A BRIDGING TECHNOLOGY FOR FUTURE MOBILITY?

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ABSTRACT

Great progress has been made in the exploration and production of natural gas in recent years. Reserves of conventional gas are plentiful, and large resources of unconventional gas have been added. At the same time, there is still a lot of pressure for climate action to reduce greenhouse gas emissions. Natural gas is the lowest-carbon fossil fuel.

Almost all medium- to long-term energy scenarios foresee a substantial increase in global consumption of natural gas. It can be used to generate both power and heat. But so far gaseous fuels have had only a niche position as an option for the transport sector. Increased discussion of gas, in particular natural gas, as a future transport fuel started just recently.

This article starts by considering the development of supply and current expectations for availability of natural gas. It discusses the various types of gas, in particular of conventional and unconventional, and technical methods, both standard and new, for gas production. It also deals with natural gas demand scenarios and future markets, including the value chain for natural gas fuels.

The article covers in particular the use of gaseous and gas-based fuels in the transport sector. It examines various production paths for natural gas fuels for transport, as well as the fuels themselves (CNG, LNG, GTL), it compares the product characteristics of natural gas fuels with those of conventional fuels (gasoline/diesel fuel) and other gaseous fuels (in particular LPG and hydrogen). It discusses the application possibilities of gas fuels in the various transport sectors. Consideration is given to the use of gas fuels in internal combustion engines in different transport sectors, with different combustion processes, including their energy efficiency (consumption/performance) and their ecological performance (air pollutants and greenhouse gas emissions).

Finally, it addresses the question of what and under what conditions natural gas fuels can contribute to an “energy transition” in the transport sector.
I. GLOBAL MOBILITY AND ENERGY CHALLENGE

The Challenges for Future Mobility

Mobilisation of mankind has increased dramatically during the past decades. Motorised mobility bears the brunt of increased human mobility. The number of registered motorised vehicles has already passed the billion mark; today’s global vehicle fleet consists of nearly 800 million passenger cars and more than 300 million commercial/duty vehicles. However, levels of car ownership still diverge dramatically – from around 600 vehicles per one thousand people in developed countries to well below 100 in developing and threshold countries.

There is a lot of space and need for further mobilisation and motorisation. However, there are some quite significant challenges for future mobility to be addressed:

- In order to be mobile, energy is needed. Most of today’s energy is based on finite resources such as coal, oil, gas and nuclear. Challenges of future energy supplies will directly affect how coming generations will organise mobility.
- Also, since energy and vehicles have a price, the question is which fuel and which vehicles will allow mobility to be affordable for everyone.
- The current world population is estimated to be at more than 7 billion people. Urbanisation is increasing rapidly, especially in Asia. Since 2007 the majority of the global population is living in cities or towns. The number of megacities is growing rapidly. New mobility and infrastructure concepts are needed.
- With the increasing demand for mobility between urban regions but in particular within urban regions the reduction of greenhouse gas (GHG) emissions and in particular of local emissions causing smog has to be addressed. Will there be a fuel and vehicle concept which can lower GHG and local emissions?
- New technologies are required to cope with these challenges. Technical innovations such as autonomous driving, continuous connectivity, night vision, active braking, distance control, advanced stability control, etc. will change how mobility is perceived.
- Other key factors are consumer values and social acceptance. New technologies that enable better information exchange and participation in social networks seem to be causing a decline in the importance of a car for social engagement amongst younger generations. For urban people “mobility on demand” becomes more important. Which factors drive social acceptance and the resulting uptake of new fuel/powertrain solutions?

There are major challenges for future mobility. But with a share of about 20% of global final energy consumption, increasing mobility and motorisation are only one aspect of a broader challenge – the global energy challenge.

Today, the global energy system is in the early stages of a transformation. Population growth, rising prosperity and rapid urbanisation will put increasing pressure on energy supplies. Energy demand could double by the middle of the century from its level in 2000. Supplying this vital extra energy will become increasingly difficult. Conventional energy sources will struggle to keep pace, even with technological advances. More and cleaner energy will be needed from even more sources. What role could Natural Gas (NG) play in the future energy mix?
Global Energy Demand and Natural Gas

In nearly all long-term energy scenarios, natural gas is the fossil fuel that expands steadily and fastest of all fossil fuels. In a Special Report to its World Energy Outlook the International Energy Agency (IEA) has developed a Gas Scenario, to examine drivers, conditions and implications of a “golden age of gas”. Natural gas benefits from a more ambitious policy for gas use in China, lower growth of nuclear power, greater production of unconventional gas and lower gas prices, while support for renewables is assumed to be maintained. In the Gas Scenario the average rate of increase in gas demand is nearly 2% per year. Global gas demand is expected to reach 3.1 trillion cubic meter (tcm) by 2035. The share of natural gas in the energy mix increases from 21 to 25%, pushing coal into decline and overtaking it by 2030.

II. ROLE OF NATURAL GAS AS ENERGY CARRIER

Hydrocarbons in the Energy Mix

The industrial revolution in the 19th century was based on the steam engine, with coal and wood as ‘solid’ sources of energy. Coal was also used for firing steam trains and steam ships. At the turn of the 20th century the advantages of liquid fuels refined from crude oil became obvious and the mobility revolution took off. Also, in urban areas coal as an energy carrier was soon replaced by kerosene and heating oil for heating purposes due to the lower emissions. Natural gas offers further advantages, with the potential of even fewer pollutant emissions, but in particular with respect to carbon dioxide.

Combustion of almost all fossil fuels produces carbon dioxide and water, which originates from the chemical reaction of carbon and hydrogen with oxygen in the air. The hydrogen to carbon atomic ratio of coal is approximately 1:1 while this ratio for gasoline is about 1:2.1 The hydrogen to carbon ratio of natural gas, with its main constituent being methane (CH₄), is about 4:1. The combustion of natural gas thus produces less CO₂ per unit of energy compared to coal, wood and gasoline. The route from solid coal, to liquid hydrocarbons to natural gas is therefore a pathway of decarbonisation. A fuel which would show no carbon dioxide emissions would be pure hydrogen. However, today’s production technologies, production of hydrogen still requires the consumption of fossil energy sources such as oil and gas. Surplus renewable power-to-gas or power-to-hydrogen might be a solution for the future.

2 ENERGY MIX IN TRANSITION

In addition to fossil fuels, renewable energy sources are available. The most important renewable energy in the global energy mix is biomass (with 10% of primary energy share). Solid biomass such as wood displays an approximate elemental composition of C₉H₁₄O₂₆₆ leading to an H/C ratio of roughly 3:2. Carbon from biomass such as wood has the potential to significantly reduce green-
house gas emissions. Solid fuels are, however, inconvenient for mobility use. Solid biomass can be transformed into liquid or gaseous fuels, for instance by hydrolysis, fermentation or gasification. Biogas can be produced in dedicated biogas plants, for instance using thermal processes, or from sewage plants or landfills. Before the biogas can be used in the gas grid or as a fuel it needs to be sufficiently purified, its methane content must be increased and carbon dioxide, water, sulphurous compounds and other impurities must be removed. Another niche process for biogas production is Synthetic Natural Gas (SNG), which is produced by a process based on coal gasification using thermochemical biomass gasification. But also dimethyl ether (DME) is another gaseous fuel, which can be liquefied at relatively low pressures of 5 bar. Due to its high cetane number DME may be considered for diesel engines. Bio DME can, for instance, be produced from biomass using a direct catalytic synthesis or using a conversion to syngas followed by catalytic synthesis.

Examples of known liquid biofuels are bioethanol or biodiesel. Different types of biodiesel exist such as fatty acid methyl esters (FAME), hydrogenated vegetable oils (HVO) or Fischer-Tropsch diesel. Besides ethanol other alcohols are also potential biofuels, such as methanol and butanol. For different reasons, not all of these biofuel concepts (gaseous or liquid) have been realised. However, it should be noted that regarding gaseous fuels in general, gases have a higher energy to mass ratio compared to liquids. This is due to the higher hydrogen to carbon ratio. The chemical reaction of hydrogen with oxygen results in more energy than carbon. On the other hand gas fuels have a smaller energy to volume ratio than liquid fuels. So, in order to utilise gaseous fuels for mobility purposes either a large tank volume is required, or the gas has to be compressed or liquefied, reducing the volume.

Global Natural Gas Resources

The world’s resources of natural gas are plentiful. They have the potential to meet rising demand for many decades to come. Remaining conventional recoverable resources are equivalent to over 120 years of current global consumption. All major regions have recoverable resources equal to at least many decades to come. Remaining conventional recoverable resources are equivalent to over 120 years of current consumption. 14 As technology advances, so do abilities to unlock gas resources.

Natural gas resources are also spread geographically among the world’s regions. Russia and the Middle East are the largest conventional gas resource holders, with Russia being expected to remain the largest gas producer and exporter to 2035. The largest unconventional gas resources are in Asia Pacific and North America, with substantial resources also in Latin America and Africa. Although resource estimates are still to be fully tested by drilling, it is likely that a large part of the recoverable unconventional gas lies in regions that are currently net gas importers, such as China and the United States.

Types of Natural Gas

Conventional gas production dominates world gas production, accounting for over 85% of total output today. The 13% of unconventional gas production has mostly been added in the last decade and unconventional resources are estimated to be in the same order as remaining conventional resources (i.e. ca. 300 to 400 tcm).

Conventional accumulations of gas are characterised by moderate to high permeability and may be produced economically by means of few wells. Unconventional gas occurs in low-permeability fields that require many more wells and new extraction technologies. Unconventional gas resources comprise shale gas, tight gas and coalbed methane (CBM). 15

- Shale gas is found in rock formations rich in organic matter and low in permeability, classified as shale (often mudstone).
- Tight gas formations are defined as having lower permeability, i.e. the ability for gas to flow through the rock is limited. They are typically sandstones.
- Coalbed methane (CBM) is natural gas contained in coals; the gas is trapped in the fractures and on the surfaces of coal.

4 CONVENTIONAL VS UNCONVENTIONAL GAS

According to the recently published IEA World Energy Outlook 2012, technically-available gas resources equal 230 years of current production. 16 As technology advances, so do abilities to unlock gas resources.

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- Coalbed methane (CBM) is natural gas contained in coals; the gas is trapped in the fractures and on the surfaces of coal.
New technologies such as horizontal drilling and hydraulic fracturing (fracking) have been developed to produce unconventional gas, in particular to stimulate the flow of shale and tight gas. Hydraulic fracturing has been practiced since the 1940s. Tight gas has been produced in North America for over 40 years now. CBM accounts for about 10% of total US gas production. Unconventional gas in total makes up about 60% of US gas production. The unconventional gas revolution has reshaped the market in the US and also affected global gas markets.

The rapid expansion of unconventional gas production has sparked public concerns about its social and environmental impacts. The IEA has developed a set of “Golden Rules”, i.e. principles that address social and environmental impacts, in order to improve environmental performance and public acceptance of unconventional gas production – including full transparency, measuring and monitoring impacts and engaging with local communities. The Golden Rules are similar to Shell’s onshore operating principles. In a Golden Rules for Gas Scenario global gas demand could rise by more than 50% between 2010 and 2035, the share of unconventional gas rising from 13% today to 32% by 2035.17

Natural Gas Demand

Natural gas is the fastest-growing fossil fuel. However, there are also marked differences in demand growth across regions: 18 OECD countries today (2010) account for 48% of global gas demand. By 2035, OECD’s share is expected to be less than 40%, although OECD gas demand will increase further, the share of gas in its primary energy consumption climbing from 22% to 29% by 2035. Non-OECD regions like China, India and the Middle East are expected to see much stronger growth in gas demand. In particular, China will increase its total consumption of natural gas by more than 1,000 billion cubic meter (bcm) per year, its share of natural gas in primary energy consumption from just 4% to 12% and move up to become one of the top five gas consumers of the world.

Among consumption sectors, the power sector will remain the principal driver of gas demand in most regions, world gas consumption for power generation is expected to increase up to 2,000 bcm. The use of gas in transportation is small in global terms – approx. 20 bcm, but it has been growing rapidly in recent years in some countries.

Natural Gas Prices

Gas prices are an important driver of global gas consumption. The North-American shale gas boom has had a significant impact on gas markets and prices. Up to the middle of last decade, gas prices had been on a similar level in the major consumption regions of Europe, North America and Asia-Pacific. However, during the past years, gas prices increasingly differ across regions. In 2012, gas prices below 3 US $/MWh (in the USA referenced Henry Hub) were three to four times higher in continental Europe (as indicated by Brent priced) and even more expensive in Asia, where LNG cargoes often refer to the “Japanese Crude Cocktail” (JCC). UK gas prices (NBP) since 2010 have moved in the direction of continental European prices, albeit from a much lower level.19

As a result of technical barriers and due to the high costs of gas transport, gas markets are relatively isolated, reflected by the different price levels between regions. Moreover, there are big differences across regions as to how prices are set.20 More than 30% of global gas production is shipped via pipeline or liquified as LNG to either Europe or Asia-Pacific, with Germany, Italy, Japan and South Korea being the biggest importers.21 Much of the natural gas traded across borders in Europe and Asia is sold under long-term contracts linked to oil prices, e.g. to Brent crude oil or oil products in Europe, or to JCC for Asian long-term LNG contracts. When crude oil or oil product reference prices are high, gas prices also tend to be high. In Asia, where LNG dominates gas trade, strong LNG demand from Japan after the Fukushima incident was an additional price driver.

6 NATURAL GAS PRICES
At the same time, the diversification of pipeline supplies into Europe continues, although the total amount of pipeline supplies is expected to remain fairly constant. This gradually reduces transit risk and the reliance on single pipelines. Essentially, all of the projected European gas demand growth is expected to be met by LNG. This has led many countries already to build their own regasification facilities, securing their gas directly and thus avoiding any possible transit issues, while also gaining access to the international spot LNG market.

The Natural Gas in Transport Value Chain

Due to its gaseous state and its larger volume than liquids, the transportation of gas has created new challenges for global distribution. Currently, most markets are supplied via traditional pipelines. However, with the exploration of new gas sources in more remote areas and the development of new markets, other methods of transport need to be considered in order to supply worldwide locations by gas. For markets not accessible by pipeline natural gas is liquefied to LNG and shipped in dedicated LNG vessels worldwide. Today, approximately two thirds of interregional/international gas trade is by pipeline, one third as LNG.

8 NATURAL GAS IN TRANSPORT – VALUE CHAIN

The liquefaction reduces the volume of the gas by more than 600 times, allowing efficient transportation. Once the LNG is shipped and arrives at the terminal, it enters the same value chain as when being served directly by pipeline. Another option for reducing the volume of gas as energy carrier is to convert the gas into a Gas-to-Liquid (GTL) product using Fischer-Tropsch synthesis.

Integrated Gas describes the part of a business where gas produced in the upstream part of an integrated oil and gas company is brought to downstream, serving diverse markets and customers, often across region and cross-business. In Figure 8 an integrated gas value chain is shown. Natural gas is finally being used as natural gas for power generation, home heating or in industry, as CNG in passenger cars, light commercial vehicles, small ships, and as LNG in heavy-duty engines such as heavy-duty and offshore vehicles and for rail and for large ships.

References:
III. NATURAL GAS MOBILITY – VEHICLES AND FUELS

Which Fuel for which Mode of Transport?

Of all modes of transport, road transport is by far the largest energy consumer. The vast majority of road transport vehicles are propelled by internal combustion engines. Vehicles with an internal combustion engine are primarily fuelled by liquid fuels; liquid fuels offer high energy density and can be stored and handled easily. Liquid fuels are hence considered to be fully compatible with all modes of transport as indicated in Figure 9. Well over half of global oil consumption or 46 million barrel per day (mb/d) is now concentrated in the transportation sector. Within the transportation sector, the fleets of Light Duty Vehicles (LDVs) accounts for the bulk of global road transport oil use with approx. 19 mb/d today, road freight transport demand is somewhat lower at approx. 13 mb/d, which is mainly diesel. The most important supplement to oil-based fuels are biofuels, with a share of 2.5% in global road transport fuels.14

Gaseous fuels can also fuel internal combustion engines. However, gaseous fuels have some disadvantages regarding energy density, storage and handling. Passenger cars and commercial LDVs can cope with gaseous fuels such as LPG, CNG and hydrogen. For long-haul Heavy-Duty Vehicles (HDVs) limited storage capacity and limited driving ranges make gaseous fuels such as CNG/LPG less practicable. But heavy trucks with their mileage of up to 200,000 km per year and short idle times could benefit from LNG.

Emobility is also a future option for short-range urban applications of passenger cars and commercial LDVs, but currently electric vehicles cannot even offer the ranges of gas-fuel propelled vehicles. Hence e-vehicles will be deployed first in urban areas and/or for short-distance travel. Aviation and maritime transport are other major fuel consumers, both relying on liquid fuels (kerosene and bunker fuels), whereas rail transport uses electricity and diesel. In particulars, for shipping as well as for other large engines and continuous operating vehicles (e.g. rail or offshore, mining), LNG is an important option for the future.

9 FUEL OPTIONS FOR MODES OF TRANSPORT

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<tr>
<th>MODE OF TRANSPORT</th>
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- Fully compatible
- With minor restrictions
- With major restrictions
- Not compatible


Natural Gas Mobility

Natural Gas Vehicles (NGVs) presently account for less than 1% of total world road fuel consumption and less than 1% of total world gas demand. Despite strong double-digit growth in the number of NGVs on the road in recent years, they still remain a niche market in global terms.13 The number of NGVs first exceeded a million units in 1999/2000. By 2011, more than 1.4 million – out of a billion vehicles were powered by methane-based transportation fuels. NGVs are now on the roads in more than 80 countries. By the end of 2010 methane became an equal alternative to LPG/Autogas as regards gaseous fuel consumption, both with 33 to 34 million tons of oil equivalent (toe). The number of CNG/LNG retail pumps rose to 20,000 by the end of 2011. On the other hand, some 17 million vehicles are running on LPG, supplied at 57,000 retail stations.25

10 SELECTED MARKETS FOR NATURAL GAS MOBILITY

Similar to LPG, more than 70% of all NGV and one-half of all NG fuelling stations can be found in just five countries: Iran, Pakistan, Argentina, Brazil and India. During the years 2000 to 2010, global leadership in NGVs deployment has passed from Latin America to Asia, with Pakistan in the lead with 2.85 million NGVds. The most spectacular changes occurred in Iran, India and China. In Europe, there are close to 1 million CNG and LNG vehicles, which makes up a market share of 0.4% of the total running fleet. Today, practically all vehicles using methane as a fuel are propelled by CNG, although LNG HDVs are becoming more popular. Available vehicle options are LDVs using CNG, HDVs such as buses and trucks using CNG, and HDV/haulage using LNG.

The slow development of natural gas mobility is associated with the very high investment costs of the required methane refuelling infrastructure, i.e. CNG and/or LNG pumps or combined CNG/LNG refuelling stations. Necessary investments are at least five times as high for conventional liquid fuels. The established natural gas mobility markets have generally needed more than 15 years to achieve a substantial market penetration. So far natural gas mobility in Europe has been confined to only a few countries, including Austria, Germany, Italy, the Netherlands, Sweden and Switzerland. In other EU member states, a public network of natural gas refuelling stations has hardly been set up to this day. In total, there are only 3,000 refuelling points (public and private) in Europe today (2011); of these, only 20 stations are equipped with LNG- or, rather with ICNG technology.27

Similarly, biogas, which may be considered as a (nearly) carbon-neutral fuel, shows large composition variations. Its methane content is about 50-75%, the remainder being carbon dioxide, water or other contaminants. In order to be fed into the natural gas grid, or for use as an engine fuel, the biogas has to be purified to gas grid quality. For engine applications the methane concentration typically should attain 97%. 25

(Natural) Gas Fuels

Natural gas as a fuel consists mainly of methane (~85-95%), the remainder being higher hydrocarbons and other incombustible components which include nitrogen, carbon dioxide, oxygen, water, traces of precious gases and sulfur components. The variation of methane content and other components is strongly dependent on its source, for example, natural gas found associated with crude oil deposits will differ from that found isolated in natural gas fields. In addition, composition can vary further if natural gas steams from different sources are mixed.

11 GASEOUS FUELS - OVERVIEW

Temperature plays an important role if a component is either liquid or vapour. In general, if a gas is cooled, it will at some point become a liquid. Temperature is directly correlated with the kinetic energy of molecules. The cooler a gas gets, the slower the molecules move in the gas. At some point the kinetic energy is so little that molecules cannot escape the molecular attractive forces anymore and the molecules stick together, forming a liquid. Likewise, the hotter a liquid gets, the more kinetic energy the molecules carry, and at a high enough temperature the molecules have enough kinetic energy to escape the attractive forces and become gaseous.

Furthermore, the more tightly the molecules are packed the higher the pressure of the fluid. In this turn means that gas molecules which are packed close together (higher pressure) can liquefy with a lower temperature. For every gas, there is, however, a temperature at which the gas cannot be liquefied by increasing the pressure, or rather no phase transition from vapour to liquid is observed. A phase transition temperature is characterised by a sudden change in density. This temperature is called the "critical temperature". Likewise, when a high enough pressure is reached, a gas cannot be liquefied by decreasing the pressure. This pressure is called "critical pressure". Critical temperature and critical pressure define the "critical point" of a component. For methane the critical point is at -82.4 °C and 46 bar. 26

Figure 13 shows the vapour pressure curve of pure methane which is bounded by the triple point at -182 °C and 0.117 bar and the critical point at -82.4 °C and 46 bar. When methane is cooled from ambient conditions (1 bar) below -161°C it condensates from a gas to a liquid. This phase transition leads to a sudden decrease in volume from 539 l/kg to 2.38 l/kg, a 235 times smaller volume. However, this volume decrease comes at a cost, since the energy of the vapour needs to be lowered in order to condense to a liquid. This energy is known as the heat of condensation which is by definition equal to the heat of vaporisation with the opposite sign.

25 Cf. FNR, Biogas, Gülzow 2012, p. 20; Deutscher Verein des Gas- und Wasserfachs (DVGW), Technische Regel – Arbeitsblatt DVGW G 262 (A), September 2011.

times higher than that of gasoline.

Besides methane as a fuel gas for mobility and relatively cheaper processing since less energy is required for the compression than for liquefaction.

compared to CNG but needs to be kept in its liquid state at cold temperatures.

on average two-thirds of the volume does not decrease to the same extent as the pressure.

bar leads to a volume of about 4.4 l/kg. This shows the limitations of the ideal gas behaviour, since the volume decreases to half when the temperature is reduced from 1563 l/kg to about 6.25 l/kg at 200 bar, which is approximately a 250 times smaller volume. Liquid methane at 1 bar even has an about 600 times smaller volume (see table 14).

Volume cannot be distinguished into either a liquid or a vapour. The volume of methane at ambient temperature and pressure is reduced from 1563 l/kg to about 6.25 l/kg at 200 bar, which is approximately a 250 times smaller volume. Liquid methane at 1 bar even has an about 600 times smaller volume (see table 14).

Therefore, different “LNG products” can be found in the market which differ in pressure: e.g. cold, super-cold, cold-saturated and super-saturated LNG shown in table 14 and indicated in figure 13.

Hence, in order to achieve an acceptable tank volume, hydrogen needs to be compressed to about 350-700 bar or liquefied at a temperature of -253°C.

Furthermore, IPG (liquefied Petroleum Gas/low Pressure Gas) is also considered as a gaseous fuel. IPG is generated during crude oil production and refinery processes and made up primarily of C3 propane (and propylene), C4 butane (with its isomers and olefins: isobutane, isobutene, but-1-ene, but-2-ene) and traces of C1, C2 and C5. Depending on its composition, IPG can already liquefy at temperatures close to ambient conditions (-42°C to 0°C). However, in Europe the permitted absolute vapour pressure of IPG is 15.5 bar at 40°C. Moreover, IPG is heavier than air, whereas methane and hydrogen are much lighter.

Liquefied gases need well insulated tanks that keep LNG at temperatures well below the phase transition, whereas compressed gas tanks must be extremely pressure-resistant and should hold pressure differences of 250 bar (or even 700 bar for H2). Compressed fluids are commonly stored in cylindrical vessels which due to their form can withstand higher pressures. Other storage opportunities are still being explored and under further development such as storing H2 not as a compressed gas or as a liquid but rather ‘chemically’, as a hydride, a compound of one or more hydrogen atoms with other elements.

Engine Concepts for CNG and LNG

Engine concepts for combusting gaseous fuels are manifold. Figure 15 describes some concepts for LNG and CNG vehicles. Each concept has its advantages but also its disadvantages. These advantages have to be considered for the application the vehicle is used for. In passenger cars, light goods vehicles, and heavy-duty vehicles with a short to medium driving range, CNG is commonly used.

These vehicles operate in urban areas such as fleet vehicles, buses, refuse collection trucks and commercial delivery vehicles.

For instance, as LNG needs a constant cool temperature to prevent methane from boil-off, the LNG tank will be rather unsuited for vehicles that are only used on random and infrequent occasions. The LNG tank will empty without having actually driven. Sometimes, liquid fuel propelled vehicles can be upgraded to operate with gas, in particular LPG vehicles. However, not all engines are suited for such an upgrade.

14 METHANE – PHYSICAL PROPERTIES

All gas-operated engines share the concept that the gas enters the engine as a vapour, i.e. LNG needs to be vaporised before entering the cylinder. Some engines with dedicated pressure regulators require specific pressures when running on LNG. It may also be considered that an additional pump is not required given that the minimum required pressure for engine operation is the same as in the tank. Hence, different “LNG products” can be found in the market which differ in pressure: e.g. cold, saturated and super-saturated LNG shown in table 14 and indicated in figure 13.

Before the gas, either from an LNG or a CNG tank, enters the engine it is being passed through a pressure regulator. A proportion of diesel is injected into the methane, which auto-ignites and acts as the spark for further combustion of the gas. The ratio of gas to diesel is strongly dependent on operating conditions: 70-75% gas is typical. However, at low load and speed this can reduce to 50-60%, whereas at high speed and high load it can be as high as 80-85%. New technologies which use a gas direct injection technique can even achieve higher proportions of gas use (85-90%).

It has become a common standard to have CNG fuel tanks with pressures from 200-250 bars. CNG tanks can be refuelled either 'fast' or 'slow'. Modern fast-fill stations can achieve comparable filling rates with standard liquid fuels. However, they require a cascade pressure storage and a large compressor capacity. Slow fillers, on the other hand, take a longer time for refuelling in comparison. However, it is common that many vehicles may be simultaneously fuelled using the same compressor, which would result in no disadvantage when compared to fast filling stations in case of refuelling a fleet overnight. Currently, there is comparatively little natural gas vehicle refuelling infrastructure, the barrier being that significant investment is required to establish an adequate infrastructure.

### Gasto-Liquids

Shell GTL Fuel is a synthetic diesel that is produced from natural gas using the Fischer-Tropsch process, which was first developed in the 1920s. The Fischer-Tropsch process uses special catalysts to convert natural gas via syngas (an intermediate gas mixture of carbon monoxide and hydrogen) into a mixture of synthetic hydrocarbons. As well as GTL diesel (gasoil) a variety of other high quality products can be produced, like baseoils, kerosene, naphtha, normal paraffins and waxes (cf. fig. 16).

#### 16 GTL – A RANGE OF PRODUCTS

Shells GTL Fuel has been produced since 1993 at Shells first commercial GTL plant in Bintulu, Malaysia. Moreover, Shell has built a global-scale GTL plant in Ras Laffan, Qatar, which was commissioned in 2010. The first shipload of GTL products left Qatar in June 2011. The Qatar plant has a capacity of 1,400,000 barrels per day, which is equivalent to about 7 million tonnes of product per year, out of which roughly 3 million tonnes can be Shell GTL Fuel, to be used in conventional diesel engines. Since Spring 2012 Shell GTL Fuel has been commercially available for captive heavy-duty fleets (trucks, buses) in the Netherlands and in Germany. Properly treated GTL diesel is fully compatible with existing diesel engine technology and can be used interchangeably (and mixed) with conventional diesel fuel. The energy density of GTL diesel is similar to but slightly lower than conventional diesel. GTL diesel results in lower hydrocarbon, carbon monoxide, nitrogen oxide, and particulate emissions when compared with conventional diesel fuel. This is a result of its unique composition: almost exclusively paraffins, with virtually no aromatic hydrocarbon or olefins content. In addition, the fuel is virtually free of sulfur and nitrogen.

#### 17 AVERAGE LOCAL EMISSION REDUCTION OF GTL IN % TO EN 590 DIESEL

<table>
<thead>
<tr>
<th>PM/0.01</th>
<th>NOx</th>
<th>HC</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>EURO I</td>
<td>18</td>
<td>13</td>
<td>22</td>
</tr>
<tr>
<td>EURO II</td>
<td>18</td>
<td>13</td>
<td>22</td>
</tr>
<tr>
<td>EURO III</td>
<td>10-34</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>EURO IV</td>
<td>10-38</td>
<td>10-2</td>
<td>10-19</td>
</tr>
</tbody>
</table>

Test data from heavy-duty vehicles (buses and trucks)
GTL diesel is treated with a commercial lubricity additive in order to fulfill the requirements of the relevant diesel norm EN 590. However, due to the fact that the density is lower than that of conventional diesel a separate classification according to CEN CWA 15940 was pursued. It is work in progress to bring this into a new EN specification for synthetic diesel fuels.

Shell GTL Fuel is an innovative fuel that can help fleet operators of buses or trucks to reduce local emissions, especially in urban drive cycles and inner cities where smog emissions are an issue. Figure 17 shows typical emission reduction potential of GTL fuel in different diesel engines, based on internal measurements and/or trials with fleet operators, OEMs and authorities. Since GTL fuel is an “drop-in” fuel, fleet operators can reduce local emissions without any capital investments: existing vehicles and refueling infrastructure can be used unchanged. Operators also reported that GTL fuel reduces smell and engine noise (in certain engines and under certain driving conditions). Other interesting applications for Shell GTL Fuel are inland navigation, diesel-generator sets in inner-cities and rail. GTL also allows “taylor-made” applications like first fill fuels, when special requirements are to be met in terms of cold flow and storage stability.

Natural Gas Fuels Retail Prices

The market penetration of NGVs is strongly correlated with its competitiveness against gasoline and diesel cars. CNG/NGV vehicles are more expensive than diesel and/or gasoline vehicles. In order to compensate for higher upfront capital costs, running costs of an NGV must be lower than for conventional vehicles. A strong incentive to switch to NGVs is competitive CNG/LNG fuel prices. Transportation fuel prices are influenced by many factors including crude oil and wholesale prices, transportation and storage, retail and marketing costs and margins. For gasoline and diesel, reliable and self-consistent data on fuel prices are available. In the EU, for example, the Market Observatory for Energy presents consumer prices and net marketing costs and margins. For gasoline and diesel, reliable and self-consistent data on fuel prices are available. In the EU, for example, the Market Observatory for Energy presents consumer prices and net marketing costs and margins. For gasoline and diesel, reliable and self-consistent data on fuel prices are available. In the EU, for example, the Market Observatory for Energy presents consumer prices and net marketing costs and margins.

Natural Gas Fuels and Air Quality

In many countries, the use of natural gas or other alternative fuels is supported for environmental reasons, in particular in order to reduce air quality emissions. Gaseous fuels combust more cleanly than refined liquid fuels with respect to nitrogen oxide (NOx) which contributes to acidification and ground-level ozone formation; sulphur dioxide (SO2) which (with NOx) causes acid rain; and particulate matter which (again with NOx) causes smog and poor air quality. In addition, unburnt fuel components could impact negatively on air quality. If combustion of hydrocarbons, either liquid or gaseous fuels, is not fully completed, not only carbon dioxide and water but also other forms of hydrocarbons could be in the exhaust gas.

With respect to pollutants, CNG/NGV emissions are especially low with NGVs having even fewer contaminants since they are removed during the liquefaction process. There is thus the opportunity to improve air quality by using gaseous fuels, especially in urban areas where the air quality is an acute problem and where most advanced vehicle technology is not yet available. A general classification in categories of worldwide emission standards is given in the Worldwide Fuel Charter.43

The market for natural gas fuels is far less developed and prices can vary strongly with local conditions. EU fuel prices, net of energy tax and EU consumption-weighted average show that natural gas retail prices including costs for refuelling infrastructure are in fast lower than gasoline and diesel prices.45 CNG retail prices are higher than household NG prices due to higher storage and distribution cost.

Finally, consumer retail prices are significantly influenced by energy taxation. Many countries have reduced energy taxes on NG fuels in order to promote NG fuels. In Germany, CNG energy taxation is 80% below current gasoline tax rate and 65% below the diesel rate, thus reducing fuel cost by 40-50% against diesel and gasoline. The German CNG tax relief runs to end of 2018. In many other European countries, CNG taxation is even lower.46

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18 NATURAL GAS FUELS RETAIL PRICES

![Chart showing retail prices of gasoline, diesel, CNG, and LNG](chart.png)

![Chart showing emission reduction potential of GTL fuel](chart2.png)

43 Cf. EDAf, Reducing CO2 Emissions in the EU Transportation Sector to 2050, Appendix 2, September 2012, p. 97/101.
In a study, the emissions of 32 Euro 4 passenger cars equipped with gasoline (with and without a direct injection), diesel (with and without particulate filter) and gas engines were compared, with focus on non-methane hydrocarbons, hydrocarbons, nitrogen oxides (NOx) and particulate matter. The tests were performed under the New European Driving Cycle (NEDC). The study showed that gas-operated Euro 4 vehicles already complied with the upcoming Euro 6 specification. This was despite the fact that the hydrocarbon emissions, in particular those of methane, were higher compared with the other engine types. Even gas-operated heavy-duty engines could at an early stage comply with emission standards which were already below the limits of LEVs (Environmetally Enhanced Vehicles).  

Other studies produce comparable results, showing that gas-operated vehicles have even lower particulate matter emissions than are produced by tyres, but that on the other hand hydrocarbon emissions, in particular for lean-burn gas engines, are higher compared to gasoline or diesel engines. Recent comparisons of diesel and CNG-fuelled vehicles (e.g. for transit/school buses, trucks or passenger cars) which were both equipped with the best emission control technologies revealed that both engines can achieve similar emission levels, but that is, however, also dependent on the use of the vehicle. Moreover, CNG-fuelled vehicles are reported to have lower noise emissions than diesel trucks. However, concerns exist that currently available data does not allow a deeper statistical analysis.  

The European Commission is pushing to reduce exhaust gas emissions for all types of vehicles (CO₂) and all other pollutants) even further. Exhaust gas after treatment is hence becoming a requirement which consequently comes at a price for vehicle manufacturers and ultimately for the customer. Gas engines can reduce the requirements the exhaust gas treatment has to cope with. However, gas propulsion systems usually have higher weight. Still there are also concerns regarding the reliability and durability of exhaust gas after treatment.  

Natural Gas Fuels and Greenhouse Gas Emissions  

Natural gas is the lowest carbon fossil fuel. A question is, whether and how much natural gas can help to reduce greenhouse gas emissions of road transport. At first glance, the answer seems to be straightforward. The combustion of natural gas emits less carbon dioxide per released energy than other fuels, 25% less than diesel and 23% less than gasoline (cf. Graph 20).

However, these are only greenhouse gas emissions from the combustion process itself. An adequate performance assessment has to include greenhouse gas emissions over the whole cycle of the fuel – so-called “Well-to-Wheel” (WTW) balances. These can be differentiated into “Well-to-Tank” (WTI) and “Tank-to-Wheel” (TTW) emissions. The main factor influencing TTW emissions is the efficiency of the gas engines (relative to the gasoline or diesel engines they replace), because it is emissions per unit of distance travelled (g CO₂/km) rather than the emissions per unit of fuel (g CO₂/MJ) which count. GHG models in Europe and the U.S. estimate WTW greenhouse gas emissions caused by the light-duty vehicle fleets (ID: passenger car). Table 21 summarizes the assumptions of these models about efficiencies of recent diesel, gasoline- and natural gas-fuelled LEVs. For both models shown, diesel vehicles are assumed to be more efficient than gasoline vehicles (10-11% better in Europe, 5-20% better in the U.S. depending on whether the gasoline vehicle is Port Injection (PISI) or Direct Injection Spark Ignition (DISI). For Europe it is assumed that CNG vehicles have a similar efficiency to gasoline vehicles. The U.S. model assumes that dedicated CNG vehicles are slightly more efficient than PISI vehicles but less efficient than DISI vehicles. Direct Injection Compression Ignition (DCI) vehicles still show the best performance. Thus CNG vehicles could potentially reduce vehicle fleet greenhouse gas emissions if they substitute gasoline vehicles (PISI) in first place. Greenhouse savings would be smaller if gas-fuelled vehicles compete with diesel vehicles and improved DISI (gasoline) vehicles (U.S.).

21 EFFICIENCY ASSUMPTIONS OF WTW MODELS FOR LDV

The above-mentioned WTW models do not contain any specific assumptions for trucks. A recent CERA study assumes that for CNG/ING-fueled long haul trucks both SI and CI (dual fuel) versions will be available (CI gas engines are not yet available for passenger cars). The SI version is assumed to have 10% lower efficiency than a conventional diesel truck engine and the CI version (dual fuel, High Pressure Direct Injection, HPDI) would have the same efficiency. Unlike for passenger cars, natural gas (CNG or LNG) in HPDI truch engines could achieve nearly maximum TTW GHG savings, namely up to 25%, when compared with diesel trucks. However, performance data from on-road operations are scarce, further field testing is needed.  


CF. Deutsches Zentrum für Luft- und Raumfahrt (DLR), Shell Deutschland, Shell LKW-Studie, Hamburg/Berlin, April 2010, p. 42.


CF. Novatlantis, Emissionsvergleich verschiedener Antriebsarten in aktueller Perspektive, Düsseldorf, November 2007.


A BRIDGING TECHNOLOGY FOR FUTURE MOBILITY?

III. NATURAL GAS MOBILITY – VEHICLES AND FUELS

22 WELL-TO-WHEEL GREENHOUSE GAS EMISSIONS FOR PASSENGER CARS

Whereas direct greenhouse gas emissions from fuel combustion are on the same level, they can differ according to their production processes (Well-to-Tank). For gasoline and diesel fuel the contribution of the WTT GHG emissions is typically 20% of the full WTW greenhouse gas balance (Graph 22).

The pathways of CNG and LNG are more diverse and can result in a WTT emission contribution range of 15-35%, influenced by important factors such as gas origin, liquefaction efficiency and transport distances. The WTW models mentioned above are aiming at describing the typical situation of a region regarding the WTT emissions but note that the make-up of the gas supply is constantly changing, as are the technologies applied, so these conclusions may change in the future.

Looking at WTW GHG emissions by CNG/LNG-fuelled LDVs in the U.S. and in Europe gives the following conclusion: at present (2010), WTW models for passenger cars in Europe show that CNG vehicles should have a GHG advantage of 24-25% compared to gasoline-fueled vehicles. This is in accordance with numbers that can be obtained from the fuel consumption data base for LDVs certified in Germany.

The WTW emission balance of diesel passenger cars is only approximately 15 percentage points higher than for CNG cars (table 23).

For the U.S., bi-fuel CNG vehicles display only minor advantages. Dedicated CNG vehicles are 5 percentage points better than gasoline PISI but 8 percentage points worse than gasoline DISI. Diesel vehicles have WTW emission 9% lower than the dedicated CNG vehicle. Consequently, compared to Europe, in the U.S. only a part of the intrinsic GHG advantage of natural gas has been realised by CNG vehicles in these WTW emission estimates. This is mainly because of the elevated WTT GHG emissions of natural gas in this U.S.

23 WELL-TO-WHEEL GREENHOUSE GAS EMISSIONS OF DIFFERENT PASSENGER CARS

Shell analysed – using the mentioned WTW models – how the situation would look like for modern LNG-fuelled long-haul trucks in these two regions. WTT GHG emissions for LNG imported to Europe are, as a result of more efficient LNG supplies and of more efficient engine technologies, relatively low for HDVs. The WTT GHG savings estimated by Shell range from approx. 10% (SI lean burn) to approx. 20% (CI HPDI) for Europe and 0% (SI lean burn) to 10% (CI HPDI) for the U.S., both compared to diesel trucks.

WTW greenhouse balances for NGVs are complex, still work in progress and have to be interpreted cautiously. Previously, WTW savings by CNG were expected to be of a similar magnitude in the U.S. The less favourable result in the U.S. is a consequence of new insights obtained by studies about upstream emissions undertaken in the last few years.

At present, the highest potential WTW GHG emission savings are expected from the substitution of gasoline vehicles by CNG vehicles and the substitution of diesel trucks by LNG-fuelled trucks equipped with HPDI-CI gas engines. Higher WTT emissions of natural gas limit the overall GHG saving potential in the U.S.

Deutsche Automobil Treuhand (DAT), Leitfaden über den Kraftstoffverbrauch, die CO2-Emissionen und den Stromverbrauch, Ostfildern 2013.


IV. SCENARIOS AND PREREQUISITES FOR NATURAL GAS MOBILITY

Natural Gas Mobility Scenarios

Depending on its application, natural gas offers several benefits as a transportation fuel. These include more diversified energy supplies, fuel-cost savings for users, local air quality improvements, noise reduction and reduced greenhouse gases. The key question for the future is: what contribution could NGVs and NG fuels make to mobility, energy supply and emission reductions in the future?

The global stock of NGVs was at 14.4 million by 2011. The global NGV fleet has grown at annual rates of more than 20% during the past decade. However, NGVs or, more specifically CNG and LNG still represent only a niche in transportation today. In the IEA New Policies (NP) Scenario the global NGV fleet could increase to 31 million by 2035. NGVs are projected to represent 1.7% of the global vehicle fleet and 60 bcm or 1.3% of the overall gas demand. In comparison, the IEA’s Gas Scenario assumes stronger action by governments and lower gas and NGV prices, encouraging the introduction of greater numbers of NGVs, resulting in 70 million NGVs in 2035. Both the New Policies as well as the Gas Scenario assume average growth rates of 3.3% and 6.8%, which are both well below recent trends.

In a High Impact-Low Probability (HILP) Scenario, the IEA also examined what the impact of a surge in demand for NGVs would look like. Assuming 10% of newly registered vehicles worldwide were NGVs, the total stock of NGVs would then grow on average by 11.3% to almost 190 million vehicles by 2035. This change in NGV penetration would have a significant impact on fossil fuel demand and also an impact on emissions. Demand for NG in transportation would increase from 20 bcm today to 381 bcm by 2035, thus relaxing the global call on liquid (oil-based) fuels by 5.7 mb/d.

NGV demand for future Natural Gas Mobility

NG fuels provide a number of economic and environmental benefits. However, for consumers they are less attractive than liquid fuels due to their lower energy density in storage, frequency of refuelling and handling. In addition, the range of special NGVs has been relatively small and the density of refuelling stations completely insufficient so far. Thus competitive prices and pricing advantages have been the key incentive to use natural gas as a fuel.

For NGVs to be attractive for consumers — whether commercial or private — the payback period of additional capital expenditure should be kept short and limited to a maximum of a few years or the typical retention period of the first owner, if possible. On the one hand, the additional upfront investment in NGV procurement should therefore not be too high against competing conventional vehicles, whether gasoline or diesel. Moreover, an attractive offer and a larger diversity of NGV vehicle models would be beneficial to wider adoption. Finally, payback periods can be kept short by means of low running costs and/or fuel prices.

Today, the net price of NG differs between regions. In regions with cheap gas resources such as North America, the uptake of NGVs might therefore accelerate faster. At the pump, national taxation has a major impact on end-consumer prices. Last but not least, sufficient consumer adoption is required for new alternative fuels.

The deployment potentials for NGVs are the greatest in the commercial sector (as CNG for LDVs and trucks), in long-haul road transport (e.g. LNG for trucks) and in public transport (such as CNG for city buses). Where no infrastructure for gaseous fuels is available and existing fleets only comply with lower exhaust gas emission standards, clean GTL fuel might be an immediate solution for diesel engines.

Various fora for the promotion of natural gas as a transportation fuel, of which Shell is a member, have required for new alternative fuels.

Prerequisites for future Natural Gas Mobility

The EU Commission recently proposed a directive to build up an alternative fuel infrastructure, according to which the refuelling infrastructure for CNG and LNG will be expanded and its density increased considerably by the year 2020 in Europe.
Fuels derived from natural gas sources could help to diversify and supplement energy supplies in transportation. Moreover, the cleanest fossil energy carrier with low carbon content, natural gas offers potential advantages in terms of emissions: for one thing, depending on engine efficiency, lower greenhouse gas emissions, and for another, lower air quality emissions, although advantages are smaller the stricter the exhaust gas emission standards.

V. SUMMARY AND CONCLUSIONS

As global mobility and motorisation will continue to increase rapidly, more fuels will be needed. Today, liquid fuels refined from crude oil together with biofuels almost completely meet the energy needs of the transportation sector. The internal combustion engine will continue to be the backbone of motorised mobility although an increasing diversity of drivelines and fuels is expected, e.g. via NG-mobility.

Natural gas resources are abundant and affordable. The shale and tight gas boom in Northern America, driven by new production techniques, has strongly improved local energy supplies and thus changed global energy markets. According to today’s level, total gas resources could cover 230 years of current gas consumption.

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In order to establish NG-mobility better on the market, however, the dilemma between a mostly too small natural gas fleet and an insufficient refuelling infrastructure needs to be overcome. Key requirements in this regard would be an adequate range of NGVs, competitive endconsumer prices for natural gas, an improvement of the refuelling infrastructure as well as building up higher acceptance with consumers.