (N2, CO2) is high and leads to misfiring.

It is necessary to work for determine the MN method of calculation of the gas. In fact several calculation methods exist but none of them has been unanimously accepted.

http://www.iea-amf.org/content/fuel_information/methane#emissions
5.1.1 Methane number calculation

The knowledge about the methane number is important, among other things, because the manufacturers can only optimise engines if they know to which minimum methane number the engine will have to handle. High methane numbers mean high knock resistance; high knock resistance, in turn, means high efficiencies and thus lower CO emissions. If methane numbers are too low, knock may cause engine damage or lead to losses in efficiency and performance if engine operation has to be adjusted to avoid knocking combustion. A low methane number might also have detrimental (rising) impact on the emissions of the engine.

The calculation methods are the followings:

  - Linear Correlation method.
  - Hydrogen/Carbon (H/C) Ratio method
- One of the most frequently used method for determining the methane number was developed by AVL in the 1970s. For all existing pipeline quality natural gases the AVL method for determining the methane number works reliably and sufficiently accurate if nitrogen is excluded from the gas composition. The AVL calculation tool is proprietary, however it can be licensed from AVL for a small fee.
- EON-GasCalculation produces end results similar to those of the AVL programme. EON-GasCalculation has the additional advantage that corrections for Nitrogen can be easily made. When using EON-GasCalculation the option without Nitrogen should be used.
- Various engine manufacturer methods.

It should be noted that today’s methods for calculating the methane number were developed for the natural gas qualities we currently see in pipelines. If in the future new types of gas, which comprise C5 and higher, are included in pipeline gas, corrections need to be made when calculating the Methane Number. This includes a number of rich LNG qualities currently on the market.

In case hydrocarbons higher than butane are present, additional corrections have to be made to compensate for the high knock sensitivity of these components.

It should also be noted that some of these calculation methods do not consider components heavier than butane. As the quantity present should be small these additional components are normally added to the quantity of butane as an approximation, but for Methane Number determination, additional development of the calculation method may be needed.

Similarly, the only methods to calculate Methane Number included in an international standard (ISO 15401-1:2006) were not developed to or are not able to predict the right trend of Methane Number when hydrogen is injected to the natural gas.

During the European Commission Workshop on Gas Quality held on 5 December 2011, EUROMOT asked for a Methane Number between 80 and 100 which would exclude the majority of available LNG from coming Europe.

During the European Commission Workshop on Gas Quality held on 5 December 2011, EUROMOT asked for a Methane Number between 80 and 100 which would exclude the majority of available LNG from coming Europe as shown in the figure 6-2.

It was proposed during a CEN/TC 234 WG 11 meeting to set the methane number >65 (±2 calculated with AVL method) in the European gas standard. This lower limit would cover all the supplies currently coming to Europe. It should also be noted that representatives of the automotive industry participating in the CEN/TC 19 have confirmed that a methane number of 65 could be acceptable (but raised to 75 in the future, which would endanger security of gas supplies to Europe).
The proposal on the range to methane number between 80 and 100 was to EUROMOT, his argument is that a MN below 80 reduces the efficiency of the gas fuelled reciprocating engines and may increase the emissions or create problems to the engine as it is shown in the following figure.

**Figure 5-2 Methane Number (AVL method) vs. Wobbe Index for LNG source during 2011**

5.2 Impact of Gas Characteristics on the Dual Fuel Operation – engines derating

Influence of the quality of gas is confirmed in operation; troubles with gas quality (high nitrogen content & superheated LNG) have been observed leading to a derating of the Dual Fuel engines and therefore a speed limitation.

5.2.1 Knocking

Knocking problems have been experienced due to the Gas Quality and High Temperature, illustrated by two examples:
First Example: on ballast voyage, in the case experienced, the forced boil off content had been about 30% of total gas consumption.

Engines tripped many times from Gas to Diesel Oil. When content of forced boil off had been reduced, from 30% to about 8%, knocking phenomenon has decreased significantly.

The heavy carbon removal tank fitted on board was not sufficient to face this higher flow of forced boil-off.

In order to run in best way, the gas quality must be considered during uploading and transfer to have even load and stable temperatures during transfer.

It’s has been observed as well that the impact of gas quality is depending on engines running hours and ambient temperature conditions.

Electronic control of the combustion is very sensitive. Depending on the different loads and various conditions, engine needs time to “learn” and adjust them selves. In particular in duration offsets of the gas valves of each engine due to total running hours. A too big offset step during switch-over and transfer, will make the cylinder drop out or start knocking.

Second example: a couple of times, High exhaust gas temperature was observed and exhaust gas valves burnt leading to the replacement of cylinder covers.

Dual Fuel Engines Maker, Wärstilä is considering that this failure of the exhaust valve may be due to dust deposit, originated from lubrication oil.

But it was as well observed that the engines having higher exhaust gas temperatures made them more sensitive regarding knocking. Therefore gas quality could be one of the root causes of these damages.

### 5.2.2 Misfiring

After loading the percentage of nitrogen could reach 30% in the Boil-Off Gas composition; therefore to avoid misfiring, gas admission valve of the engines should remain open longer to allow the admission of the required quantity of methane.

A standard fuel content specification for LNG is currently under development. Indications are that these standards will allow reasonably low levels of methane content (less than 90%). This means that engines designed to this standard may be capable of accepting fuel that has experienced a higher degree of weathering. Under lower methane content standards, there will be an even greater need to be aware of the quality of fuel as it is delivered, and to properly manage fuel usage.

For better understanding of the LNG’s Wathering we explain this phenomenon in a form more detailed bellow.

Wathering is one effect of LNG’s cryogenic properties, and it is important to understand, especially when LNG is to be used as a vehicle fuel. This effect, called “weathering” or “enrichment,” is a phenomenon that arises from the fact that natural gas is a chemical mixture. LNG produced from pipeline gas has varying percentages of methane and other hydrocarbons. The methane content can vary from 92% 99%. The other hydrocarbons found in natural gas are ethane (1% 6%), propane (1%
4%), butane (0% 2%), and other compounds. Each chemical element or compound in the liquid vaporizes at its own unique boiling point.

Consequently, over time, concentrations of the heavier hydrocarbons (such as ethane, propane, and butane) increase. Higher concentrations of these hydrocarbons will cause premature ignition and “knock.” Because uncontrolled knock causes engine damage, LNG must be used before it becomes weathered. Recognizing this potential difficulty, Liquid Carbonic set out to manufacture 99.4% pure methane LNG. With this high percentage of methane, LNG weathering cannot create harmful fuel mixtures because the potentially harmful constituents are largely absent.

5.3 Siloxanes

The European Comission presented to CEN a standarization Mandate, M/475, for biomethan in November 2010. The aim was for the development of a European Standard for quality specification for biomethane to be used as a fuel for vehicle engines and to be injected in natural gas pipelines.

This work is done by CEN/TC 408 “Project Committee – Natural gas and biomethane for use in transport and biomethane for injection in the natural gas grid”. They draft of a common list of parameters which should be included in the standard (Common (fossil) gas distribution requirements, requirements for injection into the grid and additional requirement for use as automotive fuel).²⁷

Among the parameters identified, siloxanes are expected to have potential impacts on the engines and appliances. Siloxanes are organosilicon compounds found in fermentation gases from landfill and waste water treatment. Upon combustion, siloxanes in biogases from silicon dioxide (silica SiO₂), which is known to deposit in engines, domestic equipment and turbines.

The deposition of silica in engines causes a number of problems. Ignition failure can occur as a result of silica deposits that cover and electrically insulate the spark plug. Small silicon dioxide particles can also cause wear of the engine as these sand-like particles are very abrasive. SiO₂ accumulates in the lubricating oil and coats/lacquers the cylinder wall filling the honing pattern thus ruining the lubrication of the engine.

A study²⁸ revealed that large ash content in the oil may even enhance the silica depposition. Large build-up of deposits increases the compression ratio of an engine which promotes knock. Heavy knocking can destroy an engine in seconds. Compressed Natural Gas vehicles running on biomethane may experience additional problems, for example, silica deposition can mask the catalyst thus lowering the catalysts efficiency and increasing the emissions. Besides this effect, sillica deposition can also affect the functioning of sensors installed in the engine.²⁹

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²⁹ https://www.sgn.co.uk/uploadedFiles/Marketing/Content/SGN-Documents/Environment-Docs/SGN-Siloxanes-In-Biomethane-Apr-13.pdf
Organoziloxanes are semi-volatile organosilicon compounds which, while not an aggressive gas component in terms of emissions, can be converted to solid inorganic siliceous deposits within the engine combustion chamber. They form a coating or lacquer on all surfaces contacted by the lubricating oil and can alter the oil retaining surface finish of cylinder liners.

The siloxanes can:

- Enter the engine as insoluble matter in the gas fuel, forming a white deposit in the combustion chamber.
- Be produced in the combustion chamber itself.

Siloxanes in the landfill and sewage gas convert into silicon dioxide when combustion takes place in the engine. The silicon dioxide combines with other elements in the gas, and with the lubrication oil to form a hard matrix that accumulates on the combustion surfaces.

With the deposits accumulate, the engines efficiency falls causing detonation in the combustion chambers. The resultant unburned fuel contaminates the exhaust gas increasing emissions. At this point the engine may need to be "de-rated" (Output reduced) to prevent significant engine damage and to reduce emissions.

If run unchecked, severe damage can occur to valves, pistons, piston rings, liners, cylinder heads, spark plugs and turbochargers, necessitating premature servicing and costly repairs.\(^\text{30}\)

- From a golden lacquer on components outside the combustion chamber. This lacquer can be especially evident on the piston-ring wiped surface of the cylinder liner. The lacquer has a tendency to fill the oil retaining honing pattern but rarely builds to the extent of requiring attention prior to routine overhaul.

\(^{30}\) [www.pptck.co.uk](http://www.pptck.co.uk) Brochure “Siloxane contamination and solutions”
At the combustion conditions within landfill gas engines, organic silicon compounds present in the landfill gas may be deposited on the cylinder head as solid inorganic silicon compounds. This deposited material is white to light grey, somewhat laminar, generally opaque, and may exhibit a partial to poor crystalline structure. Few analyses of these deposits are given in the literature; existing data indicate that crystalline SiO2 is present alongside other metals in solid forms (Niemann et al., 1997; Hagmann et al, 1999; M. Niemann, personal communication, 2001).

These deposits severely reduce engine life. The engine has to be stripped down and the solids scraped manually from the piston, cylinder head and valves.

During the combustion process, some silicon compounds are also partitioned to the engine oil, which needs to be changed more frequently at sites with high siloxane levels in the inlet gas fuel. Engine manufacturers thus recommend direct monitoring of silicon build-up in the engine oil. The increasing use of these compounds in consumer and commercial products suggests that problems with volatile siloxanes in landfill gas engines are likely to increase.

Siloxanes do not directly cause problems with gas engine exhaust emissions, though the increased wear may show itself as an increase in SOx emissions as lubricating oil is burnt. Typically, this is unlikely to exceed any risk-based criterion for emissions management and the decision to implement gas clean-up for siloxane management purposes is entirely based on cost.²²

5.4 Hydrogen

In the context of the development of renewable energy sources there are various projects in Europe focusing on the injection of Hydrogen into the gas grid. It should be noted that any addition of Hydrogen (Methane number 0\textsuperscript{32}) will decrease the Methane Number of the gas transported, potentially limiting that supply or preventing the use of this form of renewable energy. In particular the following technical limitations have to be assessed:

- Stress cracking at steel installations, which might potentially occur under typical gas storage operations (Cycle pressure loading).
- Possible substrate for undesired bacteria.
- Possible production of organic acid or hydrogen sulphide.
- Possible undesired impact on gas engines.

Additional parameters and limitations will be developed and reported later in the LNG-BC project.

\[32\] Pure Hydrogen is used as the knock sensitive reference fuel with a methane number of 0.
6 Measuring gas quality

The combination of small scale LNG, use of LBG, potential change of gas quality along the delivery chain and varying sensitivity of gas quality for different truck engine technologies increase the need to be able to secure that the delivered fuel is following the agreed specification.

Based on experiences from the CNG market it is also expected that a developed LNG-market for trucks will require an open ongoing dialogue regarding interaction between gas quality delivered to the trucks and the robustness of the truck engine technology.

As the gas quality for LNG might vary along the delivery chain the measuring shall be able to be done at the filling station. Testing equipment is available commercially but normally designed for large scale LNG terminals. To be able to take recurrent tests at truck refueling site a technology and methodology for taking low-cost representative gas samples is required.

Based on financing from actors participating in LNG-BC a test method different gas qualities has been developed and described in a separate report, “SGC rapport 288 Method development for gas quality determination in the LNG storage of a LNG/LCNG refueling station”, see link below. As main results the ability to take representative tests has given satisfying results, proven by careful evaluation towards experimental and calculated gas qualities. Some further improvements needs to be done especially regarding heat exchange in the vaporizer. The LNG-BC project will further consider results from this study and also include additional potential projects in this area to make cost efficient gas quality testing more widely available. This will be described in the coming project delivery D3.11 “Studies regarding ageing of fuel”.

The actual results from tests described in the SGC report 288 shows that regardless if LNG or LBG is used the gas quality in liquid phase is changing, but not significantly, as the level of fuel in the storage tank is getting lower and lower. For LBG an increase of concentration of methane in gaseous form was measured, while the concentration of methane in liquid form decreased from 99,0%-vol, when storage tank was just refueled, to 97,9%-vol. when a quarter of the tank remained. For LNG an increase of ethane was measured both in gaseous and liquid form. Another result from the study was that blending LNG and LBG in the same storage quite rapidly mixed together to the expected quality. Only 1- 2 hours after blending the LNG and LBG the measured result was in line with the expected gas quality for the blended fuel qualities. Generally, additional tests need to be done to confirm the initial results.

7 Conclusions

Gas quality will vary depending on the source of LNG, the production of LBG and the handling of the fuel along the distribution chain up to the delivery of the truck. The variation of the gas quality will not be a show-stopper, but could affect the possibility of optimizing truck engines and will also continue to be an issue of interest after the launch of trucks on the market. Therefore, continuous focus on gas quality will remain to be a critical area to keep track on.

In the LNG supply chain most BOG is generated by the LNG ships themselves. The used LNG cargo or losses of LNG cargo due to boil-off reduce the amount of cargo delivered by LNG tankers to the receiving terminal while the ageing process steadily changes the composition, quality and properties of LNG cargo during a ship’s voyage. Therefore, the quantity and quality of unloaded LNG are the key factors for the economic assessment of the LNG supply chain. As described below, geopolitical relations can make a country to use a rich or lean gas (USA uses in majority gas coming from Alaska). Despite these differences, each country has its own way to manage the gas quality. Japan and the USA are able to keep a similar gas quality over the country thanks to different management process. From the other side, Europe shows a high diversity between the different countries. Due to different gas specifications, each member imports its gas from several parts of the world so the quality at each terminal differs on the composition (Methane Number, Wobbe Index...). To get a similar quality on Europe, several measures have to be applied starting by introducing quality standards. To establish these standards different processes can be used as:

- Ballasting (N₂ injection to reduce the Wobbe Index)
- Propane / Butane injection or removal (for small Wobbe Index corrections)
- CO₂ or N₂ removal (only applicable for pipeline gas)
- Blending (Blend of LNG coming from different sources)

These measures can help to make the LNG available through Europe in the way to interchangeability.

During the report we have explained different topics related to LNG vehicle technology which could be affected by gas quality. New design parameters depending on technology platform might be found or highlighted during the demonstrations. This needs consideration regarding benefits of the amount of increased efficiency in vehicle technology vs. possibilities to provide specific gas quality at competitive price for customers.

The test method of taking samples of gas quality at the LNG filling station will have to be further developed. The increased ability to follow-up the gas quality at the filling station will lead to improved fact-based knowledge that in turn will facilitate defining potential causes of quality problems, thereby improving the LNG market for trucks as a whole.

As we already explained before Euromot recommend a methane number to 80, in this report about the gas quality, the topic to market, we have shown that this number would endanger the security of natural gas supply to the European Market.

Another important aspect to consider is that there is no commonly agreed Methane Number calculation method and one would need to be agreed, or even developed and made available in the public domain.
Including the Methane Number in the European Standard requires an agreed and reliable method of
determination and should incur minimum costs.

The Methane Number can't directly be used to optimise engine operation as there is no guarantee
that the Methane Number at the point of measurement will correspond to the gas quality at the
engine. Automation of engine emissions monitoring and automatic optimisation is the best method of
ensuring optimum operation over a range of gas qualities.

The influence of hydrocarbons from biomass gasification on the fuel quality is not that different from
that corresponding to hydrocarbons from NG. It is not worth to have a fuel production line different
from that of LNG the gas from gasification should be cracked to syngas and converted to the final fuel.
However the CO2 and H2 removal in the final upgrade should be optimized to meet specific value of
MN and LFL (Lower Flammable Limit) instead of Wobbe index, used for injection in the NG grid.

Talking about reducing the effect of silicon dioxide deposits, in the engine, various methods have been
employed. Fluid injection systems do allow the silicon matrix to soften making removal easier, however
in the long term it is preferable to remove the siloxanes from the gas before they reach the engine
preventing the formation of deposits. This aspect is very important in order to ensure the engine life.

Active carbon filtration systems are available, it filters the contaminants for a finite period. These can
be long installations (Requiring planning permissions) and need manual removal of spent activated
carbon and disposal of the contaminated medium. Recently derivatives of the active carbon principal
have been developed which offer a cartridge / silo replacement and removal service of the spent
carbon. Although this avoids some of the disposal and safety issues, it is costly and requires constant
maintenance. Normally these installations have a large footprint and require site planning before
commissioning and a costly chiller to remove the water from the gas.
8 Recommendations for the LNG-BC project

Based on the conclusions in this report it is recommended that the project LNG-Blue Corridor project keeps continuous attention to the issue of gas qualities by keeping the dialogue open between the actors. This discussion is going to be developed through the trials developed during the project. The importance of the gas quality is going to be analyzed.

In order to ensure the european import, export and market it is necessary to create, or develop gas quality standarization. The progress in gas interchangeability is vital for the market development and work in the study of the vehicle technology.

One important topic recomended about the LNG quality is to ensure a common MN calculation method for the standarization in the european market and to have a reliably criteria. It is important to know the MN and LFL index in order to optimize engines, instead of wobbe index which is used to in injection to grid gas.

In order to ensure long engine durability, it is important to reduce the siloxanes the fuel. For this reason is necessary to study the best way to perform the cleaning or filtration. In this report is talked about the active carbon as possible solution.

- About the topic to discussions on how to find marked- and technology solutions to handle varying gas qualities, bellow detailed a list about it has already been done during the project and which is being worked on: Sourcing of gas
- Fuel management solutions throughout the delivery chain.
- Solutions to secure gas quality are kept within agreed specification.
- Measuring of gas quality in small scale LNG facilities
- Evaluation regarding design criteria and possibilities for different engine technologies to be optimized toward different gas qualities in terms of robustness, engine efficiency and emission control. The project consortium is recommended to monitor and report accordingly during the demonstration period, at what extent gas quality will effectively influence engine performance, setting through substantiated observations the range of quality indicators and parameters jointly with target range values to be met to ensure proper functioning of engines.
## 9 Glossary

<table>
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<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td>Biogas</td>
<td>Raw gas from digesting plant. To yet upgraded to vehicle quality. High content of CO2 (~40%)</td>
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<td>Biomethane</td>
<td>Upgraded biogas suitable as vehicle fuel</td>
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<td>BOG</td>
<td>Boil-Off Gas</td>
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<td>CBG</td>
<td>Compressed Biomethane</td>
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<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
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<td>DFE</td>
<td>Diesel substitution factor – The share of diesel replaced with gas in a duel-fuel engine.</td>
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<tr>
<td>Dual-Fuel</td>
<td>Engine technology based on compression ignition, mixing diesel and gas.</td>
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<td>EURO class</td>
<td>European emission standard. EURO 5 valid for trucks sold until end of 2013. All trucks sold on market from 2014 must fulfill EURO 6.</td>
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<td>H-Gas</td>
<td>Gas with methane content between 87 und 99,1 Vol. %. Energy content is normally between 10,0 to 11,1 kWh/m3, i.e. high energy content compared to L-Gas, see below</td>
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<tr>
<td>LBG or LBM</td>
<td>Liquefied Biomethane suitable as vehicle fuel.</td>
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<td>L-CNG station</td>
<td>CNG station with the gas provided by an LNG tank</td>
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<tr>
<td>L-Gas</td>
<td>Gas with methane content between 79,8 und 87 Vol. %. Energy content is normally between 8,2 to 8,9 kWh/m3. Offered on some markets mainly due to historical reasons to be compatible with existing appliances.</td>
</tr>
<tr>
<td>LNG/LCNG station</td>
<td>Refueling station using liquefied gas for storage offering both liquefied and compressed gas to vehicles.</td>
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