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The Contribution of Natural Gas Vehicles to Sustainable Transport

International Energy Agency

Michiel Nijboer

WORKING PAPER

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The author remains fully responsible for the content of this working paper and any errors or omissions are solely his responsibility.

As a working paper, this document reflects work in progress; input, suggestions, corrections or comments from readers are appreciated. Please send comments to naturalgasinfo@iea.org.

Table of contents

List of figures

List of tables

List of boxes

Executive summary

Key messages:

- **The number of natural gas vehicles (NGVs) and fuel stations has grown very strongly in the past decade and continues to do so, although it is still a niche market, from the perspective of transport (less than 1% of world road fuel consumption) and natural gas markets (less than 1% of world gas demand).**

- **Natural gas can play a significant role in cutting vehicle carbon dioxide (CO_2) emissions, but over the long term there will need to be a commitment to transition to very low CO_2 gas sources, such as biogas or bio-synthetic gas. Natural gas may be especially important for cutting CO_2 emissions from heavy-duty vehicles (HDVs), since other options such as electrification appear to be limited.**

- **Vehicle and fuel technology for natural gas is available today and relatively affordable, particularly in comparison with other alternative fuel vehicles (AFVs).**

- **Depending on the context, NGV can have strong benefits in different countries including: improving air quality and reducing noise in urban areas; diverting oil from domestic consumption to export; improving energy security; and reducing government spending on road fuel subsidies. Governments should carefully consider the role of NGVs compared to other AFVs, such as electric, fuel cell and biofuel vehicles, and weigh the costs and benefits of each for different modes of transport. In this context, it appears that NGVs may compare favourably in many — but perhaps not all — national contexts.**

- **Natural gas can be competitive *vis-à-vis* gasoline where transmission and distribution grids are present; in countries where this is not the case, there is often an opportunity for simultaneous gas market development and increasing NGV market share. While investments in vehicles and retail infrastructure can generate positive returns, temporary government support may be required to establish an NGV market. Without such support, many countries are unlikely to achieve self-sustaining NGV markets with substantial penetration levels. Investments in grids are likely to take place only where other sectors can also benefit from natural gas supply.**

Market development

Although in the past decade the worldwide market for use of natural gas in vehicles has developed stronger than ever before, this technology remains a niche market as the current share of natural gas in road transportation is still very limited in all but a few countries. The countries with the highest level of market development are Argentina, Brazil, India, Iran and Pakistan.

While retrofit is still applied, especially outside Europe, there is a general tendency towards original equipment manufacturer (OEM) vehicles and more OEM models have become available over the past years, although the availability varies for different types of vehicles on a country-to-country or regional basis. The equipment to build fuel stations for NGVs is widely available and technology continues to improve.

Role of NGV in a low-carbon future

NGV programmes are usually driven by other goals than greenhouse-gas reduction, although NGVs can certainly contribute to decarbonising transportation and as such should be part of plans to move towards sustainable transport. On average, a 25% reduction in carbon dioxide equivalent (CO_2-eq) emissions can be expected on a well-to-wheel (WTW) basis when replacing gasoline by light-duty vehicles (LDVs) running on compressed natural gas (CNG). While the technology for bio-synthetic gas is not fully developed yet, biogas could provide significant quantities of a low-carbon fuel in the longer term at low or even negative greenhouse-gas abatement costs. Europe is currently seeing an increasing number of projects aimed specifically at the production of biomethane and its use in vehicles. In principle, NGVs can also provide a pathway to hydrogen but more research is required to assess how and to which degree this can be accomplished. For various reasons, the potential to reduce greenhouse-gas emissions by replacing large quantities of diesel fuel consumption in HDVs by natural gas has been underutilised.

NGV policy

NGV programmes are driven by a variety of factors, including the improvement of local air quality in densely populated areas, freeing up more valuable oil (products) for exports, reducing government spending on subsidies, stimulating economic development by promoting local production of vehicles, improving security of supply by replacing an imported fuel with a domestically abundant fuel, and overall gas market development.

Governments can stimulate NGV development at many different levels and co-ordinate an integrated approach with all stakeholders. Any national or regional NGV strategy needs to take into account a number of local factors to tailor general principles to the context. There is no "one-size-fits-all" approach.

Case studies

Brazil's remarkable average annual growth of almost 60% in number of NGV during the past decade has recently slowed down due to competition from ethanol flex-fuel vehicles and supply constraints. On the latter point, new gas discoveries/developments will lead to a marked improvement of the demand-supply situation. A major potential source of growth of natural gas consumption in Brazilian transport, notably heavy-duty transport, is very dependent on government policy. The country currently lacks strong government policy or initiatives from other stakeholders that could change this situation in the near future.

India could become the world's largest NGV market if it can manage the policy and substantial investment challenges for grid development, fuel price (de)regulation and enforcement of quality and safety regulations. Intercity buses and trucks have so far remained an unexploited potential. Another uncertainty is the potential for India to replace natural gas by biogas or bio-synthetic natural gas (bio-SNG).

Iran initiated an ambitious CNG programme to alleviate pressure on government budgets and cope with a shortage of refinery capacity in the face of (possible further) international sanctions by using a domestically available fuel. This set the country on a path of dramatic growth, which could continue in the future if the HDV segment will be included in the programme.

Driven by energy security, the Government of Pakistan has stimulated the introduction and growth of CNG use in transportation by several policy measures. This has resulted in the largest NGV fleet in the world, over two million vehicles, consuming 2.5 billion cubic metres (bcm) of natural gas per year.

The **United States** currently has very few NGVs and limited infrastructure. This may change as policy support is growing, prospects for gas supply have improved dramatically over the past two years, vehicle availability is improving and the economics are attractive for fleet owners. A strategy aimed at HDV fleets would also mean that retail infrastructure costs can be kept relatively low while still covering wide areas.

Europe would need strong policy support for NGVs to play a significant role in the transport fuel mix, but as the world's largest car market, it certainly has potential. Depending on how future technological developments play out in relation to Europe's increasingly stringent norms, the benefit of lower pollutant emissions could drive NGV growth. However, the major impetus for growth is likely to be green-house gas reduction by using biomethane, particularly in HDVs.

Future outlook

In general, in terms of pollutant emissions compared to current diesel vehicles, NGVs perform well, particularly in the HDV segment. While OECD countries could see this gap closing, many non-OECD countries have adopted standards that were the norm in Europe or the United States ten or more years ago. Therefore, improving air quality is likely to be a stronger driver for natural gas in the non-OECD countries than in the OECD countries. The simultaneous development of gas markets, public transportation and the economy in general in many non-OECD countries could provide momentum for NGV programmes. As a result, the IEA expects that the regions that are currently leading in NGVs, Asia-Pacific and Latin America, are likely to continue to do so.

While liquid fuels are taxed at least to some extent in all OECD countries, many non-OECD countries have low tax rates or subsidy schemes in place on energy prices in general and for transportation fuels in particular. Disregarding the effect of subsidies or taxation, IEA analysis indicates that natural gas can compete with gasoline in all scenarios in which gas transmission and distribution grids are present.

Some countries will need to invest heavily in vehicles, retail infrastructure, and transmission and distribution grids to accomplish the projected growth. While investments in vehicles and retail infrastructure can generate positive returns in many cases, temporary government support may be required to establish a market, as many countries are unlikely to achieve self-sustaining NGV markets with substantial penetration levels without it. Investments in grids are likely to take place only where other sectors can also benefit from natural gas supply. Tax and subsidy policies need to be sustainable in the long run in order to facilitate these investments, notwithstanding the fact that governments have a variety of instruments at their disposal to support development of NGV markets.

1. Introduction

This IEA working paper evaluates the potential costs and benefits of using natural gas as a vehicle fuel for road transportation, as well as the policy related to its market development. There are good reasons to analyse the use of energy in transportation and to explore ways to decarbonise the sector as transportation needs continue to grow in many parts of the world. The transport sector is currently responsible for 23% of energy-related CO_2 emissions, and transport associated CO_2 emissions will more than double by 2050 according to the *Energy Technology Perspectives 2010 (ETP 2010)* Baseline Scenario (IEA, 2010a).

Whereas improving energy efficiency remains of paramount importance, alternative fuels need to be evaluated to reduce the impact of growing energy use in transportation. Even with lower energy and carbon intensity, transportation will continue to have (potential) negative impacts on health, safety and environment.

There are several alternative fuel technologies, including natural gas, biofuels, full or hybrid electric vehicles (EVs) and hydrogen fuel cell vehicles. Natural gas is the focus of this paper, both from fossil origin as well as renewable gas in the form of biomethane. Natural gas can be used in a compressed (CNG) or liquid (LNG) state in several modes of transport, including road transportation, off-road, rail, marine and aviation.[1]

Notwithstanding the potential for natural gas in other modes of transport, road transport dominates the total use of energy in world transport and as such will be the scope of this working paper. This includes LDVs (passenger cars, light commercial vehicles), as well as medium-duty vehicles (MDVs) such as vans or heavy-duty vehicles (HDVs) such as buses and trucks. Potential benefits of using natural gas in transportation include cost reduction, greenhouse-gas emissions savings, local air quality improvements, noise reduction, revenue increases from oil products and energy security enhancement. The case studies in this paper will discuss the role these benefits play in Brazil, India, Iran, Pakistan and the United States, as well as review governments' policy instruments used and the stakeholders that played an important role in market development.

Considering the future potential of biomethane to substantially decrease greenhouse-gas emissions of road vehicles at low or negative abatement costs, one section is dedicated to various aspects of this fuel. This section features a general discussion of its production process, costs and future potential, and focuses on developments in Europe by discussing two pan-European projects and presenting case studies on biomethane in Sweden, Germany, Austria and the Netherlands.

The final chapter evaluates the future potential of NGVs. However, the purpose of this paper is not to produce new projections on the number of vehicles, their gas consumption and/or share of the market, but rather to discuss the requirements in terms of investments and policy based on existing projections.

This paper makes several references to specific products developed by certain companies with the aim of highlighting key technologies. This does not suggest an IEA endorsement of any given technology; rather it seeks to acknowledge innovation and avoid possible confusion. The IEA cannot, however, be exhaustive in its market survey and may not be aware of other companies that offer similar products. Any such companies are invited to bring their work to the IEA's attention for future reference.

[1] According to the International Gas Union (IGU), "Modern technologies make it possible to fly on LNG to most of the major airports in the world."

2. Current status of NGV markets and technology

Key messages:

- **Although the worldwide market for use of natural gas in vehicles has clearly developed more strongly than ever before, this technology remains a niche market, as the current share of natural gas in road transportation is still very limited in all but a few countries. The countries with the highest level of market development are Argentina, Brazil, India, Iran and Pakistan.**
- **While retrofit is still applied, especially outside Europe, there is a general tendency towards OEM vehicles for both LDVs and HDVs. More OEM models have become available over the past years, but the availability varies for different types of vehicles on a country-to-country or regional basis.**
- **The equipment to build fuel stations for NGV is widely available and technology continues to improve.**

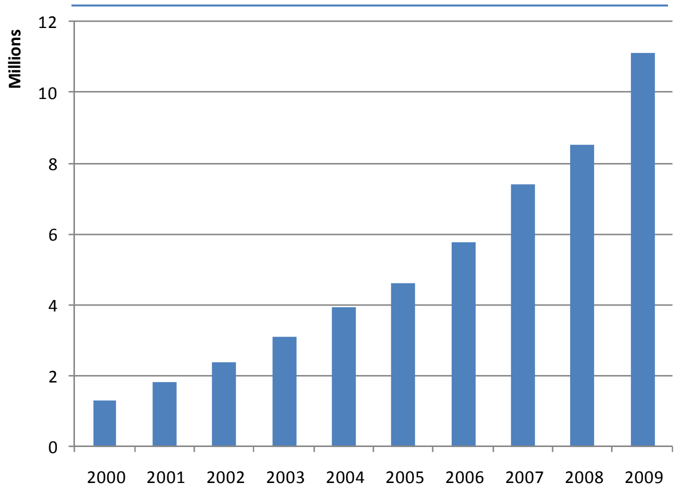
2.1 Development of NGV fleets and retail infrastructure

This section presents the past decade's developments in terms of NGV fleets, use of natural gas[2] as a transport fuel and infrastructure for NGVs in selected countries and regions.

Although the use of natural gas for the propulsion of vehicles is certainly not new, the past decade is the era in which global NGV development has demonstrated its strongest growth. Starting from a very low base of little more than one million vehicles, this has increased to a current estimate of just over 11 million vehicles.

The global fleet of NGVs consists largely of passenger cars/LDVs, although there are some regional differences in the composition (Figures 1 and 2). Forty-four percent of all passenger cars/LDVs are in Latin America. Almost two thirds of all MD/HD natural gas buses are in the Asia/Pacific region, while 53% of all trucks are in the Russian Federation and CIS, and Asia-Pacific is leading with 78% of all other vehicles on natural gas (three-wheelers and tuk-tuks).

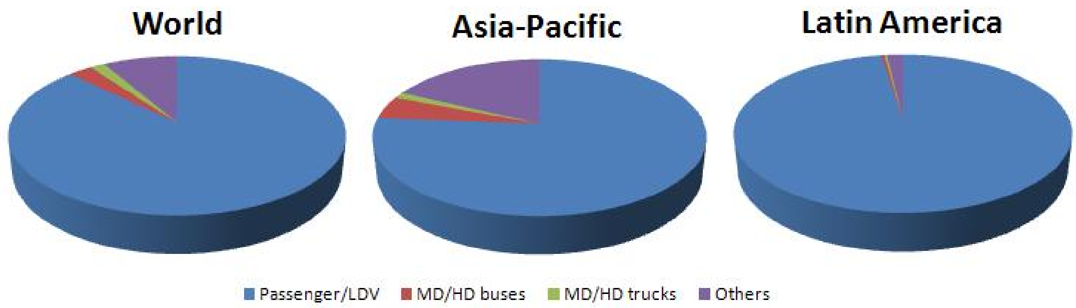
Figure 1: Total number of NGVs worldwide



Source*:* NGV Global, NGV Communications Group.

[2] Unless an explicit distinction is made, references to natural gas as a transport fuel can be gas from either fossil or organic origin.

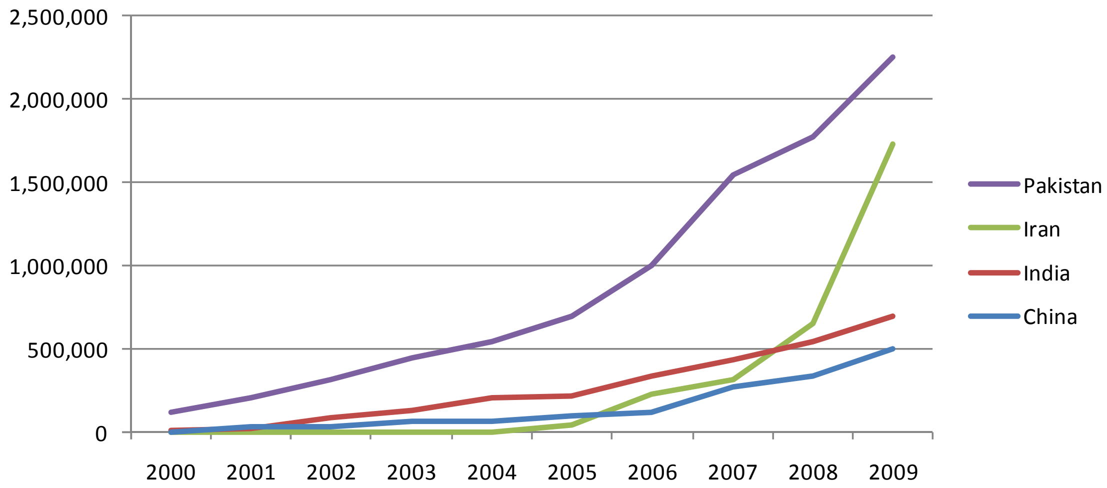
Figure 2: Composition of fleets



Source: International Gas Union (IGU) (2009).

Some countries in particular have shown a remarkable growth in recent years, albeit from a small base (Figure 3). Iran is the country that has experienced by far the highest average annual growth in the NGV fleet over the past five years. Starting out from a negligible fleet, numbers have grown to almost two millions.

Figure 3: Growth of NGV fleet in selected countries



Source: NGV Global, NGV Communications Group.

Current market share of NGV

Despite the strong growth in the past decade, the total number of 11 million NGVs still pales in comparison to a total worldwide number of around 780 million light-duty passenger vehicles in 2007 *(ETP 2010).* Few countries worldwide have attained an NGV penetration rate higher than 1% (Table 1). Bangladesh has by far the highest market share of NGVs, albeit with a very limited number of NGVs, almost 180 000 as of 2009 (NGV Global).[3]

[3] www.iangv.org/tools-resources/statistics.html

Table 1: Market share of NGV in total fleet in countries with at least 1% NGV market share

Country	NGV market share (%)	Country	NGV market share (%)
Bangladesh	61	Tajikistan	5
Armenia	30	India	5
Pakistan	26	Egypt	5
Bolivia	26	Kyrgyzstan	3
Argentina	24	Ukraine	3
Colombia	24	Bulgaria	2
Iran	14	Italy	2
Malaysia	11	Moldova	1
Myanmar	8	Trinidad & Tobago	1
Peru	7	China	1
Brazil	5		

Source: NGVA Europe, NGV Communications Group.

The stock of NGVs is not distributed evenly across countries and regions either. More than 70% of all NGVs and almost half of all fuelling stations are to be found in only five (non-OECD) countries: Argentina, Brazil, India, Iran and Pakistan. The total number of vehicles in OECD countries is less than one million and over half of these are in Italy.

Development of NGV retail infrastructure

There are currently almost 17 000 fuelling stations for NGVs worldwide. Over half of these are located in just five countries (Table 2).

These five countries also represent the most remarkable growth in terms of number of fuelling stations in recent years, although countries such as Armenia, Bulgaria, Peru and Thailand should also be mentioned. Europe has almost 3 500 stations, of which around 900 are located in Germany and 800 in Italy.

One of the indicators for measuring the development of NGV markets is the number of vehicles per fuel station. A very low number of vehicles per fuel stations has a negative impact on the economic sustainability of the fuelling stations; whereas a very high ratio may imply queues forming which, in the longer term, can be detrimental to the growth of the NGV fleet. A drawback of this ratio is that it does not account for geographical spread of fuelling stations and vehicles, in other words the proximity of the stations and the vehicles. Unfortunately, there is no regional data available.

Table 2: Number of NGV fuelling stations in selected countries

Country	Number of fuelling stations
Argentina	1 851
Brazil	1 771
China	1 339
Iran	1 260
Pakistan	3 000

Source*:* NGV Communications Group.

According to IGU (2009), 600 to 1 000 vehicles[4] per fuelling station is an economically sustainable ratio for public fuel stations. While the worldwide average of 672 is within these limits, there are few countries within this range (Table 3). Some countries exceed the 1 000 vehicles/station ratio, which could indicate the need for more stations in order to avoid queues. However, as mentioned above, in reality this is very dependent on the geographical spread of stations and vehicles, as well as the type of vehicles (as the refuelling time differs substantially for different types of vehicles).

Table 3: Countries with at least 600 NGVs per fuelling station on average

Country	Number of fuel stations	Cities with fuel station(s)	Vehicles per fuel station
Argentina	1 851	330	976
Bolivia	128	6	959
Brazil	1 704	295	912
Bulgaria	76	36	793
Colombia	485	79	618
Egypt	119	16	1 027
India	500	8	1 400
Iran	1 079	611	1 607
Italy	770	150	803
Kyrgyzstan	6	n/a	1 000
Myanmar	37	n/a	617
Pakistan	3 000	50	750
Peru	94	2	922
Singapore	5	1	900
Ukraine	283	n/a	707
Uzbekistan	63	n/a	746

Source: NGV Communications Group, NGVA Europe.

Fuel consumption

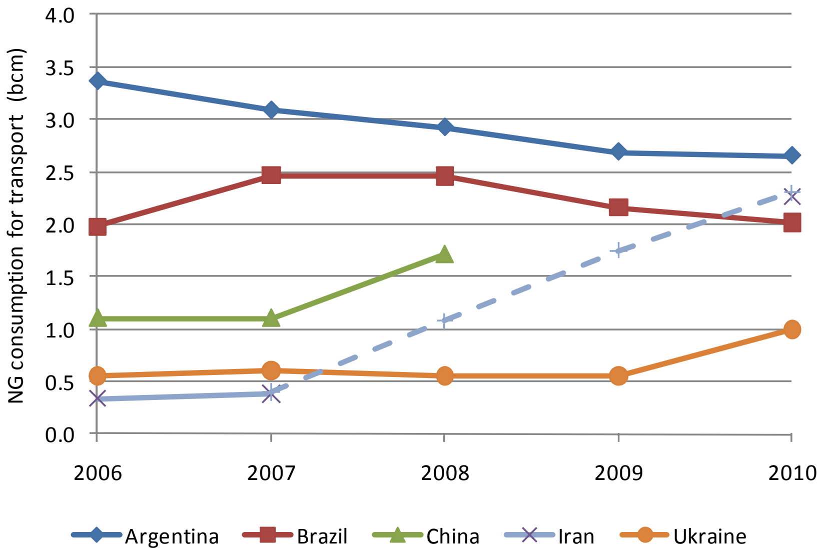
While the number of natural gas vehicles and their share in the total fleet certainly give an idea of the countries in which NGVs play a significant role, in order to measure the impacts of the use of NGVs, it is also important to look at the total amount of gas consumed by NGVs, the share of this gas consumption in total domestic gas consumption and the share in total fuel consumption for transport.

In total, the estimated natural gas consumption by NGVs in 2008 was 21.12 bcm (IGU, 2009), comparable to the annual gas consumption in countries like Belarus or Qatar or 0.7% of world gas consumption. While Latin America is still leading in terms of number of vehicles, most of the natural gas (9.94 bcm) is consumed by NGVs in the Asia-Pacific, most likely due to the higher share of buses and trucks. Figure 4 illustrates the development in estimated annual natural gas consumption[5] in selected countries (currently using at least 1 bcm/y).

[4] Car equivalents; this figure may be much lower for depot-based stations.

[5] These numbers should be treated with some caution as the estimated annual consumption is derived from monthly gas consumption data; the availability and quality of this data differ from country to country and can be highly inconsistent, incomplete or delayed.

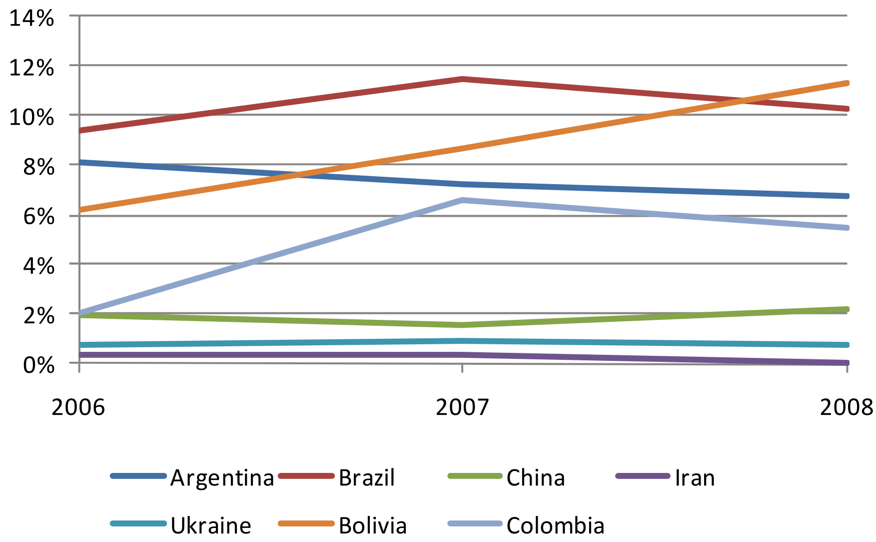
Figure 4: Estimated annual natural gas consumption by NGVs



Note: Dotted line indicates unavailability of data for Iran for 2008 and 2009.
Source: IEA analysis based on NGV Communications Group data.

The share of natural gas use for transport in total natural gas consumption in these countries is plotted in Figure 5. Two countries, Bolivia and Colombia, were added since their absolute number of gas use for transport is not remarkable, unlike their share in the total domestic gas consumption.

Figure 5: Estimated share of NGVs in domestic natural gas consumption

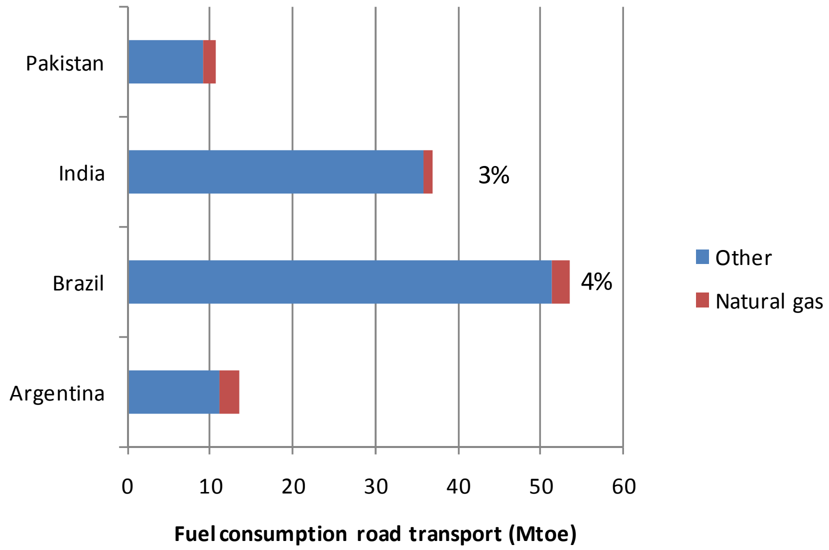


Source: NGV Communications Group, IEA data and analysis.

Another perspective is to look at the share of natural gas consumption in the total domestic fuel consumption for transport. There are currently 17 countries[6] where this share is 1% or greater. The countries with the most significant shares are included in Figure 6.

[6] These countries are: Argentina, Belarus, Bolivia, Brazil, Bulgaria, Colombia, Egypt, Georgia, India, Iran, Italy, Korea, Moldova, Pakistan, Russia, Thailand and Uzbekistan.

Figure 6: Estimated annual natural gas consumption by NGVs



Source: IEA data.

2.2 Technology and performance

Experiments with natural gas use in engines for transportation started as early as the 1930s, but the first period that saw any significant activity began in the 1970s, when natural gas was seen as a secure fuel in the aftermath of the oil crisis. Since that period, NGVs have entered and exited the stage of several countries/regions in different periods, while technology continued to evolve.

Some relevant characteristics of natural gas that have consequences for its use as a fuel for road transportation include:

- its low carbon content due to the composition (the main substance, methane, has the least number of carbon atoms per hydrogen atom in a molecule of all hydrocarbons);
- the low energy density at atmospheric pressure and temperature compared to liquid fuels, which means compression (CNG) or liquefaction (LNG) is needed to reach an acceptable vehicle range;
- the high octane number of 130, reflecting the high detonation resistance, which allows high compression ratios, reduces engine noise and eliminates the need for toxic additives such as aromatic hydrocarbons (usually used to improve the octane number of gasoline); the high octane number also makes the fuel require ignition by spark plugs or injection in a spark-ignited engine or, in a compression ignition engine, the low cetane number makes it require a pilot fuel for ignition;
- the power loss that is a result of air in the cylinder being replaced by fuel vapour;
- the fact that it is lighter than air, which in case of leakage causes the gas to disperse with sufficient ventilation;
- it is only explosive in a range of 5% to 15% mixture (by volume) with air.

This section focuses on the current state of technology, discussing the availability of engines and powertrain components for NGVs, OEM models of NGVs as well as the retrofit option. The section then features a brief discussion of infrastructure technology. Finally, drawing on existing studies and data, the environmental performance of various types of NGVs in terms of emissions and noise will be evaluated.

Available vehicle technology

Natural gas can cover almost the whole spectrum of vehicles, ranging from motorcycles, tuk-tuks, cars, vans, buses, trucks, off-road vehicles, ships and trains, including even airplanes. As mentioned earlier, this working paper focuses on the most common form of use: road transportation. This section discusses the state of technology of light-duty vehicles (LDVs), as well as medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs). No explicit distinction is made between vehicles running on CNG and vehicles running on LNG. Generally, CNG is more commonly used for LDVs while HDVs require more energy to run and tend to use LNG to maintain an acceptable range. Notwithstanding the differences between CNG and LNG in terms of gas supply, retail infrastructure and onboard fuel systems, this paper discusses NGVs at a generic level.

Light-duty vehicles

The development of NGV markets has in the past relied heavily on retrofit in many countries. While retrofit is still applied, especially outside Europe, there is a general tendency towards OEM vehicles for both LDVs and HDVs. The overall availability of OEM LDVs on natural gas has improved over the past years with vehicle manufacturers such as Fiat, Volkswagen, Mercedes-Benz, Opel, Renault, Citroën, Peugeot, as well as several Asian manufacturers adding CNG (bi-fuel) models to their product range. Availability of models varies from country to country/region to region, as illustrated in more detail in International Gas Union (IGU, 2009).

The difference in between the retail price of an OEM LDV running on natural gas versus a similar model running on petrol or diesel is an important parameter in the market development of NGVs. In many countries with succesful NGV markets, the price differential for consumers has been reduced through subsidies, tax exemptions, etc. While the premium for an NGV varies widely from country-to-country, based on data obtained through the IGU questionnaires in 2009, there is an average price difference of EUR 1 956 for an NGV versus its petrol equivalent. For the purpose of calculating abatement costs, the 2006 study by TNO, IEEP and LAT assumed values for the additional manufacturer costs of USD 2 000 (EUR 1 450) for small, USD 2 350 (EUR 1 750) for medium, and USD 2 750 (EUR 2 050) for large NGVs in the 2008-12 timeframe, which corresponds to additional retail prices of USD 2 800 (EUR 2 090) for small, USD 3 400 (EUR 2 520) for medium and USD 4 000 (EUR 2 950) for large vehicles.

Medium- and heavy-duty vehicles

In most countries and regions, the availability of MD/HD-NGVs is no longer a bottleneck in the market development of NGVs. Buses operating on natural gas are widely available, and recent developments (*e.g.* high-pressure direct injection dual-fuel engines) have improved the availability of natural gas trucks. Manufacturers currently offering natural gas HDVs include Mercedes, Iveco, Ford, Volvo, MAN, Isuzu, Nissan as well as numerous Chinese manufacturers.

Heavy-duty applications of NGVs include a large variety of vehicles, such as buses, trucks, garbage trucks, port vehicles, off-road vehicles, forklifts, tractors and other agricultural vehicles, and even "exotic" applications such as ambulances, fire trucks and 150 tonne road-trains for long-haul transport in the Australian outback. The most common application differs from region to region: buses in Asia and Europe; agricultural vehicles on natural gas in Russia and the CIS. Medium-duty vehicles (3.5-12 tonnes) include delivery vans and smaller versions of buses and trucks.

Although data on price differences is scarce, the typical additional cost for an HDV running on natural gas in comparison to its diesel counterpart lies in the range of EUR 30 000 to

EUR 35 000, although this varies from country-to-country. Conversion costs vary widely, but tend to be in the order of magnitude of half of the price premium on an OEM vehicle.

Dual-fuel[7] technology is not in and of itself a recent development, but the recent past has seen computerised optimisation of engine performance. The principle of dual-fuel technology is simple, yet promising. Due to its chemical composition, *i.e.* the properties of methane, natural gas normally requires spark ignition and is therefore used in engines that are designed to run on gasoline. Diesel engines are inherently more efficient, but use compression ignition rather than spark ignition. This means that the engine uses the heat generated by compression to initiate ignition to burn the fuel. In dual-fuel engines, a certain amount of diesel is still used for this purpose. However, the rest of the diesel fuel can be replaced by natural gas[8] which is ignited by the diesel (called "pilot fuel"). The high compression ratio that gives diesel engines their advantage in thermal efficiency can be maintained due to the high octane number of methane.

The degree to which dual-fuel engines actually replace diesel by natural gas depends on the amount of energy required ergo the load of the engine. When the engine is idling, only a small amount of energy is required, which can be fully provided by the pilot fuel. In this case, no natural gas is consumed. As the load increases, the energy consumption goes up and the degree of diesel that is replaced by natural gas as well. As a consequence, an urban cycle (stop-and-go operation) would have a lower displacement of diesel due to the, on an average, lower load than is the case for intercity transport or long-haul trucking (over-the-road operation). This means that transit buses, urban delivery trucks and refuse trucks may be less likely candidates for this technology, although there are certainly examples of this latter application (*e.g.* see section on Sweden). A different methodology is used by High-Pressure Direct Injection engines developed by Westport, which have a quantity of pilot fuel that is more or less fixed across the engine map.

Box 1: Storage of natural gas for transportation

At atmospheric pressure and temperature, natural gas has an energy content of around 40 MJ/m^3 or 50 MJ/kg, as compared to gasoline35 (MJ/L) and diesel (39 MJ/L). In order to reach an acceptable range, gas needs to be stored in a way that increases the energy density. There are currently three technologies for this. The most common are CNG and LNG. CNG is gas that is compressed to a pressure of usually 200 bar, after which it is stored in cylinders. LNG is gas that has been liquefied by cooling it to below its boiling point of -163 °C (at atmospheric pressure) and subsequently stored. There are two standards for dispensing LNG: saturated LNG (8 bar and -130 °C) or cold LNG (3 bar -150 °C). A new and promising technology that is not commercialised yet is Adsorbed Natural Gas (ANG). Through the addition of a microporous material (*e.g.* activated carbon) into the tank, either the volume can be increased at the same pressure (which results in a higher range) or the volume can be maintained at a lower pressure (which means lower costs for refuelling and a more options to shape the fuel tank). ANG potentially offers a higher storage capacity than CNG with lower costs and complexity than those associated with LNG, but there are still some technological barriers that require further RD&D.

A problem facing dual-fuel technology is the lack of formal recognition; while UN ECE Regulation 110 allows the simulataneous use of two fuels in one engine, country-by-country certification is required and European type approval is not yet possible, because the technology is yet to be defnied within European regulations and a formal test fuel is difficult to identify considering the

[7] Not to be mistaken with bi-fuel technology; a bi-fuel vehicle runs on either of two different fuels (usually to be selected by the driver), whereas dual-fuel vehicles run on two fuels simultaneously.

[8] Either compressed or liquefied and of either fossil or organic origin.

continuously varying mixture of diesel/natural gas in the engine (ENGVA, 2007b). It is expected that certification procedures for dual-fuel heavy-duty engines should be in place within the next several years (Clean Fuels Consulting, 2010).

An emerging technology for HDVs is a natural gas/electric hybrid vehicle. This is seen as a promising technology by manufacturers of HDVs, but recognition within the body of Euro VI regulations is required (ENGVA, 2007b).

Retrofit

While OEM vehicles may be preferable for their quality control systems, reliability, and engine optimisation, retrofit can certainly be a good solution as well. OEM vehicles are faced with a range of choices when it comes to AFV and also have invested massive amounts in conventional fuel technology. This means that while they are innovative, they can also be conservative in their innovation process and the uncertainties associated with a new market may cause them to direct R&D and product development and/or marketing efforts more towards conventional fuel technologies. In the absence of, or when faced with limited variety/availability of OEM vehicles, retrofit can create a market that then acts as a demand pull towards OEM.

Using natural gas in an internal combustion engine means that some form of ignition is required. While the spark-ignited gasoline engine seems to be the most obvious option for conversion to natural gas, natural gas can also be used in diesel engines despite the compression ignition principle. Besides the aforementioned dual-fuel technology, a diesel engine can also be converted to run on natural gas by replacing the diesel injectors by spark plugs. It is very important that this conversion is carried out by skilled personnel, as the compression ratio needs to be reduced and engine management needs to be optimised. While accidents with retrofitted vehicles certainly have happened, the technology and knowledge are available to ensure proper after market conversion of vehicles to run on natural gas. This technology and knowledge needs to be disseminated and the NGV industry strives to ensure its application through standardisation, certification, training and regulation.

Infrastructure technology

The equipment to build fuel stations for NGVs is widely available and technology is still improving (*e.g.* ionic compressors). Although components for fuel stations are fairly standardised and available, the design of a station needs to be tailored to each specific situation. The investment required to build a fuel station depends on a number of site specific factors, including:

- inlet capacity of the station: since CNG needs to be delivered to the vehicle at 200 bar (usually), the higher the inlet pressure, the less stages of compression are needed;
- the size and type of the station: a public station differs from a private station in terms of peak capacity, number of dispensers, redundancy in compressors, slow-fill versus fast-fill, etc.;
- planning: with careful planning of the fuelling process of different types of vehicles, the investment can be substantially reduced (*e.g.* by limiting the required peak capacity and therefore the number of compressors needed);
- dedicated CNG station or CNG dispenser(s) added to existing multifuel stations;
- required back-up capacity/redundancy;
- connection to the natural gas and electricity grid: this can be quite costly, particularly if the station is located far away.

As part of the research for this study, the IEA collected data on infrastructure costs from various sources with the assistance of NGV Global. These data were used for the economic analysis. The individual data cannot be published due to their commercially sensitive nature. Roughly, the range of investment for a public station serving an economically feasible amount of vehicles varies from USD 200 000 to USD 500 000. Costs in non-OECD countries are likely to be in the lower end of this range, whereas costs in OECD would tend to be more in the higher end of the range. The range for dedicated stations for fleetowners varies widely as well. Costs rise with the size (in terms of capacity, expressed in cubic metres per hour (m^3/hr), although there certainly are economies of scale.

Besides CNG stations, there is also the option for LNG or LCNG (liquefied-to-compressed natural gas) stations. These stations are supplied with LNG rather than pipeline gas, which means that the near vicinity of a pipeline is not a requirement, but it also means that the advantage of less road transport of the fuel itself (which can diminish congestion in certain circumstances) does not apply. These stations either distribute LNG or both LNG and CNG (in which case they are reffered to as LCNG stations). Since LNG is kept just below its boiling point, the gas can be pressurised with no need for compressors. Cost estimates for these types of stations are EUR 101/kg of gas output per hour for a LNG station and EUR 1 100/kg of gas output per hour for a LCNG station.[9] While HDVs can certainly run on CNG as well, in many cases LNG may be preferable due to the longer range the higher energy density of LNG provides.

[9] This excludes land purchase and permit costs. Based on a LCNG station with gas output of 800 Nm3/hour or 574 kg/hour. A gas station with this capacity can refuel about 50 cars per hour. Source: Cryostar in Asian NGV Communications newsletter, December 2008.

3. Environmental performance of NGVs

Key messages:

- **On average, a 25% reduction in CO_2-eq emissions can be expected on a WTW basis when replacing gasoline by LDVs running on CNG. Comparisons to greenhouse-gas emissions of diesel vehicles or comparisons between HDVs are less commonly made and appear to be more dependent on the type of vehicle.**
- **Assessing benefits of NGVs in terms of local pollutants requires detailed analysis. In general, NGVs perform well compared to current diesel vehicles, particularly in the HDV segment and when looking at the total of HC and NO_x emissions as well as PM.**
- **The benefit that NGVs have over diesel and gasoline in terms of emissions is closing as standards become increasingly stringent, but how future technological developments will play out exactly in the light of increasingly stringent emission norms is unsure.**
- **Many non-OECD countries have adopted standards that were the norm in Europe or the United States ten or more years ago. This means that NGVs have higher relative benefits in this regard in non-OECD countries. As a result, improvement of local air quality is expected to be a stronger driver for NGVs in non-OECD countries than in OECD countries.**
- **In individual cases NGV buses and trucks can have significant benefits in noise reduction, although currently in general this cannot be demonstrated with substantial data sets across a wide range of vehicles.**

The use of natural gas as a fuel for transportation is associated with several potential environmental benefits, most notably air emissions and noise. Drawing from existing studies, this chapter will evaluate the environmental impact that NGVs can have and compare the benefits against alternative means to reduce emissions.

Of all hydrocarbons, methane – the main component of natural gas – has the lowest carbon to hydrogen ratio. This means that, compared on an energy equivalent basis to conventional road fuels such as gasoline and diesel, less carbon dioxide is released into the air when it is burned. This does not take into account the efficiency with which the fuel is used in the engine. The cycle of a diesel engine is more efficient than that of a spark ignition engine, which partly counterbalances the lower carbon intensity unless natural gas is used in a compression iginition engine using diesel as a pilot fuel (see section on dual-fuel technology). The net effect on the tank-to-wheel (TTW) emissions will be discussed in this section. Notwithstanding the fact that the largest proportion of greenhouse-gas emissions on a WTW basis occur in the TTW part of the chain, the impact of the origin of natural gas is of some significance as is illustrated in various studies.

3.1 Greenhouse-gas emissions

The greenhouse-gas involved in a comparison between gasoline, diesel and CNG/LNG are CO_2, CH_4 and N_2O, though mostly comparisons are based on CO_2 equivalents. This section focuses on CO_2 emissions from natural gas of fossil origin (biomethane, which is a low or zero carbon fuel on a lifecycle basis, is addressed in a separate chapter). Several studies on the greenhouse-gas emissions of NGVs in comparison to conventional or alternative fuels will be discussed before reaching a conclusion.[10]

[10] Note that emission figures mentioned in this section are based on different reference vehicles, engine sizes, test cycles, etc. We refer to the original sources for a detailed description of test methodologies.

Engerer and Horn (2010) cite a study by Price Waterhouse Coopers, which is based on COPERT and CONCAWE, reporting CO_2 emissions on a WTW basis of just over 120 g/km for CNG versus 160 g/km for diesel and just over 190 g/km for gasoline. The only fuels performing better in this analysis are ethanol (110 gCO_2/km) and bio diesel (90 gCO_2/km). The authors claim that substantial future emission reductions of diesel vehicles will happen at the expense of efficiency, thereby increasing the CO_2 reduction of CNG versus diesel. They conclude that the "transition to CNG vehicles could, therefore, contribute to the attainment of the European Union's goal to reach emissions of 130 gCO_2/km on average for new cars by 2015.

A 2005 IEA study by Gielen and Unander (IEA, 2005) calculated a WTW CO_2 reduction of 12 $kgCO_2$/GJ to 22 $kgCO_2$/GJ (or 17% to 26%) versus conventional gasoline. CNG is outperformed by ethanol and FT gasoline/diesel from biomass and hydrogen, depending on the source of electricity.

A 2006 study by TNO, IEEP and LAT on behalf of the European Commission, based on the CONCAWE study and a TNO study from 2003, concluded the following on CNG regarding CO_2 emissions:

- Including the direct emissions of CH_4 and N_2O, the reduction in direct greenhouse-gas gases (on a TTW basis) from CNG under real-world driving conditions amount to 18% compared to gasoline and 7% compared to diesel. According to CONCAWE (2006), the reduction is 23% compared to gasoline and 17% compared to diesel. For the purpose of the study, authors assumed a TTW greenhouse-gas reduction of 22% versus gasoline.
- TNO subscribes to the view that "direct injection technology and associated technical measures have a higher efficiency improvement potential when applied to natural gas engines than to petrol engines".
- Well-to-tank (WTT) emissions are provided from CONCAWE (2006) and range from 8.4 gCO_2-eq/MJ to 21.7 gCO_2-eq/MJ of CNG, depending the origin and therefore the transport distance of the natural gas. Note that these results are specific to European gas supply options.
- Assuming marginal gas demand to be supplied from the Middle East or Southwest Asia, transported over a distance of 4 000 km, the total WTW greenhouse-gas emissions of CNG are deemed to be 144.2 gCO_2-eq/km, 83% of the gasoline level.

NGVA Europe claims 20% to 25% CO_2 reduction in cars running on natural gas over similar gasoline vehicles, whereas CO_2 savings of HD-NGVs are absent or negligible compared to diesel vehicles (NGVA Europe, 2009b; ENGVA, 2007a). Dual-fuel HDVs, retaining the efficiency of the diesel cycle by running on a mixture of natural gas and diesel, have around 20% CO_2 advantage compared to normal diesel vehicles. In a 2003 report, the former ENGVA[11] stated that by 2010 spark ignited NGVs are expected to emit about 13% less CO_2 than HDVs running on diesel (due to a loss of efficiency in diesel vehicles, resulting from an increasing amount of equipment for emissions such as NO_x and PM).

A study of the actual TTW greenhouse-gas emissions in the urban use of refuse collection trucks in Madrid (López *et al.,* 2008) compares CNG (in a spark ignited engine) to B30 (30% biodiesel) and diesel. The results show that the reduced efficiency (4%) of the Otto cycle versus the diesel cycle is compensated by the chemical composition of the fuel (the higher proportion of hydrogen to carbon in methane compared to diesel), resulting in an observed TTW reduction of 13% in CO_2-eq/km. Combined with WTT emissions data from a General Motors study, assuming an "European gas mix", the WTW emissions reduction of CNG versus diesel amounts to around 400 gCO_2eq/km or 17%.

[11] The European Natural Gas Vehicles Association (ENGVA) was succeeded by the Natural Gas Vehicles Association Europe (NGVA Europe) in 2008.

A series of 2009 reports prepared for the California Air Resources Board within the context of the Low Carbon Fuel Standard set the carbon intensity of gasoline (95.06 gCO_2-eq/MJ) and ultra-low sulphur diesel (94.71 gCO_2-eq/MJ). The greenhouse-gas emissions of the use of CNG in an HDV at 68 gCO_2-eq/MJ indicate a reduction of 29% and 28% respectively, although the latter will be lower in terms of gCO_2-eq/km since the energy consumption of a diesel vehicle is lower than that of a CNG vehicle. For LNG the picture is different: the carbon intensity is determined to be in the range of 72 gCO_2-eq/MJ to 93 gCO_2-eq/MJ, depending on the origin of the gas. This means a reduction of 1% to 22% (again, this does not take into account the energy efficiency of the vehicle).

Data from type approvals by the German KBA shows that for LDVs, compared to gasoline, the average CO_2 reduction is 20%. Compared to diesel, the picture is diverse on a car model basis. Overall, the average CO_2 emission is the same for the selected diesel models and the NGVs (bi-fuel and dedicated), 142 g/km. For the LCVs, NGVs emit on average 17% less than similar models running on gasoline whereas they emit 10% more than similar diesel models. The KBA does not provide data on CO_2 emissions for HDVs.

The overall picture that emerges is an average 25% reduction in CO_2-eq emissions on a WTW basis when replacing gasoline by LDVs running on CNG. Comparisons to greenhouse-gas emissions of diesel vehicles or comparisons between HDVs are less common and appear to be more dependent on the type of vehicle. In some cases a significant reduction compared to diesel seems attainable, but in other cases diesel vehicles emit significantly less CO_2 than NGVs (*e.g.* LCVs).

In any case, the origin of the natural gas and the steps in the supply chain are of obvious importance for the WTT emissions (Table 4), whereas the TTW emissions are determined by the fuel economy of the vehicle and the carbon content of the fuel. The share of other greenhouse gas than CO_2 appears from various studies to be marginal (TNO, 2006; Lopéz *et al.,* 2008). This means that the higher total hydrocarbon emissions of NGVs due to the tailpipe methane emissions or the higher N_2O emissions of diesel vehicles do not substantially influence the total greenhouse-gas emissions in terms of CO_2 equivalents.

Table 4: Well-to-tank emissions

Fuel	WTT CO2-emission (gCO2/MJ fuel)
Petrol	12.5
Diesel	14.2
CNG EU-mix	8.4
CNG transported over 4000 km	14.0
CNG transported over 7000 km	21.7

Source: TNO, IEEP and LAT, 2006.

Hydrocarbons (HC) are in some cases regulated on the basis of total hydrocarbons (THC); in other cases, only non-methane hydrocarbons (NMHC) limits are set. Methane is neither toxic nor reactive, but with a GWP of 21 it is a strong greenhouse gas. This can be seen as an argument to manage it as a greenhouse gas rather than a pollutant emission, even though it is a HC. The former ENGVA has made a case (ENGVA, 2007b) for managing THC and NMHC separately, arguing that one single THC limit could impair the NGV industry's ability to meet the future EURO-VI norms at acceptable costs if this limit were to be decreased significantly. In this paper, it also calls "the long term HC limits the emissions to focus on", indicating that both lower HC from the engine as well as after-treatment with catalysts may be required, where the latter option is expected to increase the costs of NGV powertrains.

The European car market is the largest in the world. In December 2008, the European Union introduced a requirement on manufacturers to reduce TTW CO_2 emissions to below 130 g/km by 2015 with a gradual phase-in from 2012 onwards. A long-term target has been set at 95 gCO_2/km in 2020. This agreement applies to cars only; a similar proposal to reduce CO_2 emissions from LCVs to 175 g/km by 2014 and 135 g/km by 2020 met resistance from several EU member countries earlier this year.[12] The targets for cars are based on CO_2 emissions only. Alternatively, they could be based on CO_2 equivalent emissions rather than just CO_2 emissions, which would mean that methane and nitrous oxide emissions are also included. This could make sense since the overall intention of this agreement is to reduce greenhouse-gas emissions from the transport sector, whereas the EURO norms are aimed at improving air quality by reducing local pollutants. If methane emissions were to be included in the ACEA agreement, limits on hydrocarbons under the EURO emission norms could be based on NMHC. The ACEA targets (and fines) could then work as a stimulus for the NGV industry to reduce methane emissions from vehicles, depending on how challenging the targets are and what the most cost-effective option is to lower vehicle greenhouse-gas emissions.

3.2 Local air quality

Transportation impacts local air quality through the emission of several gases and particles. Many of these are regulated, such as carbon monoxide (CO), particulate matter (PM), nitrous oxides (NO_x) and hydrocarbons (HC). These emissions have various detrimental impacts on public health and the environment, especially in densely populated urban areas with high traffic intensity.

The frameworks for emission limits in Europe and the United States are fairly similar, while most non-OECD countries adopt older versions of these norms. The frameworks evolve not only in the limit values, but also in the test cycles and the types of emissions included. As is discussed in the IEA Working Paper “Deploying Renewables in Southeast Asia Trends and potentials”, particularly in developing countries the severity of the problems creates a substantial potential economic value for technologies aimed at improving air quality. The exposure to PM alone has been estimated to cause 3.4 billion life years lost in 2005 in India, China and Europe. This section will be looking into the benefits that natural gas can have in this regard.

A 2009 study by VTT Technical Research Centre of Finland compared emissions from five buses. Two buses represented Euro IV emission levels; the other three represented enhanced environmentally friendly vehicle (EEV)[13] emission level technologies. The tested NGV was a stoichiometric CNG bus. This bus was the only vehicle to fall well within EEV limits on PM and NO_x (for PM even within proposed Euro VI limits). It did show significantly higher CO emissions than diesel buses equipped with Exhaust Gas Recirculation (EGR) or Continuously Regenerating Trap (CRT®), but well within proposed Euro VI limits. Unburned methane also caused the CNG bus to emit much more hydrocarbons than the diesel buses, at a level equal to or just above proposed Euro VI limits.

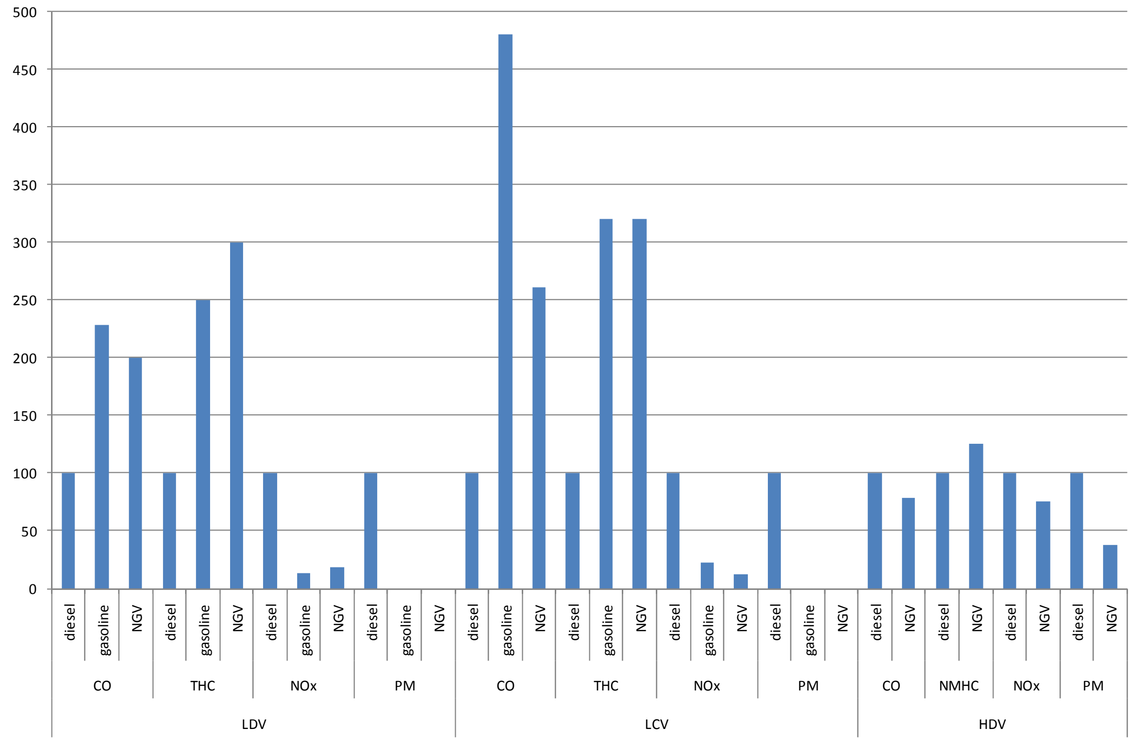
Pollutant emissions analysis based on European type approval data

The number of different vehicles available in different categories (in terms of emission limits such as EURO IV, EEV etc) and the number of different types of emissions require careful consideration, which means that a comprehensive study on this issue will inevitably get very detailed and technical, and as such would be beyond the scope of this working paper. Indeed, an analysis of type approval emissions data from the German Kraftfahrt Bundesamt (KBA) illustrates the complexity of such a task.

[12] Het Financieele Dagblad, “Blokkade treft aanscherping CO_2-normen bestelwagens”, 16 March 2010.

[13] Enhanced environmentally friendly vehicle, an EU norm for HDVs in the M2 and M3 category which is more stringent than Euro V but less stringent than Euro VI.

Figure 7: Relative emissions of vehicles in type approval analysis



Note: For each pollutant in each category (LDV, LCV, HDV) the index is set at 100 for the level of the average diesel vehicle. This means that levels of pollutant emissions cannot be compared between categories of vehicles, only conclusions about the effects of fuel can be drawn from this graph for each category separately.

Source: IEA analysis based on Kraftfahrt Bundesamt Germany.

While many data are available, the question is which vehicles are comparable and how the impacts of different powertrain options, tyres, engine configurations, test gas qualities, etc. should be included in the analysis. For the analysis of LDVs and LCVs, vehicles running on natural gas (either mono-fuel or bi-fuel) were identified and gasoline and diesel versions of the same model were selected. Where possible, models meeting different EURO standards and equipped with and without particulate filters were used. Comparison of HDVs is less straightforward; here comparable vehicles in terms of engine size and power were chosen. The selection of vehicles here also includes vehicles under different EURO norms, including EEV.

Different testing cycles exist and are used to determine the emissions of HDVs for type approval, including the ESC (European stationary cycle) and the ETC (European transient cycle). For compression ignition engines (diesel), both ESC and ETC are used with the limits on emissions differing between them, whereas for positive ignition gas engines, only ETC is used. This means that no data is available for natural gas engines for HDVs based on ESC and a comparison could only be made on the basis of ETC. It should be noted that emissions are higher under ETC than they are under ESC, but since engines are compared on the basis of the same cycle this does not influence the outcomes of the analysis.

For diesel vehicles, no separate data for HC emissions are available, but numbers for NO_x emissions and the total of HC and NO_x are available. The reason for this is that the trade-off in diesel vehicles between HC emissions and NO_x emissions has led the industry to focus on the total of these two types of emissions. To reduce workload in type approvals, measuring HC emissions separately is not required. For natural gas vehicles, PM levels are often near or below detection levels and lower than for diesel vehicles, even when equipped with a PM filter. Emissions data for HDVs are expressed in g/kWh rather than (m)g/km.

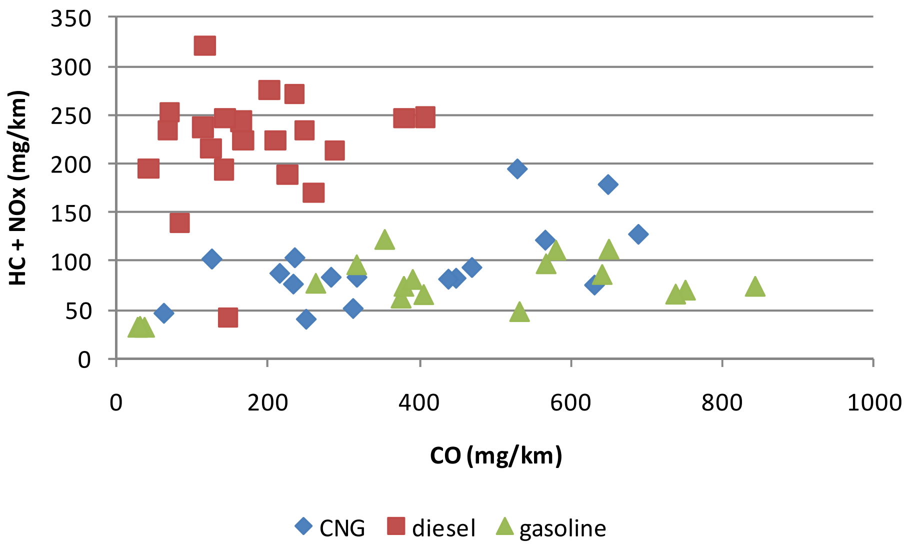
The data from the KBA also facilitate comparisons between mono-fuel CNG vehicles versus bi-fuel NGVs running on natural gas or bi-fuel NGVs running on gasoline versus their mono-fuel gasoline counterparts. The results for these comparisons will be discussed in the following sections. Figure 7 summarises the average values of all emissions for LDVs, LCVs and HDVs, expressed in an index number.

Light-duty vehicles

The analysis of LDVs includes 62 vehicles, 19 of which are NGVs (four dedicated and 15 bi-fuel gasoline), 24 diesel vehicles and 18 gasoline vehicles.

As becomes clear from Figures 7 and 8, NGVs tend to have somewhat lower CO emissions than gasoline vehicles, but diesel vehicles outperform NGVs on CO emissions. On HC+NO_x emissions, the situation is reverse: NGVs perform better than diesel vehicles, but worse than gasoline vehicles (on both hydrocarbons and NO_x). As pointed out earlier, though, most of THC emissions from NGVs are methane emissions, which are neither toxic nor reactive and in that sense incomparable to other pollutant emissions. Unfortunately, for LDVs no separate data on NMHC emissions are available from this source. The emissions of PM are not specified for NGVs nor for gasoline vehicles, whereas diesel LDVs emit on average 6 mg/km, up to 38 mg/km. When equipped with a filter, this is reduced to 0.3-2.8 mg/km.

Figure 8: Light-duty vehicle (car) emissions



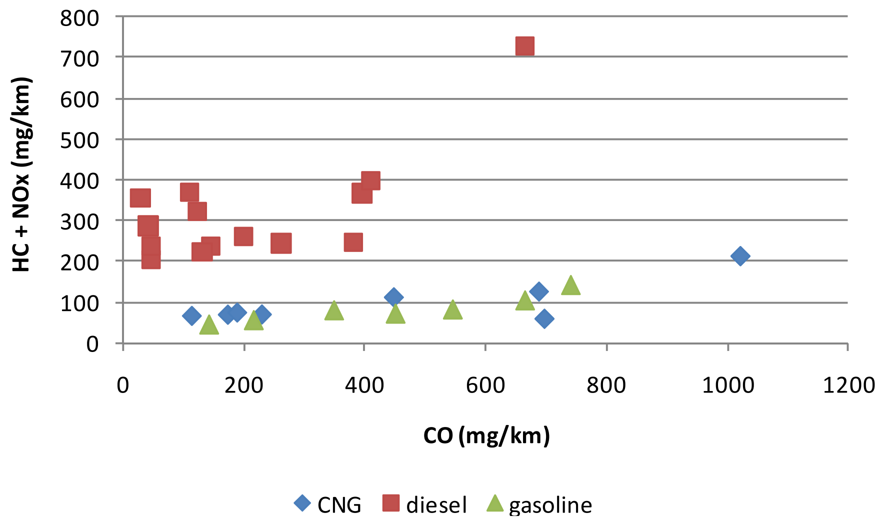
Source: IEA analysis based on Kraftfahrt Bundesamt Germany.

As noted, most of the NGVs in this analysis are bi-fuel. While this allows for a longer range, in terms of emissions the mono-fuel CNG vehicles tend to perform better than a bi-fuel NGVs running on CNG. Also, a bi-fuel NGV running on gasoline tends to emit more than a gasoline vehicle. This illustrates that some sacrifices have to be made in terms of engine optimisation to allow for the flexibility of using two fuels in one vehicle.

Light commercial vehicles

The analysis of LCVs includes 41 vehicles, 13 of which are NGVs (two dedicated and 11 bi-fuel gasoline), 18 diesel vehicles and 10 gasoline vehicles.

Figure 9: Light commercial vehicle emissions



Note: Two extreme values for gasoline LCVs were excluded from the graph (3 281 mg/km CO).
Source: IEA analysis based on Kraftfahrt Bundesamt Germany.

LCVs running on natural gas emit substantially less CO than diesel, while compared to gasoline the difference is much less pronounced (Figure 9). The same applies when comparing NGVs and gasoline vehicles on HC and NO_x emissions: they each perform better than the other in a similar number of comparisons. Again, the picture is much clearer in comparison to diesel: NGVs outperform diesel in all comparisons of similar vehicle models. As is the case with LDVs, there are no data on PM emissions for gasoline and NGVs. Diesel LCVs emit PM in a range of 20-80 mg/km, but this is reduced to 1 mg/km with a filter.

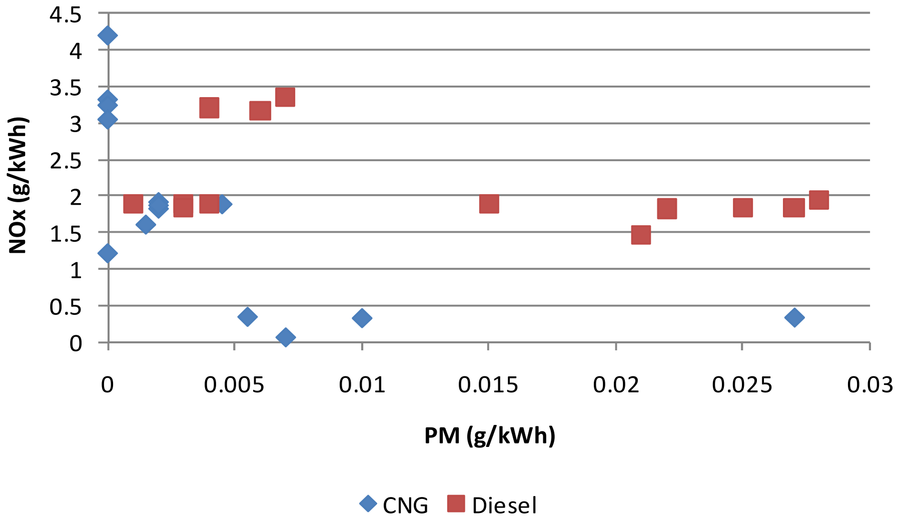
With a limited number of vehicles to compare, it is more difficult to determine whether the flexibility of bi-fuel comes at a cost of higher emissions. There are only two dedicated CNG vehicles in the LCV category and there is no similar bi-fuel version for these models. Comparing the bi-fuel NGVs to similar gasoline models results in a mixed picture , with the NGVs generally emitting more CO and NO_x but less HC.

Heavy-duty vehicles

The analysis of HDVs includes 28 vehicles, 12 of which are NGVs (11 dedicated and one bi-fuel gasoline) and 16 diesel vehicles.

The selected NGVs in the analysis emit on average 34% less CO, 24% less NO_x and 79% less PM than their diesel counterparts (Figures 10 and 11). However, they emit 28% more NMHC and when methane emissions are added, total HC emissions are six times higher on average than for diesel vehicles. The wide range of methane emissions from NGVs (0.02 for a vehicle with EEV classification to 1.19 for a EURO III vehicle) suggests that technology in this respect is advancing and available. It should also be noted that N_2O is (obviously) not included in the NMHC measurements since it's not a HC, but nevertheless it is a powerful greenhouse gas that also contributes to the depletion of the ozone layer (Ravishankara *et al.,* 2009).

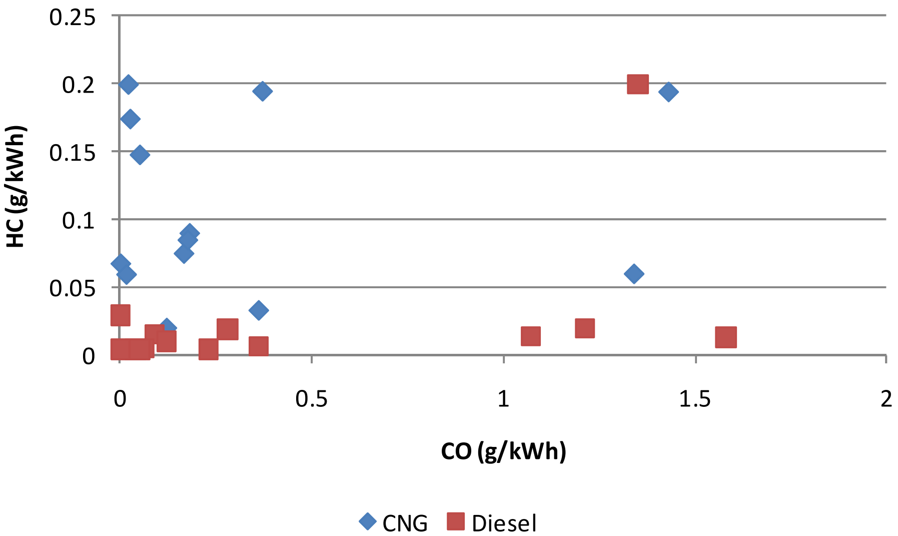
Figure 10: Heavy-duty vehicle emissions: NO_x and PM



Note: One observation for a diesel HDV with extreme values was excluded from the graph (PM 0.13 g/kWh, NO_x 4.8 g/kWh).
Source: IEA analysis based on Kraftfahrt Bundesamt Germany.

A 2007 position paper by ENGVA (ENGVA, 2007b) provides some useful insights into the technical options available to car manufacturers to meet EURO-VI limits in several scenarios with natural gas. In this document, NO_x and HC emissions are considered to be the most challenging to meet. The report states the expectation that the industry will be able to meet CO and PM emission limits fairly comfortably with existing technology. It concludes by mentioning that "all proposed sets of heavy-duty Euro-VI emissions limit values can be reached with natural gas vehicles using already available stoichiometric technologies" and also that costs are not expected to "differ very much from those in making heavy-duty diesel vehicles meet the respective emissions limit values for CO, HC and NO_x", although there is some uncertainty regarding methane sensitive catalytic equipment. Lean-burn technology may provide added benefits, such as lower exhaust gas temperatures and higher efficiency, but require experimental research.

Figure 11: Heavy-duty vehicle emissions: HC and CO



Note: One observation for a CNG HDV with extreme values was excluded from the graph (HC 1.26 g/kWh, CO 0.02 g/kWh).
Source: IEA analysis based on Kraftfahrt Bundesamt Germany.

Unregulated emissions

So far, the discussion of vehicle emissions has concentrated on regulated emissions. However, regulatory systems differ from country-to-country and from region-to-region, so what is regulated in one country/region is not necessarily regulated in a different part of the world. Naturally, the degree to - or the manner in – which a certain type of emission is regulated can also vary. It is recommendable that the health effects of vehicle emissions that are currently unregulated are studied in order to revise some systems of emission limits accordingly.

As this is a highly technical subject on which data are (unsurprisingly) scarce, it requires a detailed discussion of the causes and consequences of different compounds. However, such a discussion would be beyond the scope of this working paper. Since it is relevant for policies related to NGVs, though, reference is made to the aforementioned 2009 study by VTT, which shows that the CNG bus overall outperformed diesel vehicles on unregulated emissions. The most notable differences are found in aldehydes, nitrous oxides, sulfates, nitrates, polyaromatic hydrocarbons (PAH) and mutagenicity of particles.

The CNG bus in the study emitted 0.29 g/km of ammonia whereas this is negligible for the diesel vehicles. The proposed new Euro-VI norm for HDVs includes NH_3 (ammonia) norms for the first time (10 ppm limit). While there have been reports of high test values for NGVs, the industry attributes this to calibration issues combined with catalyst selection and does not seem to expect NGVs to encounter any problems in meeting this standard.

Discussion

The benefit that NGVs have over diesel and gasoline in terms of emissions is diminishing in countries and regions with the most stringent emissions standards, Gbut given that all technologies are constantly evolving, it is unsure how future technological developments will play out exactly. This does give rise to the question if major investments in natural gas as an alternative fuel can be justified on the basis of local air quality and/or greenhouse-gas emissions, at least in countries or regions where the current vehicle stock is based on fairly recent norms. Many non-OECD countries have adopted standards that were the norm in Europe or the United States ten or more years ago. This means that the benefits of NGVs are much more pronounced, if at least fairly recent NGV technology is used. While using the newest vehicles based on conventional fuels would obviously also help combat air pollution problems, NGVs may in these circumstances be a more cost-effective option as the benefits of NGVs were much more pronounced for the "slightly older than latest technology". The current and expected future growth in the number of vehicles in these countries and their use in densely populated areas creates a good potential for the development of NGV markets. Leapfrogging to the next generation technology can be too big of a step in many of these countries, meaning that natural gas can be a transition fuel for a longer period of time. As a result, natural gas may be playing a role in a wider range of modes of transport in non-OECD countries and regions than in OECD countries and regions.

3.3 Noise

Noise reduction is not often cited as one of the main advantages of NGVs, but in some circumstances the use of NGVs can help to reduce noise in areas where it matters. In developed countries, norms often exist which may impose limits on for example overnight urban delivery or the construction of new buildings in a certain area. In developing countries, noise reduction may not be the first priority when coping with rapid growth of transport and norms do not always exist. The key questions for this brief discussion of potential benefits NGVs can have in terms of noise reduction are:

- Why is noise a problem that should be addressed?
- To what extent can NGVs contribute to solving this problem?

Noise from traffic is more than a nuisance, it's a real and difficult to avoid problem in densely populated areas. As a 2007 study by CE (CE, 2007) mentions: "noise is very costly to society [and] should be taken as seriously as other forms of pollution, as it is similarly damaging to human health". Various studies show that noise (or in some cases vibration/pulsation) from traffic can negatively impact human health and wellbeing, as well as the condition of structures such as buildings, roads, tunnels and bridges. More specifically, a study by the WHO (2008) shows that severe annoyance and sleep disturbance can already occur at levels as low as about 40 dB(A). According to this study, the effects for which sufficient evidence is present for an association with road transport-related noise exposure include: annoyance, sleep quality, sleep disturbance, insomnia, hypertension and ischemic heart disease and reduced cognitive functioning. While the study provides a framework for noise, rather than an overview of the status of transport-related noise problems, it does give some guidance by stating that "50 or 55 dB(A) (L_{den}, outdoors) could be used as a threshold value for health impact assessment for severe annoyance and severe sleep disturbance". The aforementioned CE study mentions that in 2000 "about 44% of the population of the EU 25 (over 210 million people) were exposed to road traffic noise levels above 55 dB(A)."

While there is a wide array of possibilities for noise mitigation, including noise barriers, lower speed limits, low-noise road surfaces, no-go zones for HDVs, optimisation of traffic flow, tire design etc, the engine remains an important source of traffic noise that can be combated directly. As the CE report states: "The most cost-effective measures are those at the level of vehicles." This can be done by shielding the source of noise, but also to address the root of the problem.

Notwithstanding recent technical developments, diesel engines are inherently noisier than petrol and natural gas vehicles. This is due to the pressure wave in the cylinder which is caused by the sudden ignition. While substantial sets of data from independent research into the comparative noise production from NGVs relative to diesel vehicles are scarce, there is some information available.

A good source is the data from the aforementioned type approvals by the German Kraftfahrt Bundesamt. For LDVs, NGVs do not have an advantage over either gasoline or diesel vehicles in terms of noise production. Vehicles running on gasoline and diesel actually produced less noise in most comparisons. Having said this, LDVs on average emit significantly (9 dB) less noise than HDVs. LCVs on average produce slightly more noise than LDVs and again, NGVs do not have a clear advantage. In stationary mode, NGVs tend to be noisier than diesel vehicles but less noisy than gasoline vehicles. Whereas in motion, NGVs tend to produce less noise than diesels and perform similar to gasoline vehicles. For HDVs, only diesel vehicles are available for comparison. The data illustrates the importance of taking into account various elements in the powertrain of an HDV (exhaust, transmission) as these can make a difference of up to 10 dB. The data does not support the statement that HDVs running on natural gas produce less noise than diesel, although this is the case in a limited number of comparisons. In most cases there is either no difference or NGVs produce 1 dB to 3 dB more. In two cases, the NGV produces 2 dB and 3 dB less. The average HD-NGV produces 89 dB in stationary mode and 79 dB in motion, while the average diesel produces 90 dB (stationary) and 79 dB (in motion).

In conclusion, the type approval data from the KBA indicates that while NGVs do not have a pronounced overall advantage of producing less noise than diesel or gasoline vehicles, in individual cases there can be significant advantages. This is confirmed when individual examples are considered, such as a specific Iveco truck. This truck runs on LNG or liquefied biogas (LBG) and is the first to be certified for meeting the PIEK light norm in the Netherlands, which sets a 72 dB maximum to reduce noise from urban delivery.

The case of garbage collection in Madrid (NGVA Europe, 2009a) also illustrates the benefits that NGVs can have in noise reduction. In this case there is an extra need for silent vehicles, since garbage collection is carried out at night, while inhabitants tend to leave windows open. While not a requirement for homologation, noise has become part of municipal tenders. Noise from CNG vehicles was found to be almost half that of diesel vehicles (5 dB(A)).

Several other cases confirm that in individual cases NGV buses and trucks can have significant benefits, although currently this cannot be demonstrated with substantial data sets across a wide range of vehicles.

4. Economics and policy

Key messages:

- **Data on end-user prices show that while liquid fuels are taxed at least to some extent in all OECD countries, many non-OECD countries have low tax rates or subsidy schemes in place on energy prices in general and for transportation in particular.**
- **IEA analysis indicates that natural gas can compete with gasoline in all scenarios where gas transmission and distribution grids are present.**
- **Literature provides categorisation of policy instruments for NGVs, but no evidence on the effectiveness of various policies. Governments can stimulate NGVs development at many different levels and co-ordinate an integrated approach with all stakeholders.**
- **Any national or regional NGVs strategy needs to take into account a number of local factors to tailor general principles to the context, there is no "one-size-fits-all" approach.**

The additional costs for vehicles and investments required for infrastructure have been addressed in the chapter on technology. In this chapter, differences in prices as a result of different regimes for taxation and/or subsidies will be discussed and different regional pricing systems for natural gas will be outlined briefly, looking at how these relate to oil prices as well. Also, the outcome of an analysis of greenhouse-gas abatement costs, based on the IEA Mobility Model, will be presented. Since the economic aspects of NGVs are heavily influenced by policy and regional pricing systems for gas, many of these aspects cannot be discussed on a global basis but should be addressed at a national or regional level. For this reason, this section will start with some brief general comments about the theory of policy related to NGVs, but in the next chapter look more closely at the practical side and economics in a number of different NGVs markets in OECD as well as non-OECD countries.

4.1 Fuel prices

One of the most significant paramters when introducing a new fuel for use in road transport, or increasing its market share, is the relative prices of fuel and the regimes for taxation and subsidies. It would be beyond the scope of this working paper to provide a complete overview of subsidies and taxation on road fuels in place worldwide. Rather, some key data will be provided and a number of countries will be discussed more in-depth in chapter 5 with case-studies. On average, it is clear that taxes tend to be a large portion of end-user prices for fuels in OECD countries (Table 5).

Table 5: Taxes as percentage of end-user fuel prices in OECD countries 2009

Country	Minimum	Maximum	Average
Argentina	0.4%	64.4%	42%
Bolivia	17.2%	72.6%	57%
Brazil	7.8%	48.5%	25%
Uzbekistan	4.8%	51.1%	18%

Note: The numbers for natural gas refer to residential consumers; when used as a fuel for transportation, natural gas is often taxed differently, in many cases lower.

Source: IEA.

Data on end-user prices also show that, while energy prices are taxed at least to some extent in all OECD countries, many non-OECD countries have low tax rates or subsidy schemes in place on energy prices in general and for transportation in particular. This leads to large differences in end-use prices between countries and between fuels (Table 6).

Naturally, CNG prices before subsidies and/or taxation differ from country to country and particularly, from region to region, as well as a result of different regional pricing systems for natural gas. A more detailed description of this topic is included in *Medium Term Oil and Gas Markets* (IEA, 2010b), this section provides a brief overview of the three main systems.

The North-American market (Canada, Mexico and the United States) is very much a spot-based market. Natural gas prices are the result of gas-to-gas competition on various hubs in this region, where very substantial volumes are traded. The United States has by far the most liquid spot market for natural gas worldwide. While the option of LNG imports and (to a lesser extent) exports imply that prices in no market can be set in complete isolation from other regional markets, the North-American market is driven mostly by regional demand and supply, notwithstanding the effect that changes in other variables (such as coal, power and CO_2 prices) can have on gas supply and demand. This was illustrated by the effect that the production of shale gas plays and a 1.7% decline in demand had on prices. For example, on the Henry Hub (the most liquid of US hubs) the average spot price in 2009 was USD 4/MBtu or half the level in 2008.

Table 6: End-user prices for road fuels

Country/Region	Diesel (USD/lge)	Gasoline (USD/lge)	CNG (USD/lge)
OECD Europe	0.70	0.74	0.39
OECD North-America	0.31	0.31	0.16
OECD Asia	0.74	0.96	0.33
Argentina	0.30	0.34	0.14
Bangladesh	0.22	0.36	0.12
Brazil	0.47	0.66	0.38
China	0.33	0.41	0.22
Egypt	0.10	0.09	0.04
India	0.35	0.55	0.18
Iran	0.01	0.05	0.02
Malaysia	0.30	0.33	0.12
Pakistan	0.37	0.50	0.26

Notes: Data are taken at various points in time and can therefore vary from data elsewhere in this document; gasoline refers to regular gasoline, except for Pakistan (only premium available).

Source: NGV Europe.

The second regional price system is Europe, which is a hybrid market in the sense that while the conventional system of long-term oil-based contracts is still in place, spot markets are increasingly influencing natural gas prices. The UK hub, National Balancing Point (NBP) is the most liquid hub and hubs in continental Europe tend to follow NBP prices in a fairly narrow band as the United Kingdom is emerging as a transit country for European gas due to its LNG terminals and pipelines (IUK and BBL[14]) connecting the United Kingdom with continental Europe. Since demand started to drop in mid-2008 as a result of the economic downturn and the United States maintained high production levels, spot prices have remained very low, while

[14] Although strictly speaking no physical or virtual flow is possible yet through BBL from the UK to the Netherlands.

oil prices recovered. This has resulted in a gap of on average USD 5/MBtu in 2009, which leaves many experts questioning the sustainability of the oil-based pricing regime. Some adjustments were made to long-term contracts early 2010. It remains to be seen whether these adjustments will be extended beyond 2012.

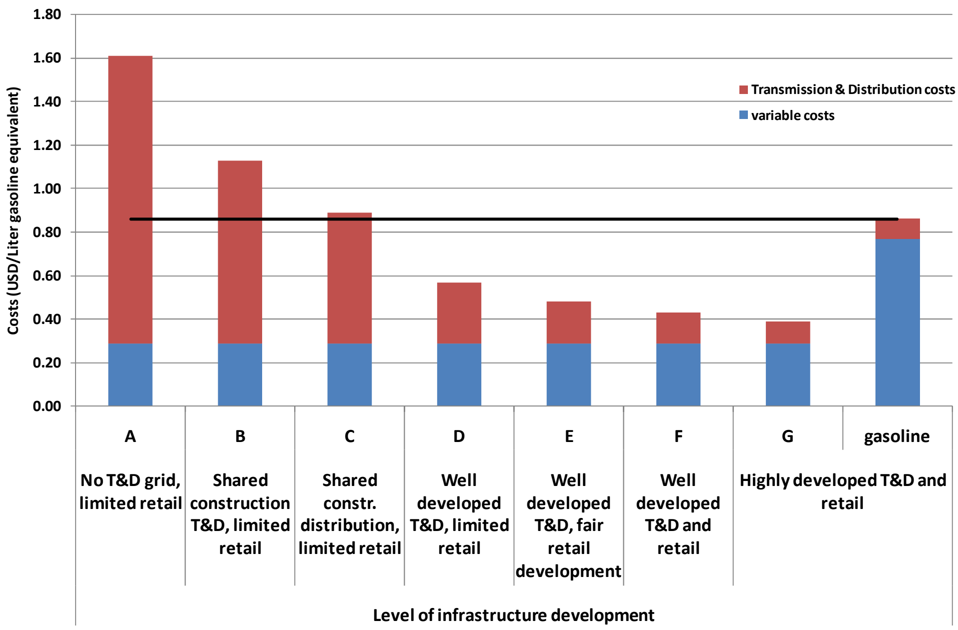
The third regional pricing system is the Asian or Pacific price system, which is mostly characterised by Asian countries situated at the Pacific basin and importing/exporting LNG to and from each other and the Middle East. LNG prices are oil-indexed and despite a drop in mid-2009 have remained much higher than spot prices in North-America and European markets, while also increasingly deviating from European oil-based prices.[15]

In other markets (such as the FSU, MENA and Latin America), prices are often regulated by governments as is discussed in *World Energy Outlook 2009 (WEO 2009)* (IEA, 2009). Therefore, when assessing relative CNG prices, it is important to recognise the regional gas pricing system, as well as national regimes for fuel taxes and subsidies.

4.2 Competitiveness of CNG

To assess the competitiveness of CNG with current fuels, an analysis was made to compare the variable costs and fixed costs for CNG in different scenarios of transmission and distribution (T&D) grid development. The purpose of this analysis is to conclude at what levels of T&D grid development natural gas as a transportation fuel can compete with the most commonly used fuel today, gasoline. Calculations were made using the IEA Mobility Model and input on CNG retail infrastructure has been obtained from various sources in the NGV industry. At an oil price of USD 80/bbl a natural gas price of USD 9/MBtu was assumed, which corresponds roughly to average prices for the past five years under oil-linked contracts in Europe or Asia/Pacific. Natural gas can compete with gasoline in all scenarios where T&D grids are present (Figure 12).

Figure 12: Costs of CNG versus gasoline in different scenarios of grid development



Source: IEA analysis.

[15] While still indexed to oil, these prices have recently become affected by other influences as well, leading to different price than one would expect on the basis of oil price development only.

This analysis is based on resource costs and as such does not reflect any influence from taxes or subsidies, which means that in cases where natural gas is cheaper per unit of fuel (scenarios D-G) this is a result of the difference in costs only. What is also clear from this analysis is that the infrastructure costs for gasoline are lower than they are for natural gas in all scenarios but G, which is compensated by much lower variable costs (the actual fuel) for natural gas. This suggests that in principle, natural gas is cheaper as a fuel, but gasoline benefits from the position that it built up over the course of many decades.

4.3 Theory on NGV Policy

Several studies have evaluated the options and challenges for policies aimed at replacing an incumbent transport fuel technology with new AFV technology. This section will provide a brief overview of the main conclusions from existing literature.

Policy instruments can be categorized as regulation (outcome, technology or fuel based), incentives (targeted at consumers or suppliers) and market creation (government fleets, direct investment in infrastructure) and policies should be designed to reduce key barriers affecting each stakeholder group (Yeh, 2007). Policy instruments that have been used include increasing taxes for conventional fuels (*e.g.* Argentina), subsidizing conversion (*e.g.* Colombia, Pakistan, China, Thailand), subsidising the purchase of vehicles and/or fuel consumption (*e.g.* United States, Thailand), regulation of the fleet (*e.g.* India, Iran, Egypt) and promotion of infrastructure development (*e.g.* United States, China). In some countries the relatively high share of NGVs is explained by historically low natural gas prices (*e.g.* Ukraine, Armenia), which raises doubts over future development (Engerer and Horn, 2010). IGU (2009) states that government incentives for NGVs (and clean fuels in general) should be linked to the relative share of market growth. When market share is low incentives need to be higher and then adjusted over time to reflect increased market penetration. Further research is needed on the effectiveness of various policies and on network analysis of interactions and ties' strength between stakeholders where one stakeholder provides incentives for other stakeholder (Yeh, 2007).

In addition to changing regulatory conditions and providing financial incentives, the public sector can co-ordinate stakeholders to align their expectations and actions towards a common goal of replacing a socially inferior equilibrium by a more preferable equilibrium. When expectations diverge, establishing a strong, shared belief in a certain technology is imperative (Yarime, 2009). Struben (2006) also points out that adoption of AFVs will not take off without co-ordination between automakers, fuel suppliers and governments. Co-ordination is essential on pilot region selection, target market, vehicle portfolio selection, asymmetric incentives for urban and rural stations, other incentive packages and standardization.

Government intervention is required to break through the technological lock-in of existing technologies or path dependence. Technological lock-in originates from strong complementarities among components of a complex technological system (Yarime 2009). Specifically, three types of positive externalities contribute to path interdependecy: knowledge spillovers, economies of scale through demand for the same inputs and positive user externalities through technologies using the same infrastructure (Cowan and Hultén, 1996). In addition to government policy, several factors are identified which can help automobile fuel markets to escape the lock-in of existing technology, including a crisis in the existing technology, technological breakthroughs, changes in taste, tailoring a technology to a particular niche in the market and scientific measurements of relative merits of AFVs (Cowan and Hultén, 1996). Consumers tend to underestimate the true economic benefits of investing in NGVs and vehicle image and functionality have proven to affect consumers' decisions as well (Yeh, 2007).

Consumers view availability of stations as an obstacle if the number of CNG fuelling stations is less than 10%-20% of conventional stations. The challenge is attaining an optimum ratio of vehicles to refuelling stations. The vehicle-to-refuelling-station index (VRI) indicates the spatial density of network and profitability of stations; optimal from empirical research is 1 000 vehicles for each station (this is confirmed by Engerer and Horn, 2010). Development of VRI in the countries studied suggests that programmes must be sustained for long periods before adoption becomes self-sustainable: "[…]at the current stage, none of the countries examined here [which includes Argentina, Italy, Pakistan, India and United States] is likely to achieve self-sustaining NGV markets if favourable government policies are removed." (Yeh, 2007). Struben (2006) finds through modelling that underlying dynamics are much more complex than simple chicken-egg analogies suggest and explains why AFVs generally fail to exceed penetration levels of a few percent.

4.4 Local factors for NGV policy

When designing regional or national NGV policies or transport policies involving NGVs, it is important to take into account several factors that play a role at this level, including:

- the current state of the vehicle stock in terms of shares of fuels in mix, vehicle emissions and fuel economy;
- the presence of local air quality issues: where do they occur, which emissions are involved, how severe are the problems (now and on the longer term, taking into account future developments such as population growth, urbanisation, growth of transportation needs, etc.);
- the level of national greenhouse-gas reduction targets/ambitions and alternative strategies to accomplish these goals;
- the availability of natural gas through domestic production and/or imports;
- the level of grid development: overall length, but more importantly grid density, vicinity of densely populated areas and opportunities to create synergy with grid extension for other sectors;
- the availability of (OEM) vehicles and refuelling equipment: diversity of models available, the state of technology, domestically produced/import, costs;
- marketing, consumer preferences, public acceptance of CNG/LNG as a vehicle fuel;
- the institutional context: which stakeholders are involved, which interests do they have and how can an incentive structure be designed to align the interests;
- government finance: in what way can CNG be stimulated while not putting any/too much strain on government budget or even, how can CNG strategy help to solve government finance issues?

5. Case studies

Key messages:

- **Brazil's remarkable growth in NGVs during the past decade has recently slowed down due to competition from ethanol flexfuel vehicles and supply constraints, but recently the demand-supply situation has eased. A major potential source of growth of natural gas consumption in Brazilian transport, being heavy-duty transport, is very dependent on government policy. There are currently no strong signals that the lack thereof will be restored in the near future.**

- **India could become the world's largest NGV market, if it can manage the challenges of substantial investments for grid development, fuel price (de)regulation and enforcement of quality and safety regulations. Intercity buses and trucks have so far remained an unexploited potential. Another uncertainty at this point is the potential for India to replace natural gas by biogas or bio-SNG.**

- **Iran initiated an ambitious CNG programme to alleviate pressure on government budgets and cope with a shortage of refinery capacity in the face of (further) international sanctions by using a domestically available fuel. This set the country on a path of dramatic growth, which could increase further in the future if the HDV segment will be included in the programme.**

- **Driven by energy security, the government of Pakistan has stimulated the introduction and growth of CNG use in transportation by several policy measures. This has resulted in the largest NGV fleet in the world, over two million vehicles, consuming 2.5 bcm of natural gas per year.**

- **The United States currently has very few NGVs and infrastructure, but this may change as policy support is growing, prospects for gas supply have improved drastically over the past two years, vehicle availability is improving and the economics are attractive for fleet owners. A strategy aimed at HDV fleets would also mean that retail infrastructure costs can be kept relatively low while still covering wide areas.**

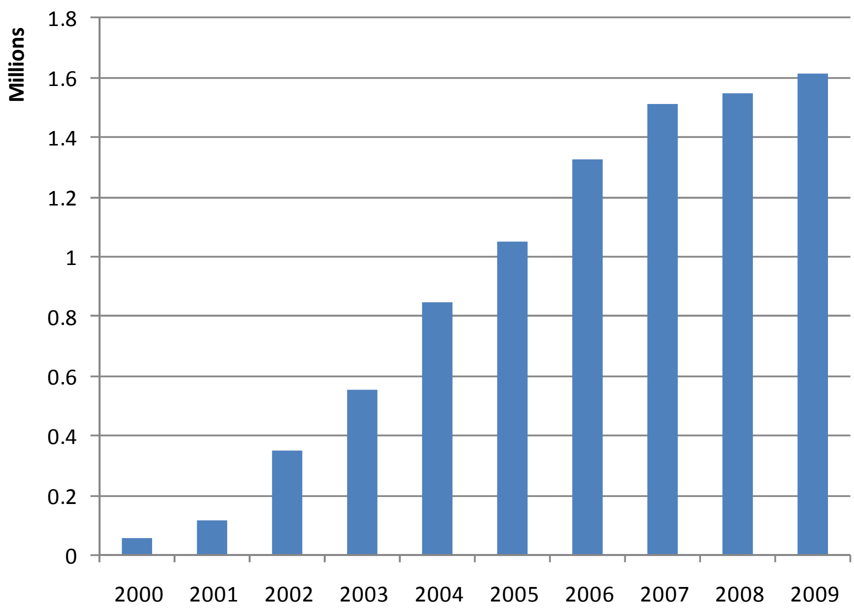
- **Europe would need strong policy support for NGVs to play a significant role in the transport fuel mix, but as the world's currently largest car market it certainly has potential. Depending on how future technological developments play out in relation to Europe's increasingly stringent norms, the benefit of lower pollutant emissions could drive NGV growth. However, the major impetus for growth is likely to be greenhouse-gas reduction by using biomethane, particularly in HDVs.**

This chapter provides a more in depth review of Brazil, India, Iran, Pakistan and the United States, focusing on the development of the NGV market and the policies driving the development, or lack thereof. Some recent developments in policy and market development in Europe will also be discussed.

5.1 Brazil

Brazil is Latin America's largest economy in terms of population, GDP and energy consumption. While the country's transport sector is mostly associated with its extensive use of sugarcane ethanol (blended with gasoline), the growth of natural gas use in transportation has been remarkable in the past decade. While the NGV programme started in 1991/92, the authorisation in 1996 to use natural gas in any vehicle really got the growth started that became particularly strong in the first half of the past decade, although it has slowed down in the past three years (Figures 13 and 14). As has been the case in other Latin American countries, the Brazilian NGV market was mostly created through aftermarket conversion of vehicles, in particular taxis and light commercial vehicles as these are able to recover costs quickly due to their high mileage. All vehicles are flexfuel, capable of running on either gasoline or ethanol combined with natural gas. NGVs represent almost 5% of total vehicle stock in Brazil, 4% of total road fuel consumption and 10% of natural gas demand.With just over 1.6 million NGVs, Brazil is at the fourth position worldwide and third in terms of refuelling stations.

Figure 13: Number of NGVs in Brazil

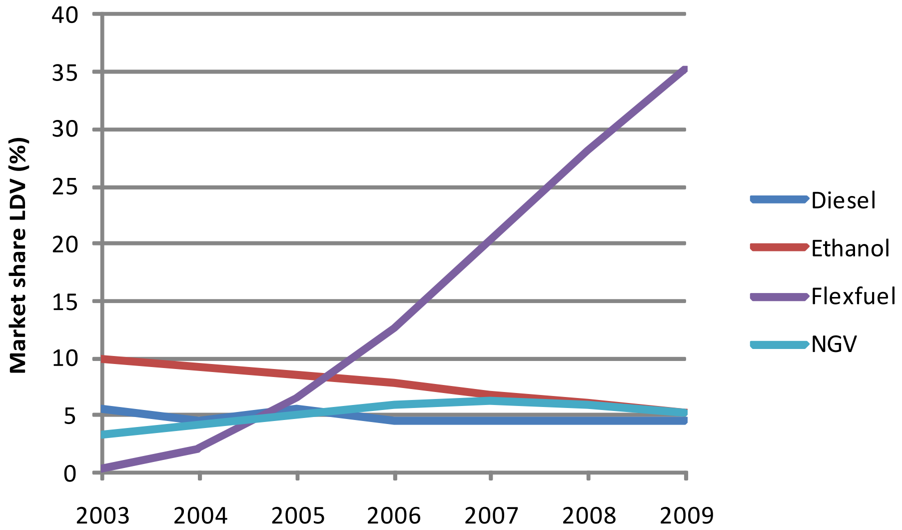


Source: NGV Communications Group.

There are currently virtually no MDVs or HDVs running on natural gas, although recently some efforts are starting to be directed at encouraging the use of natural gas for these modes of transport as well. The IGU (2009) and other sources cite a number of reasons for the lack of natural gas use in HDVs, including: high costs, lack of distribution infrastructure, taxes, diesel culture, bus operation concession contracts by municipalities, lack of government policy and incentives and questionable environmental standards. While there are a number of major OEM of HDVs in Brazil, the lack of demand for the reasons mentioned causes them not to produce HD-NGVs. The ethanol producers lobby is also said to play a role in keeping natural gas out of the HDV segment.

The 1 771 refuelling stations are public CNG stations integrated with liquid fuel stations (Table 7). There are virtually no private stations or LNG/LCNG stations in Brazil. These stations are all connected to the grid while an additional 50 stations are not grid-connected and are supplied by trucks (so called mother-daughter systems). On a national level there are on average 912 vehicles per refuelling station, which is a level that is considered to be economically sustainable for station operators and does not create large queues for vehicle owners (IGU, 2009). Most of the stations are located in the major cities, and as of May 2010, in total 295 cities have CNG refuelling stations (NGV Communications Group). The Blue Corridor initiative may in the future provide a stimulus to NGVs in Latin America. However, this 'gas highway' which would connect Argentina, Brazil, Chile and Uruguay, faces a number of challenges. A 2005 study concluded that based on the geography, existing infrastructure, current and future cargo and passenger transport, the potential integration benefits and estimated investments and costs, the project should be put on hold. There has not been any progress (reported) on this project since this study was completed.

Figure 14: Market share of alternatives to gasoline in Brazilian LDV market (26 million vehicles)



Note: Gasoline share declined from 81% in 2003 to 50% in 2009.
Source: Losekan and Vilela in Fernandes (2010).

The growth of NGVs in the past decade is largely due to Petrobras' policy to encourage the use of the suddenly abundant natural gas through low prices after the Gasbol pipeline started operations. The payback period for the conversion costs of on average USD 1 390 equal around eight months compared to ethanol. Besides the low prices, the Brazilian government also encouraged NGV conversion by providing loans to acquire conversion kits for taxis and by installing a lower tax on the ownership of NGVs (1% compared to 4%). The main drivers for government include reducing the costs of imported fuels, economical development and reducing emissions from transportation.

The case of Brazil also illustrates how promoting NGVs can go hand in hand with development of a gas grid. Local distribution companies encouraged NGVs in order to create gas demand, but also because it stimulated the development of the grid. In remote areas NGV demand can be met by using mother-daughter systems, supplied with LNG from Brazil's two regasification terminals (a third terminal is to come online 2013). This supply solution is commonly used to supply stations located at 150-200 km from the nearest pipeline.

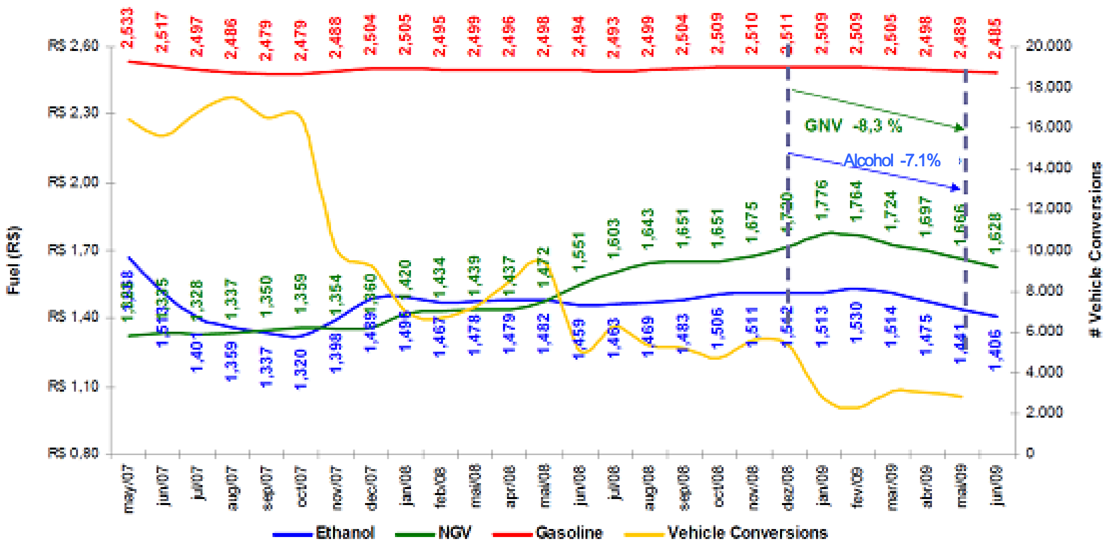
Table 7: Number of NGV stations in Brazil 2006-10

Year	NGV Stations
2006	1 320
2007	1 486
2008	1 633
2009	1 702
2010	1 771

Source: TNO, IEEP and LAT, 2006.

One reason for the recent slowdown of NGV growth in Brazil is increased competition from ethanol (Figure 15). Ethanol has become cheaper than CNG for transportation since mid-2008 and technology for flexfuel cars has developed; nowadays many different models exist that allow their owners to benefit from various different types of fuel that are available and show different pricing differentials at various points in time. Brazil currently has no biomethane projects underway.

Figure 15: Fuel prices and conversions to NGVs



Source: ANP/IBP.

Other reasons for the recent slowdown of NGV growth include the diversion of natural gas to power generation, since initially hydro capacity could not keep up with growing electricity demand and possibilities for increasing gas supplies were limited. Times have changed, though. Heavy rainfall in 2009 increased hydroelectric power generation, the crisis lowered demand and Brazil is now facing a 22 mcm/day oversupply.[16] Imports from Bolivia reached the minimum level of 24 mcm/d in late 2009 and Petrobras was not running its second LNG terminal near Rio de Janeiro. Gas demand is expected to recover in 2010 and set to grow in the next decade, but much will depend on Petrobras – virtually the only producer – structurally lowering its prices under long-term contracts, rather than occasionally offering gas in auctions.

Brazil relies on imports for about half its demand, most of which is sourced through the Gasbol pipeline from Bolivia, the largest gas exporter in Latin America. With these volumes unlikely to grow further in the future due to Bolivia's nationalisation of companies and policy of encouraging domestic consumption, Brazil will increase future LNG supplies to meet growing gas demand, particularly from power generation. Brazil's proven gas reserves amount to 365 bcm as of the end of 2009 and domestic gas production reached 14.3 bcm in 2008, which results in a R/P ratio of around 25 years.

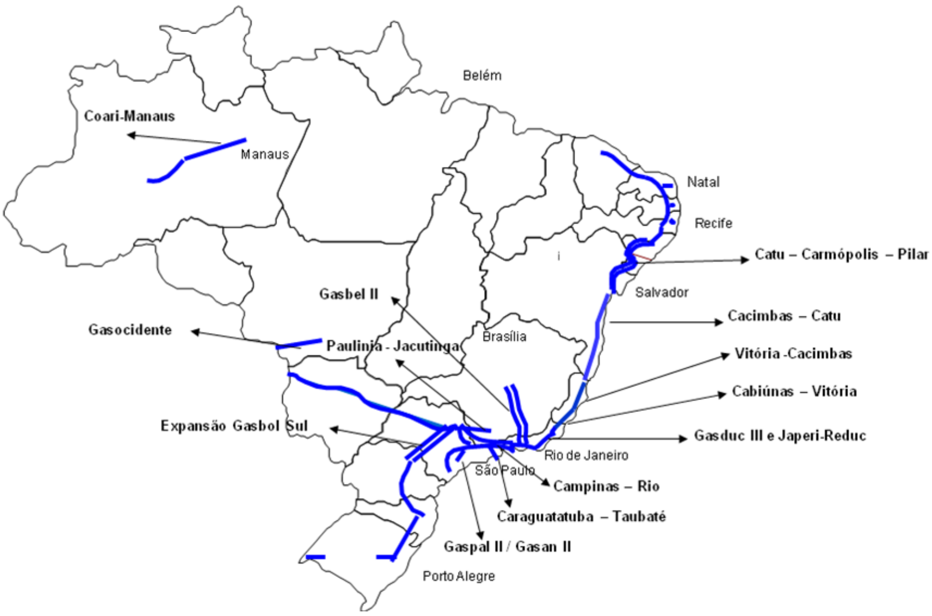
The institutional framework of the Brazilian energy sector is relatively well developed since the 1997 reforms that saw the adoption of the Petroleum Investment Law and ended the legal monopoly of Petrobras. The regulator ANP, established in 1998, enjoys a high level of autonomy (2006-2009 Triennium Work Report of the IGU's programme committee C on developing gas markets) in overseeing the value chain from E&P to distribution. Future challenges include further deregulation, reducing government involvement in the sector and the dominant position of semi-public Petrobras. Brazil has the ambition to further develop its natural gas resources, including subsalt deposits and reserves in the Amazone, and to become a gas exporter.

Brazil's gas network is relatively well developed along the coast and Southeastern areas, but much less so inland (Figure 16). The main transmission grid has a total length of 9 219 km. The distribution grid is over 18 000 km long, most of which is located in the states of São Paolo

[16] World Gas Intelligence, 31 March 2010.

(8 228 km) and Rio de Janeiro (4 934 km). The system is linked with the Bolivian and Argentinan gas grid; talks with Argentina and Venezuela to build a new pipeline have not yet led to investment decisions.

Figure 16: Gas infrastructure in Brazil



Source: ANP.

Recently CEG Rio reported that is is expecting the market to improve again in 2010 on the back of a price differential that favours gas consumption over ethanol. The company reports that in Rio de Janiero, the number of conversions to natural gas increased from 2 300 per month in the first half of 2009 to 5 400 in November 2009 and it is now engaging in a campagne aimed at convincing consumers of the financial benefits of converting their vehicles to run on natural gas (NGV Global News, 27 January 2010).

The case of Brazil is an interesting one, because it illustrates that although Latin America as a whole is well supplied and a net exporter of natural gas, improving cross-border interconnections and investment climates through institutional change and regional co-operation will be key for this region to become an integrated market. This would enhance transparency and the security of both supply and demand, which promotes the growth of NGVs as well. The recent slowdown of growth in the market share in the LDV segment may come to a halt if the supply situation improves, but much will depend on competition from flexfuel ethanol vehicles as well. A major potential source of growth of natural gas consumption in Brazilian transport, being heavy-duty transport, is very dependent on government policy. There are currently no strong signals that the lack thereof will be restored in the near future.

5.2 India

With many densely populated cities and ambitious plans to extend the transmissions and distribution network, India is regarded as a country with a big, possibly the biggest potential worldwide for the use of NGVs and indeed the country has seen very significant growth in recent years. India also faces a number of challenging reforms and developments that will shape the evolution of the Indian gas market as well as the NGV market. This case study reviews the

NGV market development, discusses the drivers of the CNG programme, the relation with gas market development, the state of technology and the role of stakeholders.

NGV market development: Past, present and future

When discussing NGV development in India, the Court rulings are commonly cited as the major driving force. Notwithstanding the unique and important role that the legal system played in development of NGV markets in India, this is only part of the story. Initially, the development in Mumbai was driven by public policy as well as a price differential between petrol and CNG that drove commercial interest from the owners of taxi fleets.

In Delhi, the public campaign to improve local air quality was the major driving force in the later 1990s, aided by the Supreme Court's decision in 1995 which installed and empowered a multi-stakeholder body. This body, the Environmental Pollution (Prevention and Control) Authority, assessed in 2001 that CNG, among others, could be regarded to be environmentally acceptable. This freed the way for CNG programmes as the Supreme Court had issued a directive aimed at the use of clean fuels, while only specifying the use of CNG for city buses.

During the past decade, CNG programmes were introduced in nearly 30 cities, in some cases ordered by the court, leading to a steady growth in the number of NGVs in India up to a current estimated number of 935 000 vehicles (NGV Global), including buses, three-wheelers, taxis and small commercial vehicles. In total all NGVs in India consume less than 2% of domestic natural gas demand. The 30 cities are mostly located in Maharashtra and Gujarat, in the (North-) West of the country, while Delhi and Mumbai are by far the leading cities (Table 8).

Table 8: Five cities in India with most developed NGV market

City	Number stations	CNG volume (mcm/y)	CNG price (USD/kg)	Number vehicles	Cars/taxis (%)	Autos (%)	LCVs (%)	Buses (%)
Delhi	171	507	0.42	290 000	61	32	2	4
Mumbai	136	402	0.49	191 000	29	68	1	1
Pune	7	0.7	0.62	600	8	79	0	14
Vadodara	3	11	0.53	3 900	16	80	0	4
Surat	25	55	0.61	80 000	46	51	0	1

Source: CSE, 2010.

Some individual state governments have taken supportive actions to stimulate growth of NGVs. While some of the success can certainly be attributed to these measures, unless harmonised, these efforts could lead to costs and revenues being spread unevenly between states (CSE, 2010). Delhi has taken several initiatives, including:

- lower interest on loans for the purchase of CNG three-wheelers and taxis;
- VAT subsidies to replace old diesel LCVs by CNG vehicles;
- full exemption of CNG for automotive use from sales tax;
- taxation of diesel fuel (USD 0.006/L) to fund clean transportation subsidies.

The development of public bus transport programmes in many cities in general and the National Urban Transport Policy in particular provide momentum for NGV development as the country is on the verge of making significant investments in the purchase of vehicles, which will mean that a long-term choice has to be made.

Drivers for NGV programmes

There are two main drivers for NGV programmes in India: improving local air quality and alleviating the pressure on the budgets of government and oil marketing companies for effectively subsidizing imported fuels, despite the subsidies in place on natural gas.

The share of diesel vehicles in new car sales has already increased from 4% in 2000 to 30% in 2010 and it is expected to increase further to 50% by 2012 (CSE, 2010). This leads to an increasing share of diesel vehicles that are certified according to emission standards equivalent to European standards about a decade ago, which has significant detrimental effects on local air quality in the many densely populated cities of India. Particularly emissions of PM and NO_x cause sever health problems, as is confirmed by several studies. Diesel fuel was found to have contributed up to 61% of total PM 2.5 ambient concentration in a 2004 study suported by the World Bank while another study found diesel engines to contribute 40 % to NO_x emissions from vehicles.

In the past five years, the government of India has been forced to come to the rescue of Oil Marketing Companies that incurred very substantial under-recoveries, amounting to over USD 25 billion in FY 2008-09 (IEA, 2010). While the APM[17] has been formally abolished for petroleum products in 2002, implicit subsidies remain in place by the government's policy to protect Indian customers by not allowing OMC to effectuate price increases that would reflect changes in global market prices.

Gas market development

The development of the natural gas market in India will be the topic of a forthcoming IEA working paper and regulation of downstream fuel prices in India has been discussed extensively in a recent IEA working paper. Therefore, the discussion here does not go into great detail, but focuses on recent developments and future challenges for increasing domestic production, expansion of T&D grids and price (de)regulation.

Reserves, production and domestic demand

India has 1 074 bcm of proved and indicated gas reserves as of 1 April 2009 and production has been almost flat around 30 bcm since 2002. Production is estimated to have reached 46 bcm[18] in 2009, though, which would partly reduce the gap between supply and potential demand. The expected doubling of production between 2008 and 2011 and increased regasifcation capacity are likely to set gas demand in India on a path to significant growth. IEA forecasts India as one of the fastest growing gas markets worldwide with an annual increase of 5.4% over 2007-2030, reaching 132 bcm by 2030 (*WEO 2009,* Reference Scenario).

Infrastructure

Expansion of city gas distribution networks is expected to cover around 150 to 200 cities by 2014 (CSE). GAIL's future plan titled "The road ahead" foresees very significant investments for the next 15 years regarding CNG programmes. A total number of 298 cities are seen as the potential target until 2014. An investement of around USD 8 billion could bring 27 bcm/y of CNG

[17] Administrative Pricing Mechanism, the pricing system under which the Government of India directly controls prices for petroleum products.

[18] Based on this number, the R/P ratio for natural gas in India equals 23 years.

to almost 15 million households and four million vehicles. For the period up to 2020, an additional USD 1.8 billion investment would bring 6 bcm/y to 117 cities that are located at max. 200 km from existinting or planned pipelines. Ultimately, by 2025, 69 cities that will not be in the near vicinity of a pipeline remain to be supplied with 4 bcm/y of CNG at an investment of roughly USD 1 billion. The Petroleum and Natural Gas Regulatory Board estimates that in the next five years, around USD 13 billion will be required for expansion of the natural gas grid and an additional USD 2.2 to USD 3.3 billion for city gas distribution networks. Whether the required investments will be obtained depends on the regulatory context.

In June 2009, the Ministry of Petroleum and Natural Gas published its "Vision 2015 — For Consumer Satisfaction and Beyond". The strategy laid out in this document includes the ambition to extend the CNG and pipeline distribution network across the country. The aim of this strategy is to increase the number of NGVs and access of households to natural gas, thereby reducing the dependency on LPG. At present, CNG is supplied to 35 cities and 860 000 households are supplied with natural gas from pipelines (PNG). The government has now decided to increase the supply of CNG and PNG multi-fold so that more than 200 cities could be covered by 2015.

The oil and gas industry plays an important role for growth of NGVs by developing gas infrastructure and markets. The most common form of organisation is where GAIL forms a joint-venture with public sector oil companies, which is often applied in programmes with CNG prices under the APM (CSE, 2010). Alternatively, private companies can source gas at free market prices and develop city gas distribution.

The downside of India's focus on three-wheelers and small LCVs is that the limited fuel up-take of these vehicles does not create large CNG demand, which may make it difficult to justify investments in city gas distribution. Providing about 500 mcm/y of CNG requires an investment of roughly USD 55 to USD 65 million. It is clear that CNG in itself creates insufficient demand, synergy with other sectors is essential. Synergy can be created by connecting industry, decentralised power and residential sectors to new grids as well. If no synergy can be created while there is significant demand for CNG in transportation then mother/daughter systems can be a more cost-effective option than a dedicated pipeline to supply regions with CNG.

Price (de)regulation

The state government does not differentiate between fuels for excise duties, but the unique pricing scheme of India with its administrative price mechanism (APM) and market-based gas prices does still favour NGVs to a certain extent. CNG programmes in cities such as Delhi and Mumbai benefit in the past from lower gas prices under the APM, but since the decision in May 2010, to raise prices under the APM, CNG prices have gone up considerably from USD 0.49 to USD 0.61/kg.[19] A few weeks later the rise of diesel and petrol fuel prices restored the price differential to petrol being 47% and diesel being 31% more expensive than CNG in Delhi.

Other regions, such as Gujarat, with more recent CNG programmes are less dependent on APM and to a certain degree exposed to free market prices. While price differentials with diesel are still sufficient to support CNG programmes, some argue that a tax policy should ensure that this is sustained, as taxing other fuels is likely to provide more long-term stability than direct subsidies (CSE, 2010).

[19] Note that the prices in table 6 date from before this increase.

Considering the increasingly important role that India is attributing to LNG in its natural gas supply, the effect of LNG prices on CNG prices is also an important factor for NGV programmes in the future. Attracting LNG will mean that India will have to compete on global gas markets. The Indian state government has in the past indicated that it will take measures to ensure the competitiveness of CNG in a deregulated scenario, but no clear details are known at this point while markets are slowly moving towards liberalisation.

Technology, quality and safety

Since NGVs are aimed at reducing local air pollution, it is important that heavily polluting vehicles are replaced with NGVs that perform substantially better, not only in the short term but over the whole lifetime of the vehicle. Several studies have shown that CNG programmes in Delhi have indeed contributed to a significant (24%) drop in PM levels compared to 1996 and had the most significant impact on air quality in this city (CSE, 2010). Studies also indicate that reduction of sulfur in diesel and petrol had had a siginificant impact and warned that an increase in usage of vehicles can offset the lower per kilometer emissions. While Euro II CNG buses, equiped with a three way catalytic convertor, emit more CO and HC than Euro II diesels do, they perform much better on PM and NO_x (Energy and Resources Institute, 2004 in CSE, 2010).

India has both retrofitted vehicles and OEM vehicles. Retrofitted vehicles are likely to be less fuel efficient than OEM vehicles (CSE, 2010). In particular, threewheelers and cars will tend to emit more CO_2 than counterparts running on gasoline or diesel (Table 9). India produces a large share of OEM vehicles domestically. The vehicle industry has had to respond quickly to the fuel substition strategy and did so for regulated types of vehicles (buses, three-wheelers, taxis and LCVs) more pro-actively than it did for cars, since there was no legal obligation to drive stable growth of this segment. As a result, the car market in India is dominated by aftermarket conversion as the car industry has only very recently begon to show interest in producing OEM cars on CNG due to the price differential creating a market pull effect. Large trucks on CNG (or LNG) are currently not very common in India, neither through aftermarket conversion nor from OEM.

Table 9: CO_2 emissions from vehicles in India

Vehicle	Engine displacement	Vintage	Gasoline two-stroke/four-stroke	Diesel	CNG OEM four-stroke/ retrofit two-stroke
Three-wheeler	< 200	post-2000	62/-	174*	78/58
Three-wheeler	< 200	post-2005	72/74	132*	n/a
Car	<1 000	1996-2000		129**	149
Car	<1 000	post-2000	126		144
Car	1 000-1 400	post-2000	127	156**	131

* diesel values for three-wheelers refer to engine displacement < 500 CC
** diesel values for cars refer to engine displacement < 1 600 CC
Source: ARAI in CSE, 2010.

Buses are an important part of the NGVs fleet in India, mainly as a result of government policy in conjunction with Supreme Court rulings. The CNG bus market is being served predominantly by two major Indian producers, while other players are entering the market as well. Innovation is important in this segment and producers find it hard to match growing demand. The policy of many Indian cities to increase public bus fleets is likely to drive a further increase in the number of CNG buses, which puts pressure on the industry to develop technologies to simultaneously address PM, NO_x and ozone emissions as well as fuel efficiency. While 11 cities are currently introducing Euro IV technology, Euro III remains the norm in most of India. Technology has to be optimised in terms of engine concept (stoichiometric or lean-burn) and aftertreatment of exhaust gases and choices of technology have to reflect the long lifetime of vehicles.

Technical problems have occurred in both aftermarket conversion of vehicles and OEM vehicles. Aftermarket conversion is generally the cheapest option; in 2002, conversion of a diesel bus to run on CNG cost about USD 9 000 while a new OEM bus would cost four times that amount. India has seen around 12 CNG bus fire accidents in 2001 and 2002 as a result of bad conversion practice and even now, enforcement of safety regulation remains an issue of paramount importance. In total about 2 800 buses have been converted in India and while regulations for authorisation and accreditation of conversion workshops is in place as well as periodic audits, implementation has not been sufficiently stringent. Quality or safety issues associated with OEM buses and three-wheelers have been identified and solved relatively easier, as most of these vehicles are produced by domestic companies. The Delhi Transport Corporation, owner of 4 500 CNG buses and in the process of acquiring another 5 000 CNG buses, has decided to buy only OEM vehicles.

The non-adulterable characteristic of CNG is an advantage in comparison to liquid fuels. Fuel adulteration refers to the (illegal) practice of blending different liquid fuels with other fuels or substances, usually with the aim to profit from financial incentives arising from different taxes that are imposed on different fuels. This practice, which is a common problem in India, can be detrimental to human health as well as engine performance, resulting in higher emissions.

The bus industry in India is taking its first steps towards some future technologies as well, including CNG/hybrid buses and H-CNG. A CNG-plug-in-hybrid bus prototype has been developed, which is claimed to reduce fuel consumption by 20%-30% compared to a conventional ICE. At this point no data on fuel economy, emissions, costs or introduction strategy is available. As for H-CNG, after five years of R&D a first H-CNG dispensing station has been commissioned at Dwarka in January 2010. Three-wheelers and cars can run on H-CNG but need to go undergo engine calibration to achieve the targeted emission. The 80/20 CNG/H_2 blend has been identified by the stakeholders involved as the optimal ratio in terms of costs, range and emissions. Two ministeries jointly funded the USD 1.1 million investment for the station. Costs of hydrogen production remain a bottleneck for larger-scale introduction. India aims to reach one million hydrogen vehicles by 2020 (mostly two- and three-wheelers) as well as 1 GW of power generation, which in total would require a USD 5.6 billion investment.

Outlook

India is clearly progressing in the implementation of CNG in the LDV and LCV segment as well as transit buses. The intercity buses and trucks have so far remained an unexploited potential though, while there are indications that these contribute heavily to pollution (CSE, 2010). This heavy-duty segment could be a very interesting market for CNG/LNG as well. Currently, CNG stations are concentrated in cities but perhaps a limited number of fuelling stations along major routes could help replace a large amount of diesel fuel by natural gas as these HDVs tend to travel by predictable routes and use large quantities of fuel. Also, one single fleetowner tends to own many vehicles which means that few stakeholders are involved. For this strategy to succeed it is important that OEM of HDVs are involved and produce dedicated NGVs, where on board fuel storage is optimised for transportation of cargo and engine performance.

Another uncertainty at this point is the potential for India to replace natural gas by biogas or bio-SNG. While the replacement of old diesel vehicles by more modern CNG technology will likely bring some benefits in greenhouse-gas reduction, a long-term contribution to reducing CO_2 emissions from India's transportation sector[20] would benefit greatly from either the direct or indirect (through certificates) use of biogas in vehicles. Agricultural residues as well as garbage and seage treatment are likely to provide feedstock for biogas production as the country struggles to meet food crop demand, meaning cropland is not likely to be allocated to biofuel feedstock. Current efforts related to biofuels are focused on liquid fuels, but bio-SNG could theoretically cover 27% of total transport fuel demand (IEA, 2010). However, to realise this potential more mature technology, government incentives and private investments are required. The question is also whether demand and supply of biogas will not be geographically remote from each other.

5.3 Iran

With 434 thousand barrels per day (kb/d) in 2009, Iran is among the world's main consumers of gasoline. Demand is stimulated by substantial government subsidies. While the country has the world's second largest oil reserves, it currently lacks the refinery capacity to meet its transport fuel demand and it imports about 50% of its gasoline and 10% of its diesel demand. International sanctions prevent technology transfer and funding,[21] required to increase refinery capacity, and cause International Oil Companies to curb gasoline exports to Iran. Attempts to tackle fuel subsidies – and ultimately lower demand – do appear to be moving forward with the intention to gradually phase these out until they are fully eliminated by 2015, but face fierce opposition in the Iranian society. This situation has led the government to ration gasoline and develop alternatives. In this context, a strategy aimed at natural gas vehicles can alleviate several problems simultaneously.

First, there is the tremendous cost to the Iranian government of subsidising current road fuels. The real cost of gasoline is around USD 0.52/L to USD 0.57/L and the retail price was USD 0.09/L to USD 0.14/L, which implies a subsidy of USD 0.38/L to USD 0.48/L. Although the price of natural gas was doubled in November 2009, subsidies ensure that the retail price of natural gas is equal to or less than half the gasoline price (IGU, 2009) or around USD 0.04/Lge (litre of gas equivalent). Assuming a market price of natural gas of USD 5/MBtu, this implies a subsidy of around USD 0.1/Lge, roughly one-quarter to one-fifth of the subsidy on gasoline. This leads to the conclusion that reduced fuel subsidies compensate for the government investments in developing the NGVs fleet and infrastructure. Naturally, an elimination of gasoline subsidies would create an economic incentive for CNG sales and vehicle conversions, which would mean that the government could cut back spending on conversion subsidies.

By the establishment of Iranian Fuel Conservation Organisation (IFCO, subsidiary of NIOC), the government aims to promote NGV market development (among others). In recent years, the number of NGVs and fuelling stations has expanded dramatically due to government supported conversion. As of May 2008, Iran had over 1.8 million NGVs of which 99% were cars or LDVs, 7 000 were buses and 80 were minibuses. So far the government has paid for 90% of the expenses incurred for converting petrol vehicle to NGVs for 1.5 million vehicles. At about USD 750 per vehicle, this brings the total government contribution to USD 1.125 billion. While this

[20] Although growth of the vehicle park can increase total transport CO_2 emissions.

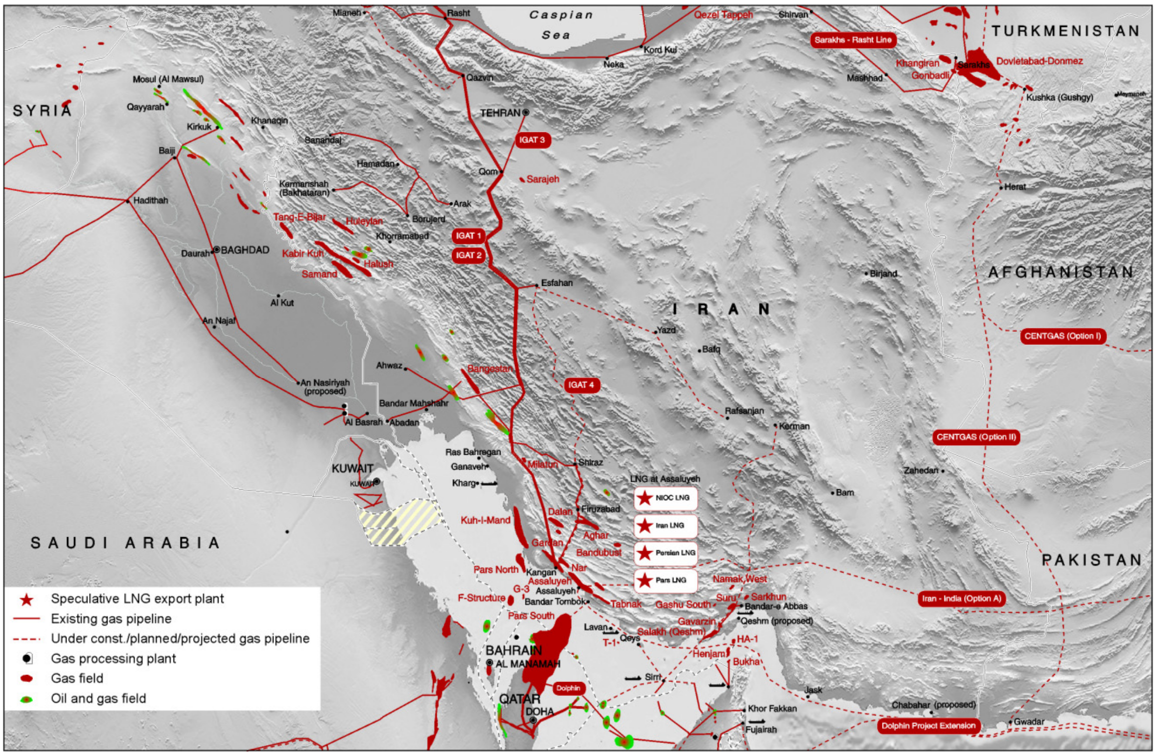
[21] In the calendar year ending 20 March 2010, Iran managed to attract only USD 8 billion of the required USD 35 billion in foreign investment into the O&G industry (IHS CERA).

represents a very significant investment indeed, it is important to note that the import bill of gasoline for the Iranian government is reported to have been USD 8 billion in its calender year ending 20 March 2010.

Second, gas is an abundant resource in Iran and despite delays in the country's efforts to increase gas production from the South Pars field, the current level of 630 mcm/d (IHS CERA) can certainly support current NGV demand of 2.3 bcm/y and even siginificant expansion of the NGVs fleet would pose no challenge for supply to match demand, although seasonality in gas supply and demand in Iran can cause sort-term gas shortages. The infrastructure for natural gas is sufficient for establishing NGV markets and the expectation is that future network expansions will ensure that this continues (Figure 17).

The rapid expansion of the grid is driven by the government's ambition to reduce dependency on oil, regional shortages of gas, and to promote industrialisation and employment (IHS Cera 2010). The network covers 560 cities and 3 226 villages. Currently there are 1260 CNG stations in operation in 611 cities (as of December 2009, NGV Communications Group). The large majority of these are public CNG or gasoline/CNG stations. Almost 800 more stations are under construction. Establishing a network of refueling stations was a multi-stakeholder effort. City councils were involved, ministries and military organizations provided land, National Iranian Oil Company provided budget, National Iranian Gas Company provided natural gas, the Ministry of Energy provided electricity, the Ministry of Industry was involved, OEM were involved to manufacture NGVs and IRISI was involved for issuing regulation and standards, etc.

Figure 17: Natural gas infrastructure in Iran



Source: IEA.

Third, an NGVs strategy can create employment opportunities and economic growth. IFCO promotes public awareness and acceptance of NGVS, the development of standards, creating production of parts for NGV markets (*e.g.* cylinders, compressors) and R&D on NGV technology.

Conversion centres and after-sales for OEM NGVS have been set-up and technical staff has been trained. In the medium to longer term the aim is to produce all OEM NGVs domestically (initially bi-fuel and eventually dedicated). Already, vehicle manufacturers are mandated to make NGVs 40% of their production portfolios (600 000 out of 1.5 million annually) and the government actively supports R&D of NGVs. For now, the Iranian OEM of vehicles are dedicated to supplying the domestic market, but in the future exports to Turkey and Pakistan may be an option.

The government will continue to support and subsidise the conversion to and the domestic production of NGVs. Iran has set a target to have 2.4 million NGVs on the road and 2 400 CNG stations by the end of the next Iranian year (20 March 2012) and 3.5 million NGVs by 2015, which demonstrates that what may have started as a technology to solve a short-term problem is now part of a longer-term strategy. If this goal is attained, one third of the total vehicle fleet would be powered by natural gas, replacing roughly 112 000 b/d of refined crude oil.

Finally, while it was not the main target, NGVs can contribute to a healthier living climate in densely populated cities as well. However, Iran has not set any emission limits for NGVs. It has adopted the Euro 3 norms per 21 March 2008 and will adopt the Euro 4 norms from 21 March 2012; these apply only to gasoline and diesel vehicles. NGVs are expected to be able to meet Euro 4 norms.

The Iranian government policy to encourage CNG use in transport is aimed at LDVs, while the available conventional fuels are directed towards HDVs. The plan to produce 6 000 OEM CNG buses in a five-year period does not seem to attract much government support. Having said this, all buses and most taxis in the 12 million people capital run on natural gas.[22] Since diesel costs only USD 0.02/L (IRR 160/L) [23], the economics do not currently encourage HDV owners to switch to natural gas.

In conclusion, while Iran's CNG programme is driven partially by factors that are unique to this country, namely the internationally isolated position and the threat of further sanctions due to its nuclear programme, it is certainly worth evaluating its drivers and strategy. Iran illustrates how an NGVs strategy can work at multiple levels, involving government finance, security of supply, gas market development, employment and environmental issues. It will be interesting to follow its future progress, particularly if natural gas use in the HDV segment were to be promoted.

5.4 Pakistan[24]

Pakistan's first introduction of CNG goes back to 1992 and with more than two million NGVs and over 3 000 CNG stations today[25] located in 50 cities (as of April 2008, NGV Communications Group), it is the world's leading country in terms of NGVs. CNG represents a growing part of Pakistani gas consumption (Figure 18) as the number of vehicles more than doubled in just three or four years. An overall investment in NGV market development of approximately USD 1 billion has been made, half of which in the last two fiscal years, and the government intends to continue its growth path to reduce pollution from transportation and reduce pressure on its depleting reserves of foreign currency. These reserves are under pressure due to (among other reasons) the steep drop in the exchange rate of the Pakistani rupee as well as the

[22] Energy Tribune, "Pushing the Gas Pedal: Tehran Makes NGVs Top Priority", 13 March 2009: www.energytribune.com/articles.cfm?aid=1434).

[23] IRR = Iranian rials.

[24] This section draws heavily on Pakistan's country report to the 2010 IANGV conference in Rome.

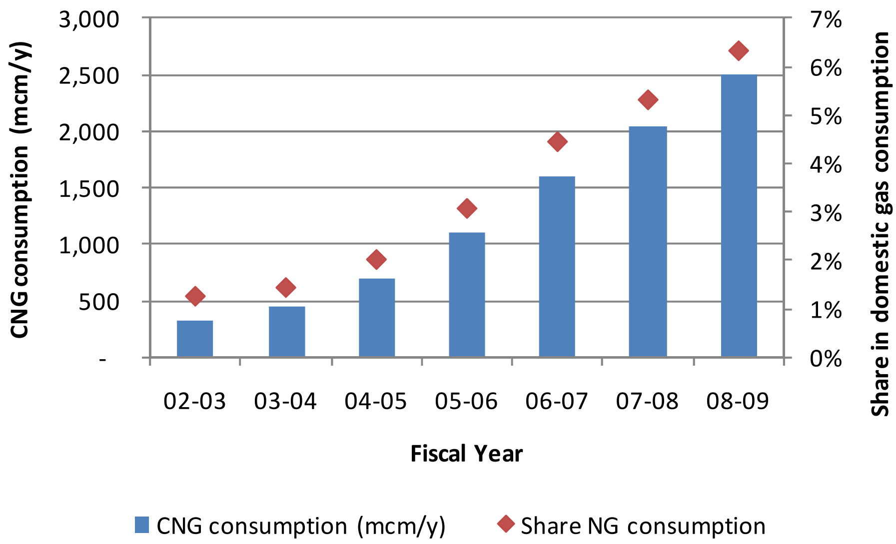
[25] About 74% of these are on independent sites.

government's policy to protect the domestic market from sharply rising global oil prices. As in many non-OECD countries, prices of oil, gas and power are regulated and subsidized in Pakistan.

The Pakistani government has stimulated introduction and growth of CNG use in transportation by (partially or completely) exempting CNG equipment from duties, specifically promoting the use of CNG in rickshaws and buses, subsidizing the testing of cylinders, encouraging training programmes and setting a specific tariff for CNG to create a price differential. NGVs are predominantly bi-fuel OEM vehicles, produced in Pakistan by (subsidiairies of) OEM such as Suzuki, Toyota and Santro. The job creation involved is also seen as one of the benefits of this programme. Fuel stations are owned by private companies.

Energy security is a major driver for the government. Pakistan has substantial gas reserves, estimated at 852 bcm as of the end of 2008 (Cedigaz). With natural gas production reaching 38.6 bcm (IEA) in 2009, the R/P ratio is 22 years. A significant share of gas is consumed in gas-fired power generation (11.7 bcm in 2007, IEA). Since Pakistan currently has no cross-border pipelines or regasification terminals it has no options to import or export gas. Plans to build LNG regasification terminals have all been delayed or put on hold due to financing or other issues. It is also difficult to see how Pakistan would be able to attract LNG supplies at prices that are not much higher than the average price that the government sets for the domestic market. Pakistan did succeed in securing a natural gas sales and purchase agreement with Iran recently, which will bring almost 8 bcm/y of gas into the country from 2014 through a pipeline that is to be constructed. Earlier plans of India being part of this agreement have been cancelled, so this gas will be destined for the Pakistani market and be partly used to satisfy growing power demand.

Figure 18: CNG consumption in Pakistan



Note: Share in gas consumption has been calculated on the basis of calender year data.
Source: Country report Pakistan (2010 IANGV Conference), IEA.

The transmission grid in Pakistan has a total length of 8 502 km transmission. The distribution grid is 62 625 km, which is similar to the networks in Belgium or Spain, while Pakistan is singificantly bigger and more than half as densely populated as Belgium. The Oil and Gas Regulatory Authority (OGRA) is the responsible body for licensing of stations and equipment and regular safety inspections. Currently there are biomethane projects in Pakistan, but these are primarily for power generation rather than for vehicle fuel.

5.5 United States

The United States is an interesting market to evaluate in terms of NGVs, not only because of the potential that the huge volumes of fuel consumed in the transportation sector offer, but also because a policy may be adopted in the near future that would help the existing market-driven efforts gain force. It is also an interesting case, because the approach is mostly fleet-driven, focusing on making HDVs run on natural gas. This is illustrated by the average fuel consumption in the United States of roughly 10 000 m^3 per vehicle (1 bcm and 100 000 vehicles), which is very high compared to the world average of roughly 2 000 m^3. It is also worth noting that LNG accounts for 20% in terms of fuel volumes of the US NGV market as LNG is used to drive HDVs. Having said this, 87% of all NGVs in the United States are cars and LCVs and only 4 000 vehicles run on LNG.

It has often been noted that NGVs are riding the proverbial shale wave and it is indeed likely that the impressive growth and persistance of gas production from shale plays has contributed to the perception of gas as a domestic fuel that can help the United States in its difficult challenge to reduce dependency on foreign oil. Whether it can and will actually achieve this is a question worth looking into a bit more.

As in any market, if natural gas for transportation is to become a success in the United States, economics have to be sound for both vehicle owners and fuelling station builders/operators. This means that either aftermarket conversion or OEM models have to be available, the conversion costs or price premium on OEM NGVs must either be limited or subsidised, a good fuel price differential needs to be in place and a good strategy for a refuelling station network based on commitments from fleet owners is required. These factors will now be evaluated more closely.

For cars, the availability of OEM vehicles running on natural gas is extremely limited in the United States. While the 1990s saw some cars coming to the market, they disappeared again and so far, the Honda GX is the only OEM car currently available that runs on natural gas. Other car manufacturers, such as Mercedes, are considering to bring their European models to the US market though and US car manufacturers are now also considering coming back into the market.[26] Converting vehicles after leaving the factory with certified systems is an option that is available for a range of cars, pickups and vans as well. Although the costs are substantial, in the range of USD 12 000 to USD 18 000, these are offset by federal income tax credits and the quality is assured nowadays as the systems are tested to comply with the same emissions performance requirements as OEM vehicles (NGV America, 2010).

For commercial vehicles and HDVs, it's a different story as the availability is certainly improving. A wide variety of models is now available and trucks can reach a range up to 600 miles on LNG. LCVs and truck owners are demanding customers. Their vehicles are required to run cheaply, reliably and efficiently to make money in a business that is characterised by small margins. This means that factors such as vehicle range, reliability and maintenance, refuelling time and convenience are important. In this regard it is telling that out of 1 900 AFVs in the fleet of UPS, one of the largest fleet owners in the United States, CNG accounts for 1 100 vehicles. Heavy-duty natural gas vehicles are seen in many different applications in the United States, including specialised vehicles in marine ports and airports, school buses, waste collection, transit buses and long-haul trucks. Non-road applications including railroad and cold-ironing of ships in ports may also be promising applications, but fall outside the scope of this working paper.

[26] GM recently announced the marketing of CNG powered vans in the US: www.ngvglobal.com/cng-powered-gmc-and-chevrolet-cargo-vans-ready-for-late-2010-0518.

Table 10: Typical economics of a L-NGV truck in the absence of tax credits and subsidies

Natural Gas price (USD/MBtu)	**5.00**
LNG costs (USD/gallon diesel equivalent)	2.03
Diesel fuel consumption (gallons/y)	20 000
Diesel price (USD/g)	3.00
Fuel costs savings (USD/y)	19 384
Incremental costs LNG truck (USD)	40 000
Pay Back Period (y)	2
Savings over seven-year lifetime	95 688

Source: Neandross (2009).

Incremental costs and savings for an NGV truck vary, but Table 10 summarises some typical data as reported by the industry. This illustrates that even in the absence of subsidies in the form of grants, tax credits etc., the fuel price differential is sufficient to make the economics of NGVs interesting for fleetowners, notwistanding the fact that some fleetowners will require a pay back period shorter than the two years mentioned in this example. Figure 19 illustrates the historic price differential (nationwide average) of various alternative fuels compared to gasoline and diesel.

Figure 19: Price of natural gas compared to other road fuels in the United States

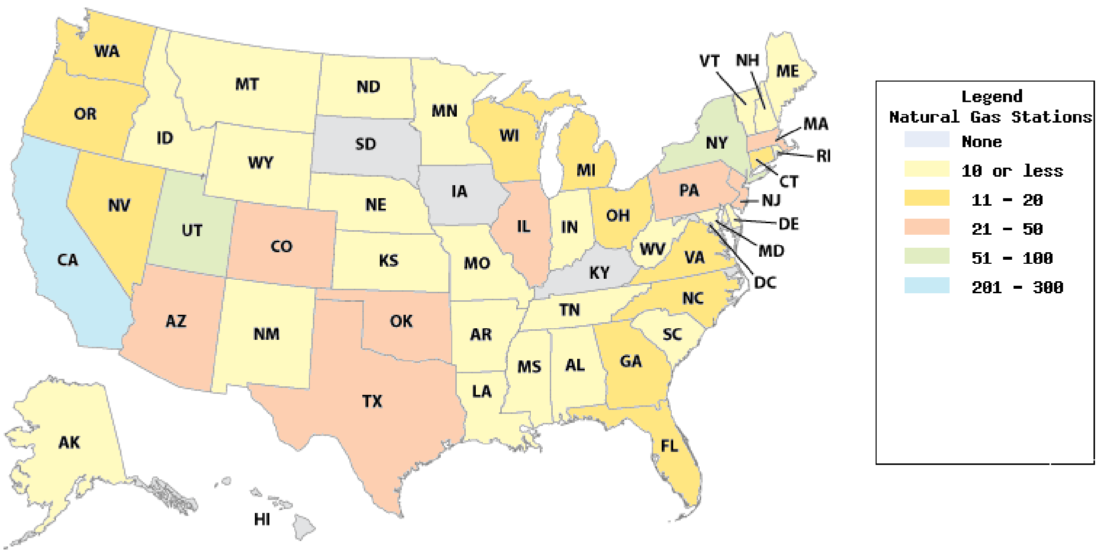
Source: DOE Clean Cities Alternative Fuel Price Report, April 2010.

Even though economics look already quite attractive for vehicle/fleetowners, legislation may be on its way that would provide substantial incentives for the use of natural gas in transportation to both vehicle owners and infrastructure builders, the so-called NAT GAS Act 2009 (New Alternative Transportation to Give Americans Solutions). If adopted, the NAT GAS Act would amongst others extend for 10 to 15 years the existing USD 0.50/GGE tax credit for CNG/LNG when used in vehicles as well as the income tax credits for the purchase of an NGV. Furthermore, several tax benefits would be provided to encourage infrastructure investments. While the IEA does not currently have the data to assess to which degree infrastructure investments require subsidisation, it seems that the vehicle/fuel side of the market may be oversubsidised if the NAT GAS Act were to be implemented in the sense that part of the subsidies will be used to finance investments that are the result of sound business cases already.

Besides the economics for fleetowners, other factors are seen as important too, such as having champions: major companies in a certain industry who take the lead will cause others to follow. Some believe that reputation may be even more important than subsidies, although sound economics do remain a *conditio sine qua non*. In this respect, the role of US gas industry is also worth noting. While the industry supported NGVs up to the liberalisation of markets in the 1990s, it retreated soon after that. However, the rise of shale gas combined with the increased availability of LNG means that gas producers find themselves more and more looking for demand in an oversupplied market. So obviously, any new market presenting itself can certainly count on a healthy interest from gas producers, who can certainly help to drive NGV market development by either investing directly or actively support lobbying or PR/marketing campaigns. This development is illustrated by EnCana's Natural Gas Vehicles Drive Project, which aim is "converting several fleet vehicles to natural gas, purchasing natural gas-powered Honda Civic GX vehicles for employee use and embarking on a consumer- and industry-focused education campaign about natural gas as a transportation fuel".[27] The importance of reputation (heavily influenced by knowledge or the lack thereof) goes beyond the fleetowners as LNG production sites have also suffered from NIMBY effects.

As has been mentioned before, the industry is mainly targeting large fleetowners. To illustrate the type of projects that the United States is currently seeing: large transportation company JB Hunt secured USD 19 million in state and federal funding for 262 LNG trucks and two refuelling stations and logistics company Cal Cartage received USD 12 million in funding for 132 LNG trucks (currently they have 400 LNG trucks) plus USD 1 million for two LNG fuel stations.

Figure 20: Natural gas stations by State (as of 2010)



Source: DOE, AFDC.

Refuelling networks are emerging slowly but steadily (Figure 20). Station builder Clean Energy recently reported that it currently builds one station per week (NGW, 5 April 2010). In terms of LNG infrastructure there are 60 fuel stations, eight production plants plus landfill LNG sites. The "stationary" characteristic of the LNG market is illustrated by the fact that 54% of the market represents transit buses, 30% refuse vehicles, 12% port applications and only 4% is on road use,

[27] http://coloradoenergynews.com/2009/07/natural-gas-vehicle-program-unveiled-by-encana

although the industry expects the latter to grow substantially in the next five years as it target the fleet of, in total, three million trucks in the United States.

California has a high concentration of LNG and CNG stations, with many in and around Los Angeles. In Los Angeles, refuse trucks were used to solve the chicken and egg dilemma and other vehicles followed six to seven years later. Now, 350 out of 750 trucks run on LNG. To illustrate the costs involved, an LNG project for the city of San Bernardino (CA) received USD 1.7 million in grants, of which USD 1.23 million was used for the station and USD 492 000 was used to purchase 20 trucks (Neandross 2009). Another city, Barstow, received USD 2.8 million in federal, state and local funding for a public access LNG station and a backup CNG tube trailer (which covered all costs).

The Interstate Clean Transportation Corridor covers the greater Los Angelos region and makes it possible to drive a L-NGV anywhere in the state (Figure 21). This project started in 1996 as a multi-stakeholder approach with involvement of Gladstein, Neandross & Associates as LNG consultant, UPS as a fleetowner and the government at a federal, state and local level. It involves two landfill LNG sites, but it does rely on subsidies as it could not otherwise compete with pipeline gas. So far, it has received USD 28.9 million from the government to develop 23 refuelling stations and deploy 505 HDVs and 160 LDVs on natural gas and LPG, replacing 26 million litres of diesel annually.[28]

Figure 21: Interstate Clean Transportation Corridor, California

Source: Neandross (2009).

Since EPA's decision that greenhouse gases contribute to air pollution and as such pose a danger to public health, it has been engaged in various efforts to reduce greenhouse-gas emissions. Among these efforts is a joint EPA/DoT proposal to gradually improve the average fuel economy of cars by 2016 to 35.5 miles per gallon (MPG), or a 42% improvement compared to the current average of 25 MPG. This is estimated to raise prices of cars by an average USD 1 300 by 2016, although the savings over the lifetime of a vehicle would amount to USD 2 800. The consequence of this would be that for LDVs, the impetus for NGVs growth would be (further) diminshed as potential fuel cost savings decline. While there certainly is

[28] http://ictc.gladstein.org.

opposition to EPA's mission to develop mechanisms to reduce greenhouse-gas emissions in general and a lawsuit has been raised against this specific regulation, the Alliance of Automobile Manufacturers has supported the policy since the White House announced it early 2010.

5.6 Europe

Potentially, NGVs could be one of the few growth markets for natural gas in Europe. Residential demand is expected to decline as thermal efficiency increases in many countries, population is set to decline in the future and the stock of houses is not strongly increasing. Industrial activity will show limited growth as GDP increases and the average energy intensity of GDP is slowly declining. Power production is a major source of uncertainty: while gas is likely to be the default fuel for new power generation projects other than renewables, its average load factor in this sector will be lower when it fulfills a back-up function.

Europe is unlikely to see a bottom-up approach in NGV market development, in the sense that a market pull from consumers and fleet owners will create a market for NGVs and refuelling stations. Besides the chicken and egg dilemma and the fact that NGV technology is not very well-known with the general public, one of the reasons for this is the high market share of diesel, also in the LDV segment. Diesel vehicles provide good economics for their owners, which are hard to beat. What this means is that NGV market development will have to be policy driven. However, strong policies aimed at the use of natural gas vehicles are not present at a European level and also lacking on a national level in most European countries. The question is then to what extent NGVs can provide benefits that would be able to drive NGV programmes.

Considering that the greenhouse-gas benefits for LDVs of natural gas compared to diesel engines are in principle either non-existent or limited, this does not provide a strong driver for policies aimed at growth of NGVs. For HDVs things look different as 5% of European CO_2 emissions are caused by trucks,[29] for which dual-fuel technology and/or biomethane may be very good options in a greenhouse-gas reduction strategy. At the moment, the EC has only just started to plan the introduction of CO_2 limits on HDVs and this is likely to take a lot of time to implement.[29] Gasoline vehicles on the European road on average have a higher fuel economy than they do in the United States, which also takes away some of the potential benefits of NGVs compared to this country. As discussed in the section on greenhouse-gas emissions, the ACEA agreement forces the European car industry to reduce the weighted average of the CO_2 emissions of their car sales, which could provide a stimulus for them to actively promote the sales of NGV models since this would allow them to sell more of the more profitable models that tend to have higher CO_2 emissions. How this plays out exactly will depend on the strategy of car makers, who could also decide to put more effort into developing and selling more efficient gasoline or diesel vehicles, rather than investing in AFV technologies.

What remains as potential drivers are benefits of NGVs in terms of reduced local pollutants, reduced noise and a transition to biofuels or hydrogen. As discussed in the section on local pollutants emissions, NGVs at this point have some benefits over gasoline and diesel vehicles. The main uncertainty that faces policy makers is to what extent these benefits will be sustained within the next five to ten years as increasingly stringent emission norms drive car manufacturers to produce cleaner gasoline and diesel engines or develop powertrain options for exhaust gas treatment. It has often been commented that at some point for conventional fuels (particularly diesel) a trade-off will emerge between lower pollutant emissions and lower greenhouse-gas emissions, as adding more powertrain options to treat exhaust gases will add

[29] Het Financieele Dagblad 29 April 2010, "Brussel legt trucks CO_2-regels op".

mass to the vehicle and create counterpressure to the engine, both of which are detrimental to the fuel economy. This would be advantageous for NGVs which in principle require no aftertreatment of exhaust gases and benefit from many of the efficiency improvement options available to gasoline and diesel vehicles as well.

At this point the IEA has insufficient information to judge whether NGVs will be able to sustain their benefits in terms of emissions as much of the information on cutting-edge technology is still in a proprietary stage. Also, only policy makers can decide at what point the acceptable level of pollutant emissions is reached. This is really the start of the discussion: which emissions should be regulated and what is the maximum acceptable level. This decision should reflect a trade-off between which technology is available at a reasonable cost and which implications for public health are acceptable in densely populated areas. It should then be left to the market (car manufacturers and their customers) to decide the fuel of choice to meet these targets, although policy initiatives may be necessary to ensure that options are available.

In principle, direct subsidies on vehicles or fuel would distort the market and lead to inefficient allocations although it should be noted that infrastructure investments for any AFVs may need subsidisation to overcome the advantage that the incumbent fuels have in terms of existing infrastructure. This government support can be of temporary nature, though, and not necessarily take the form of subsidies. Guarantees for loans can provide a solution in case of sound economics but financing difficulties in a tight credit market. Governments can provide a guaranteed off-take of fuel by purchasing NGVs or converting vehicles for their own fleets. Granting privileges to clean vehicles in cities, for example parking spaces or lanes on highways can also stimulate demand at no costs. For noise, the same principle applies: if governments wish to set noise limits from traffic in densely populated areas, it can consequently be left to the market to decide which technology is best equiped to meet these limits. Governments do need to ensure that regulation is designed to provide potential candidates access to the market. For example, in many European countries the simultaneous use of two fuels, such as in a dual-fuel engine, is not yet allowed.

Looking at two key countries, Italy and Sweden, the share of CNG vehicles in new car sales over 2009 and the first four months of 2010 has been quite limited. Sweden saw some relatively good sales numbers, which some contribute to a demonstration of biogas use in a racing car but could also be due to the introduction of the first turbo-charged CNG sedan in Europe at the beginning of 2009, leading to a market share just under 3% on average. Italy had an average market share of CNG in new car sales of 5.6%[30] although this fell sharply after the first quarter of 2010 as incentives were not continued. Some fear that overall demand could drop by over 30% and state that government stimulation is required to increase the current network of roughly 750 stations (NGVA Europe in Gas Vehicles Report, June 2010).

[30] As a result of government incentives, NGV accounted for 6.9% of new car registrations over the first half year of 2009, of which 6.2% were OEM vehicles and 0.7% retrofit: www.ngvaeurope.eu/average-monthly-ngv-passenger-car-registrations-in-italy-now-14200-vehicles-or-almost-7-of-the-total-market.

6. Sustainable pathways for NGVs

Key messages:

- **NGV programmes are currently seldom based on the goal to reduce greenhouse gas, which is not to say that there are no potential benefits in this respect. Taking a long term perspective is essential when assessing the role of NGVs in a regional or national low-carbon strategy, as is a careful consideration of the types of vehicles that will be targeted with certain policy instruments.**
- **While the technology for bio-synthetic gas is not fully developed yet, this could provide significant quantities of a low-carbon fuel in the longer term at low or even negative greenhouse-gas abatement costs. While biogas can also be used for other purposes, it is one of the few cost-effective alternatives to significantly reduce greenhouse-gas emissions from especially heavy-duty transport.**
- **Europe, most notably Sweden and Germany, is currently seeing an increasing number of projects aimed specifically at the production of biogas, its upgrading to biomethane and use in vehicles, either directly by supplying fuel stations or indirectly by allocating the gas through certificates.**
- **In principle, NGVs can also provide a pathway to hydrogen but more research is required to assess how and to which degree this can be accomplished.**

While it is not a very common driver for NGV programmes, the introduction of NGVs can certainly be part of a greenhouse-gas reduction strategy. The different options to reduce greenhouse-gas emissions from transport need careful consideration, though. The relative merits of NGVs need to be compared with other options in terms of their total greenhouse-gas reduction potential, the marginal abatement costs as well as non-greenhouse-gas related aspects of various fuels. It is extremely important to take a long term perspective when assessing the role of NGVs in a regional or national low-carbon strategy as technological developments can over time change the relative merits of AFVs significantly and locking-in a certain technology creates barriers for the succeeding technology.

This said, at this point replacing light-duty gasoline vehicles by NGVs generally results in a 25% savings of CO_2-eq/km on a WTW basis. Replacing light-duty diesel vehicles by NGVs will in most cases not result in a reduction of greenhouse-gas emissions. Replacing heavy-duty diesel vehicles by NGVs can be a very interesting option, but is very dependent on the exact type of vehicle, the technologies (engine type, powertrain, exhaust gas treatment etc) that are compared as well as the actual real-world use of the vehicle. In general, the greenhouse-gas reductions resulting from the replacement of a heavy-duty diesel vehicle by a HD-NGV are likely to be present, but not very substantial. This means that programmes that aim to reduce greenhouse-gas emissions from buses and trucks by replacing diesel with natural gas should consider ways to maximize the greenhouse-gas reduction, such as using dual-fuel vehicles and/or the physical or virtual[31] use of biogas.

[31] Virtual refers to the usage of certificates.

6.1 Potential for biogas use in transport

Organic alternatives for fossil natural gas (sometimes referred to as "green gas") can be produced in two ways. Currently, most large-scale production sites (such as sewage treatment plants and landfill sites) use anaerobic digestion of biomass to produce biogas. In the long run, the potential volumes that can be produced with this technology are rather limited due to the specific feedstock that is required. Bio-synthetic natural gas (SNG) can be produced from a wide range of biomass feedstock by a process involving thermo-chemical conversion (gasification) and cleaning/methanation (removing sulphur compounds, halogenated compounds, siloxanes, ammonia, dust and particles). The technology for bio SNG is not fully developed yet. According to the German DFBZ, the R&D required includes demonstration of the overall chain, plant availability and reliability, use of approved system components and cost reduction.[32] Also, measuring the quality and quantity of biogas produced are challenging aspects of the process as they can be quite costly.

For both anaerobic digestion and gasification, the resulting gas is usually upgraded to bring it up to standards for grid injection or use in vehicles. This involves removing CO_2, which is one of the more costly parts of the process but also provides a valuable by-product. Typically, propane or LPG is added to biogas increase the caloric value; in Sweden around 7% - 9% vol. is added.[33] Overall, the typical investment for a treatment plant with a 300 Nm^3/h of raw gas capacity, the investment is in the order of magnitude of USD 1 350 000 (EUR 1 million) and the operating costs for a 200 Nm^3/h plant are in the order of USD 2.0 ct/kWh (1.5 €ct/kWh) (IEA 2006). There are various upgrading technologies: Pressure Swing Adsorption (PSA), water scrubbers and chemical/physical scrubbers. The energy consumption of different technologies ranges from 0.25 kWh/Nm^3 for PSA and water scrubbers to 0.6 kWh/Nm^3 for chemical scrubbers. Which technology is most recommended depends on the situation and in particular on the availability of water. Combining CAPEX and OPEX, costs range from USD 1.6 ct/kWh (EUR 1.2 ct/kWh) to USD 3.2 ct/kWh (EUR 2.4 ct/kWh) of biomethane for various capacities and upgrading technologies. There are significant economies of scale in upgrading.

Biomethane is a term commonly used to describe gas that has been upgraded to around 97% methane. Although upgrading is not always strictly necessary, it does reduce problems due to the variety of gas composition and it increases the energy content (and thus vehicle range). A vehicle running on biomethane has a range that is typically 15% higher than it is on fossil natural gas,[34] liquefaction (LBG) results in a tripling of the vehicle's range.

While the NGV industry is working on biogas projects, it generally does not see this as the fuel that will enable it to reach its targets, since the volumes will remain limited for some time to come. The prospect of creating a pathway to a carbon neutral or even carbon negative solution (if methane emissions are avoided) is a powerful one, though, which can help the industry convince policy makers to support NGV strategies. In IEA's view, it is important that efforts are combined. This section will show that bio-SNG has the potential to significantly reduce greenhouse-gas emissions at greenhouse-gas abatement costs that are lower than those for fossil natural gas. Also, it will show that bio SNG production could (in theory) cover full NGV demand. Therefore, on a horizon of one or two decades, the aim for NGVs strategies should be to maximise the share of biogas in transportation.

[32] DFBZ presentation "Biomethane as fuel", Berlin 1 October 2009: www.fnr-server.de/cms35/fileadmin/allgemein/images/veranstaltungen/biofuelconference/S3_3_Mueller-Langer.pdf.

[33] How much needs to be added depends on the common gas quality in the country.

[34] Due to the higher methane content, not to the organic source.

There are basically two ways to connect NGVs to biogas. The direct link would be to transport locally/regionally produced biogas directly to a refuelling station for NGVs, with no link to the network (other than for demand/supply balancing). The indirect link means that biogas injection into the grid and utilisation of natural gas in vehicles are not physically connected, but only administratively linked through the issuance and purchase of certificates. In the latter case, one could ask why it should be the responsibility of the NGV sector to ensure that gas production is sustainable. Usually, the demand side is not very much concerned or involved with upstream matters and in most countries, NGVs will have the lowest share in domestic gas consumption. However, if an NGV strategy is founded on the aim of reducing greenhouse-gas emissions, then this does imply a responsibility to make sure that greenhouse-gas reductions are indeed attained and maximised. As in most cases a direct, physical link between biogas production and its consumption in a vehicle is difficult and unnecessary, green certificates provide an efficient and practical way of making vehicles carbon neutral through the use of CNG/LNG.

Although biogas production is unlikely to exceed total gas demand in most (if not all) countries and other gas consuming sectors could naturally also buy these certificates, other sectors are likely to have more alternatives to reach the same goal. So in essence, there is a trade-off between low or zero carbon technologies for transport (such as EV and hydrogen) versus low or zero carbon technologies for other gas consuming sectors, such as the residential, industrial and power sector. Improving efficiency remains paramount though in all energy consuming sectors and will in many cases also be the cheapest option in terms of greenhouse-gas abatement costs, and in many cases it can provide net savings.

Vehicles add another potential application of gas that can be useful in some circumstances, but biogas, bio-SNG and biomethane can be injected into the grid and need not necessarily end up being used in vehicles. The CO_2 saving from a 100 m^3/h biogas plant is dependent on the utilisation of residual heat (based on the situation in the United Kingdom) (Table 11). If biogas is produced in a remote location where there is no baseload demand for the residual heat and a gas grid is nearby it is preferable to inject the biogas into the grid. In principle, using this gas for the production of electricity yields a higher saving than the end use in transportation does as the maximum (indeed even the average) efficiency of a gas-fired power plant is much higher than that of an internal combustion engine (although the CO_2 savings obviously depend on the existing power mix). But as mentioned before, under many circumstances there are more alternatives for decarbonising power production that there are for decarbonising transport (particularly HDVs).

Table 11: CO_2 savings from different uses of 100 m^3/h biogas production

Option	CO_2 savings (t/y)
On site electrification (no use of waste heat)	754
On site electricity and use of waste heat	1 723
Grid injection, end use in transport	1 305
Grid injection, end use in heat generation	1 026
Grid injection, end use in power production	1 567

Source: Renewable Energy Association, CNG Services.

Where there is no gas grid available, gas can be transported to stations with CNG tube trailers as the case of Sweden illustrates. Also, landfill sites may produce gas that can be used to fuel vehicles that serve in nearby cities, which produce the waste for the landfill site, creating a locally closed loop in terms of waste management and greenhouse gas, while simultaneously reducing local pollutants and noise in densely populated areas. Another reason to use biogas in vehicles can be that grid injection requires that summer demand is high enough to facilitate baseload injection throughout the year, which is not always the case. Vehicles can then either help to increase baseload demand of natural gas from the grid, as gas demand for transportation is less likely to have seasonal fluctuations) or be fuelled with locally produced biogas directly.

While costs are an obstacle in the short term, in the long term bio-SNG is expected to be at the low end of the cost range for advanced, low-greenhouse-gas biofuels. Table 12 provides the greenhouse-gas abatement costs relative to a baseline gasoline vehicle for a number of options in the near term and the long term, based on the IEA Mobility Model. These calculations are based on an LDV (car) with a mileage of 200 000 km in a 15-year lifetime and a 7.5 Lge/km fuel consumption in the baseline case. For the level of grid development, scenarios D and F (as used in Table 12) were assumed for the near term and long term, respectively. The ranges indicate dependency of the costs on the fuel mix of power generation or conversion technology.

Table 12: Greenhouse-gas abatement costs across different technologies

Technology	Near term (USD/tCO_2 avoided)	Long term (USD/tCO_2 avoided)
Oil price scenario (USD/bbl)	80	120
Baseline vehicle – bio-SNG	300	-40
Efficient vehicle – gasoline hybrid	110	-30
Efficient vehicle – bio-SNG	230	-10
Efficient vehicle – gasoline	140	-5
Efficient vehicle – plug-in hybrid	245-560	30-55
Efficient vehicle – natural gas	275	60
Baseline vehicle – natural gas	510	105
Electric vehicle, range 150 km	600-1 930	80-205

Source: IEA.

Combining the potential for bio-SNG production by 2030 according to a recent IEA study (IEA, 2010c) with the forecasted natural gas consumption by NGVs in 2030 according to the IGU (IGU 2009), demonstrates that availability of just over 10% of global agricultural and forestry residues suffices to produce enough bio-SNG to cover demand from NGVs (Table 13). However, while the production of bio-SNG shows a considerably higher conversion efficiency than other (liquid) biofuels (cellulosic-ethanol, biomass-to-liquid [BTL] diesel), it should be noted that these fuels will ultimately compete for the same feedstock, in particular since there are little liquid alternatives to fossil fuels than can be used in marine vessels and airplanes.

Table 13: Bio-SNG potential versus NGV gas demand in 2030

Region	Bio-SNG at 10% residue potential (billion Lge)	NGV gas demand (billion Lge)
Africa	20	1
Americas	60	64
Asia, Middle-East and Oceania	107	151
Europe, Russia and CIS	34	31
World	221	247

Source: IEA (2010c), 2010 IGU Study group 5.3 report June, 2009 (BAU sub-scenario 2).

Large-scale grid injection of biogas, bio-SNG or biomethane requires that the institutional framework be developed to create incentives and provide clear expectations for all parties involved in the value chain. In many European countries, policies incentivise power generation from biogas but not grid injection. In addition, international standards concerning the composition of the gas and quality and quantity measurement need to be established. Some countries, such as Sweden, Switzerland and Germany have developed national standards which in some cases differentiate between quality standards for limited volumes and standards for unlimited volumes.

6.2 Biomethane projects in Europe

The main focus of this working paper is on the use of natural gas in vehicles, be it from fossil or organic origin, and as such it does not aim to provide a complete overview of the principles and practice of biogas production. However, considering its potential to decarbonise the power sector, it is worth to explore current activities related to biogas in transport. Europe is an interesting region to analyse in this regard as it is seeing more and more initiatives aimed at using biogas specifically for transportation. Another reason why biogas is particularly interesting in the region is that locally produced biogas would fit well in a diversification strategy, aimed at reducing reliance on imported gas as total demand grows. This also reduces greenhouse-gas emissions in the WTT part of the cycle. This section briefly descirbes some pan-European projects and looks at developments in Sweden, Austria, The Netherlands and Germany.

BiogasMax

Much valuable experience has been gained through the EC Integrated BiogasMax project, funded under FP6. In eight cities/regions,[35] pilots were set-up and progress was monitored in the production, upgrading, distribution and grid injection of biogas and its use in vehicles. In total 100 HDVs in waste collection and public transport plus 789 LDVs from private companies and private transport were involved and monitored during 4.5 million km over one year. The gas was mostly sewage gas, landfill gas, biomethane from biowaste and in some cases produced from agricultural crops. Some main conclusions were:

- high satisfaction of fleet managers and drivers, training is essential;
- high vehicle reliability, more frequent maintenance;
- energy efficiency needs to be improved (now 30-40% less than diesel engines);
- need for additional fuel storage capacity and saftey requirements for garages.

The project involved several different types of policy measures, ranging from obligations for public authorities to use clean vehicles to subsidies in various forms (including tax exemptions, waiving of excise duties, congestion charges, parking fees, investment grants etc). Besides the common barriers of limited vehicle availability, higher costs and lack of infrastructure, a number of biomethane specific barriers were identified:

- a lack of incentives for the use of biomethane as a vehicle fuel rather than for electricity production and incentives aimed at promoting biomethane over fossil natural gas;
- a lack of awareness, knowledge and information about biomethane;
- a lack of standards for biomethane quality;
- high investment costs for biogas plants.

[35] These cities and regions are: Berne (Switzerland), Göteborg and Stockholm (Sweden), Lille (France), the region of Lombardy and Roma (Italy), Torun and Zielona Góra (Poland).

This illustrates that while biomethane is very suitable as a fuel for transportation, there is work to be done by policy makers, regulators and the biogas industry to remove barriers for full-scale market penetration.

Madegascar project

The goal of the MADEGASCAR project is to increase the number of NGVs, with a focus on light vehicles, and improving supply and infrastructure. Targets are to increase the number of NGVs by 5 000, construct 40 new fuel stations and 100 new biogas production plants in the 13 partner regions.[36] The project is about halfway in terms of time and has already exceeded the first two targets by far, but the 100 biogas production plants has proven to be not achievable in practice (it is now ten). Knowledge building and dissemination is also an important part of the project and among others, the project has produced a number of fact sheets which can be found at the project website www.madegascar.eu.

Sweden

Sweden is a very interesting case in the sense that the by-and-large marginal CO_2 free power generation capacity[37] means that transport is the logical choice of policy aimed at climate change targets. Transport accounts for about half of the national CO_2 emissions and indeed, the Swedish government aims in the long run to decouple CO_2 emissions from road freight from GDP growth. Partly, the country can reach its goals by replacing road passenger and freight transport with electric railroad, but the use of biofuels and diesel instead of gasoline (which reduces CO_2 emissions) are also part of the government's strategy. Since Sweden's natural gas network only covers the western coast (which consists of 540 km transmission and 3 000 km of distribution pipelines), it may make sense to use biogas in the near vicinity of its production, which makes a good case for its use in NGVs (Figure 22).

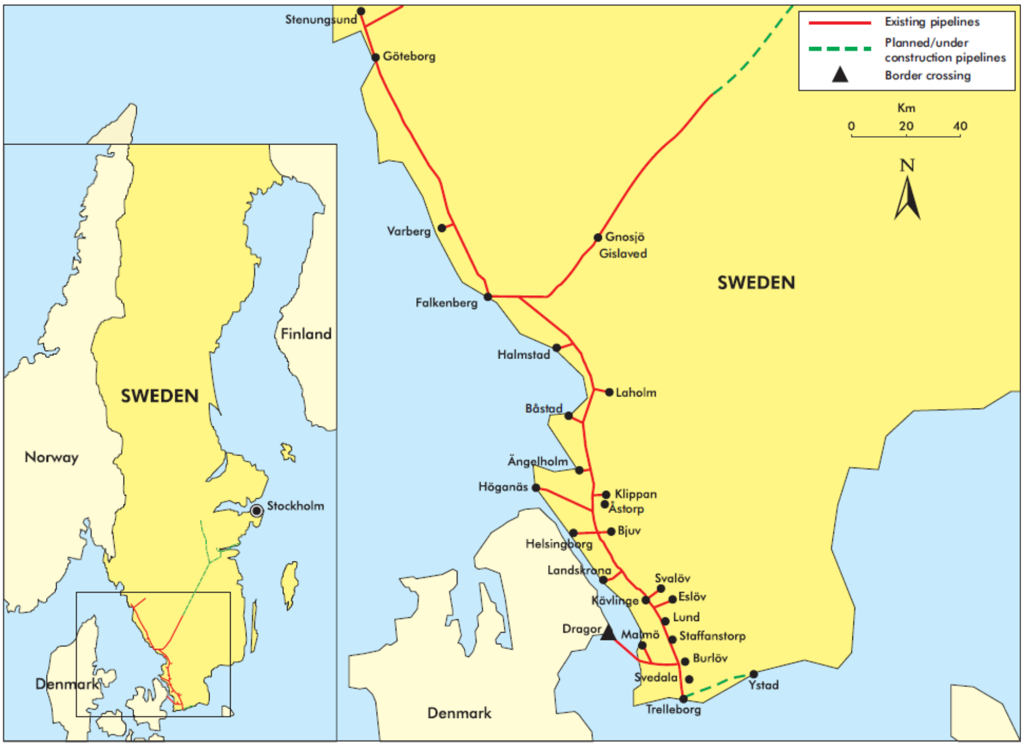
Sweden currently has over 23 000 NGVs, the majority being LDVs and LCVs, which consumed more than 67 million cubic metres (mcm) in 2009. Although this is not a significant volume, it represents a growth of 16% compared to 2008, and 65% of this volume is biomethane (Energigas Sverige). Currently 26% of biomethane produced is used as a vehicle fuel while 50% is used for heat, 8% for electricity and 14% is flared. In December 2009, there were 136 refuelling stations in Sweden (as of June 2009, NGV Communications Group), of which 104 public and 32 private, and 55 more were under construction.

Sweden currently has a total of 227 biogas plants, of which 140 municipal sewage treatment plants, 54 landfill sites, four industrial waste water treatment plants, 17 co-digestion plants and eight farm plants (Swedish Energy Agency, 2010). There is a huge but unrealized potential in bio-SNG production from on-farm plants and bio-SNG from forest residuals, total potential biomethane production from waste and residual products is estimated at 74 TWh (Swedish Gas Center). The ultimate goal is to replace 99 TWh of energy used in transport in the for of oil products. Incentives for the use of biogas in vehicles are in place in Sweden and examples of biomethane projects are abound (Biogas Öst, 2008).

[36] These regions are located in 10 countries: Austria, Bulgaria, Czech Republic, Germany, Lithuania, Poland, Slovenia, Spain, Sweden and the United Kingdom.

[37] Sweden has the lowest carbon-intensity of energy supply among IEA countries (IEA Country Review Sweden, 2008).

Figure 22: Swedish gas infrastructure



The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptable by the IEA.

Source: IEA data and analysis.

The Linköping Biogas[38] plant (located in the East of the country, where there is no gas grid) has an annual treatment capacity of 100 000 tonnes of biomass, coming from animal manure and different food industries in the vicinity of city (which has 140 000 inhabitants). It produces 4.7 million m3 of upgraded biogas (97% methane), used in 64 buses and a number of HDVs (trucks) and LDVs (private cars, taxis and distribution vehicles). The plant started production in 1997 and this year the first buses also started running on biogas. Since 2002, the urban transport fleet consists of only biogas buses, resulting in a CO_2 reduction of 9 000 t/y. In addition to the slow filling station for buses, which are refuelled during the night, there are also 12 public biogas fast filling stations, some of which are supplied through a low pressure pipeline from the upgrading plant and some of which are supplied through a container system. The total investment was USD 19 million (EUR 14 million). In 2005, a diesel powered train was converted to run on biogas by changing the engine and equipping it with storage cylinders for compressed biogas (CBG), allowing it a range of 600 km. This was cheaper than electrification of the track. Emission levels were lowered from Euro 1 to Euro 5 levels and greenhouse-gas emissions are now zero (on a lifecycle basis). Apart from the transportation aspects of the project, artificial fertiliser has been replaced by digestate from the biogas plant and an environmentally sound process is now available for the treatment of regional organic waste.

Arlanda airport is an example of an off-grid fuelling station that is supplied with canisters that are transported by trucks. It's noteworthy that the equipment here was replaced twice in three years time, because the original compressors could not cope with the high inlet pressure from the canisters. The costs for this were USD 0.9 million (SEK 7 million), additional to the orginal

[38] Source: IEA Bioenergy Task 37, "100% Biogas for urban transport in Linköping, Sweden", available at http://www.iea-biogas.net/Dokumente/casestudies/linkoping_final.pdf

investment of USD 270 000 (SEK 2 million), which illustrates the importance of the planning and design phase of a station. The 250 taxis, five airport transfer buses and a number of refuse trucks consume 3 000 Nm^3 each day. CO_2 caps and special taxi stands were used as incentives.

Västerås illustrates different parties working together in a waste-to-energy project, involving farmers, an energy company and a waste company who set up a common biogas production and upgrading plant and two filling stations, one for 40 buses and 12 refuse trucks and the other publicly accessible and serving around 50 vehicles per day. The filling station for buses is a fast filling station, which refuels a bus within five minutes[39] and up to four buses simultaneously. Some minor difficulties have emerged, but could generally be overcome fast enough not to influence bus traffic.

Eskilstuna has a long history with biogas production and started with biogas upgrading to vehicle standards in 2002 with sewage sludge, organic household and food industry waste as feedstock. It is now home to a production plant, an upgrading plant, a filling station for buses (500 000 Nm^3/y) and a public filling station serving around 50 vehicles per day and almost 300 000 Nm^3/y. For this project it's interesting to note the co-operation with the gas company AGA Gas to sell excess volumes and have fossil natural gas as a back-up in case of deficits. Technology came from New Zealand and has generally worked well, though some software problems have arisen and support and spare parts have not always been readily available in the past.

Norrköping is another example of a co-operation between a municipality, a gas company (E.ON) and the state and it also shows the high relative up-take of fuel by HDVs. The filling stations for buses provides 700 000 Nm3 annually to 16 buses, while the public station supplies 70 000 Nm3 to around 20 customers per day (E.ON company cars, taxis and a number of private cars). Balancing demand and supply was previously arranged by storage (capacity of two days consumption) and lorry transports from elsewhere in Sweden, but now the E.ON station is connected to another biomethane station in Norrköping, which is supplied from another production plant and shortages of gas are rare. The Swedish state provided 30% funding for the USD 1.2 million (SEK 8.9 million) investment required for the filling stations and the storage facility.

Uppsala originally invested USD 0.7 million (SEK 5 million) in a filling stations (including grid connection), which has been expanded several times leading to a total investment of USD 2.7 million (SEK 20 million). The station now serves biomethane at a petrol-linked price to 54 buses, two trucks and ten to twenty cars on a daily basis. The municipality is the owner and operator and as such has no profitability objectives and indeed is losing money on the production system. Since a reconstruction around five years after the original construction, no technical difficulties have been experienced and in case of shortages, natural gas can be delivered by lorry from Norway. The lack of a consistent standard in Sweden for the handling of biomethane as a vehicle fuel has led to confusion among concerned authorities.

The municipality of Kungsbacka operates eight dual-fuel garbage trucks which run on 70% biogas and 30% RME.

Biogas is exempt of tax up to at least 2013. The tax reduction on natural gas used as automotive fuel will be phased out during 2011-15. Continuation of the fringe benefit taxation of a company car with an environmental classification after 2011 is currently subject to debate (Swedish Gas Center, 2010).

In general, the most important lesson to be learned from these experiences is that the design of a station is a crucial phase. Selection of equipment, capacity of the station, the location, grid

[39] Usually this takes a bit longer, 10-15 minutes. Fast-filling a car takes 2-5 minutes. Slow filling takes several hours, but usually means that a whole fleet is fuelled simultaneously from the same compressor.

connection, land ownership, safety requirements and a supply route in combination with a back-up/balancing strategy are interrelated aspects that must be thought through very carefully to avoid costly changes in a later stage. It is clear that investments are substantial (ranging from USD 0.2 to USD 1.3 million, SEK 1.5 to SEK 10 million) and large fleet owners provide the best guarantee for a stable off-take of substantial volumes.

Austria

A biomethane demonstration project in Bruck an der Leitha, Lower Austria, demonstrates a potential solution for the "summer injection problem". Due to the lower pressure it is often preferable to inject biogas into a local distribution grid rather than the transmission grid. However, biogas production is most cost-effective as a continous process, which means that injection needs to be baseload. While additional gas can usually be provided from fossil sources if the baseload is not sufficient to cover demand, in summer, local demand in the area that is served by the distribution grid may be too low to guarantee off-take of the baseload volume of biogas. The facility near Bruck an der Leitha is connected to two grids. In the winter months all the biogas produced fed into the distribution grid (operating at 3 bar) and consumed in the community, while in the summer months, excess biomethane is fed into the regional grid (operating at 60 bar). The facility produces purified biogas at natural-gas standard at a rate of 100 m3/h, feeding up to 800 000 m^3/y into the grid which is "virtually" used in NGVs[40] and used for combined heat and power (CHP or district heating). It's interesting to note that vehicles were chosen as the "virtual destination" for the biogas because of the profitability in this segment of the market (high taxes on conventional fuels create a good margin for bio-CNG). This project also includes research on the demand side of biogas, namely utilisation in a Fuel-Cell and diesel engine.

The Netherlands

The Netherlands has a large number of farms, which creates the potential for anaerobic digestion of manure for biogas production, plus most of these farms are connected to the natural gas grid. Indeed, several projects involving biogas injection into the distribution grid have already emerged in the past decades. Usually, the feedstock is from sewage treatment, landfill sites, agricultural residues and/or liquid waste streams. Gasunie, the holding company of the Dutch TSO Gastransport Services recently gave the green light for biogas injection into the transmission grid, if the biogas produced meets certain quality standards (Table 14). Gasunie also developed a certification system, which means that green gas production and consumption can be linked virtually. One Dutch car importer supplies the purchaser of a new NGVs with 90 000 km worth of green gas certificates (from biogas produced in The Netherlands).

What is lacking in the Netherlands is the NGVs retail infrastructure. The country is seeing some activity in this field, but numbers remain low. There are currently only 2 000 vehicles and 51 refuelling stations, although the industry expects to have 100 stations by 2011. The Dutch government facilitates the construction of stations through investment subsidies (not limited to biogas stations) and has made a USD 290 million (EUR 214 million) subsidy scheme available for biogas production in 2010. About 10% of all public transportation buses in The Netherlands run on natural gas, either fossil or biogas.

[40] NGV Global: www.ngvglobal.com/austrian-trial-biomethane-facility-overcomes-barriers-0702#more-9100 and project website: www.virtuellesbiogas.at.

Table 14: Composition of various types of biogas compared to fossil gas in The Netherlands

Vehicle	Biogas	Groningen gas	Upgraded biogas (grid injection)	Biomethane	Bio-LNG
Methane	< 200	post-2000	62/-	174*	78/58
CO_2	< 200	post-2005	72/74	132*	n/a
Caloric value (MJ/m^3)	<1 000	1996-2000		129**	149
Energy content in fuel tank (MJ/l)	1 000-1 400	post-2000	127	156**	131

Source: Platform duurzame mobiliteit (2009).

According to a 2007 report by the working committee "EnergieTransitie Platform Nieuw Gas", 10% of Dutch gas consumption could be biogas by 2020, increasing to 50% in 2050. The Dutch government adopted these values as targets.

Germany

Germany currently has 900 fuelling stations (Erdgas Mobil, 2010) in 735 cities (as of December 2009, NGV Communications Group), thereby surpassing Europe's main NGVs country, Italy. Interestingly, the number of NGVs is quite limited compared to the number of fuelling stations at around 90 000 vehicles (of which 30% are LCVs and 15% are HDVs, Erdgas Mobil 2010). Even though this is only a fraction of the total stock of roughly 50 million vehicles, this does represent a doubling of numbers in five years' period. This growth is mainly due to strong government policy in the beginning of the century aimed at a rapid development of the public CNG filling station network, investments by the gas industry and a commitment from the administration to keep reduced tax rates for CNG as a vehicle fuel up to 2018 and for biomethane up to 2015. Some local governments provide incentives for the purchase of NGVs by consumers. The market share of NGVs in new car sales and total vehicle stock in Germany is negligible and it has been suggested that heavy promotion of sales of NGV models at the expense of gasoline and particularly diesel models in the domestic market is not part of the strategy of German vehicle OEM, despite their interest in selling NGV models in other markets.

The UK-based Renewable Energy Association states that the biogas industry is now Germany's fastest growing renewable energy source, attracting investments over USD 1.35 (EUR 1 billion) p.a. The DVGW states that currently 99% of the 4 500 biogas plants do not inject biogas into the grid but produce electricity instead and in most cases the heat is lost. The government wants to address this and aims to substitute 10% of natural gas with biogas by 2030 (currently 1.7%). Injection capacity has grown from 6 000 m^3/h in 2008 to 20 000 m^3/h in 2009 and it is expected to grow to 48,000 m^3/h in 2010, since the industry is becoming more and more interested. Technical standards focus among others on sulphur compounds and minimizing flaring to decrease methane emissions from upgrading and storage.

Biogas Partner[41] lists 38 upgrading plants in Germany currently operating, with a total capacity of 23 853 Nm^3 biomethane per hour. Another 15 plants are under construction and 29 are in the planning phase. If all these plans were realized, that would put the total capacity at 57 093 Nm^3/h. The biggest plant in Germany (Güstrow) has a feed-in capacity of 5 000 m^3/h. German law states that the minimum flow of summertime demand is not a valid reason to limit the entry of biogas into the grid. Another provision states that injection should be economically feasible for the grid operator, but at the moment all costs related to this are allowed to be included in the regulatory operating costs, which the grid operator is allowed to include in the tariff.

[41] www.biogaspartner.com.

Nevertheless the physical reality is relevant: where will gas actually be used and how tolerant is the equipment to (changes in) the gas quality. The fact that biogas feed-in is allowed to exceed the off-take level of the market in the summertime means that for the largest part of the year the gas has to be pressurized, which is costly and these costs are shared among all consumers.

According to the Berlin Energy Agency, gas market regulation in Germany creates barriers for biomethane to access the gas grid. The Gasnetzzugangsverordnung regulates preferential access for biomethane and cost sharing between the biogas producer and the network operator, but regulatory barriers still exist. For instance, different gas grid operators have differing quality demands following from their specific equipment.

The Rathenow biogas plant near Berlin produces 1 150 m^3/h of raw biogas which is upgraded to biomethane. Biomethane is injected into the grid at a feed-in capacity of 520 Nm^3/h and around 2 315 MWh of electricity is produced annually. BioCNG20 is made available to the Berlin fuel stations. The investment for the whole plant (including CHP) was USD 12 million (EUR 9 million), which was financed partly by the government. No overview of the cost structure is available as this is commercially sensitive information, but the produced gas is 8-9 €ct/kg more expensive than CNG. The price of Bio-CNG is USD 1.3/kg to USD 1.4/kg (EUR 0.95/kg to EUR 1.02/kg) in Berlin.

The German public/private energy agency Dena recently published recommendations (Dena, 2010) for a strategy aimed at increasing the share of natural gas and biomethane in Germany's road fuel mix, in order to reach the targets included in the federal government's 2004 fuel strategy. If the goals of 0.5% to 1% share in road fuel mix by 2010 and 2% to 4% in 2020 are to be attained from the 2009 level of 0.3%, a staggering annual growth of 29% is required. The only way for Germany to reach this level of growth is to maximize the growth in the LCV and HDV segment and to develop an integrated approach.

While Germany is often cited as an example of stakeholders co-operating towards the common goal of growth of NGVs numbers, Dena (2010) states: "…policy makers and government, the petroleum industry with its filling station networks, the gas industry (including biomethane producers), vehicle manufacturers and dealers and research institutes, each with their own particular interests, have not been taking a harmonised approach to users." The document provides a fairly detailed overview of the actions that are required and which stakeholders are involved in this action. Dena's estimates of CO_2 savings are 24% on CNG (average EU natural gas mix), 39% for BioCNG20 and 97% for pure biomethane (which is similar to 100% wind electricity powered vehicles on hydrogen or electricity).

6.3 NGVs: A pathway to hydrogen?

Natural gas can to a certain degree be mixed with hydrogen, which results in lower pollutant emissions, particularly CO and NO_x and CO_2 emissions due to the increase in hydrogen to carbon ratio (Fernandes 2010; Simio, 2010). While some tests show that energy efficiency of the vehicle is improved up to 15% as hydrogen is added, even beyond merely the replacement of carbon atoms with hydrogen, the evidence to support this statement does not appear to be conclusive. The overall CO_2 emissions on a WTW basis are obviously largely determined by the way the hydrogen is produced.

Various tests and studies have pointed out the factors involved in choosing an optimal volume ratio of hydrogen/natural gas, such as vehicle range, WTT and TTW CO_2 emissions, costs, and pollutant emissions. As the WTT emissions increase linearly with a higher share of hydrogen while the rate of decline in TTW emissions decreases as the share of H_2 increases, the WTW emissions decrease initially but increase from a certain point onwards. A 15% - 20% (vol.) share of hydrogen is often mentioned as optimal. So far, most tests have involved stoichiometric engines, while the application of hydrogen/methane in lean-burn or dual-fuel engines is seen as a promising route for further research. As the combustion properties of hydrogen differ from methane (hydrogen has a lower ignition temperature), engine tuning is required.

The CarbonSaver® technology that has been developed by Atlantic Hydrogen Inc. over the course of the past decade to decarbonise natural gas may become interesting in the future. This system would be inline with the fuel delivery system in the fuel station and removes carbon from natural gas by use of a patented plasma technology, which results in a mixture of methane and hydrogen and pure carbon powder (which is a valuable by-product). This technology is expected to see pilot projects in the near future.

More research is required to assess how and the degree to which NGVs can pave the way for a hydrogen economy in terms of investments in infrastructure, technology development and policy.

7. Conclusion and outlook

Key messages:

- **The regions that are currently leading in NGVs – Asia-Pacific and Latin America – are likely to continue to do so.**
- **For the projected growth to materialise, substantial investments will be required in vehicles and retail infrastructure as well as transmission and distribution grids in some countries. While investments in vehicles and retail infrastructure can generate positive returns in many cases, temporary government support may be required to establish a market. Investments in grids are likely to take place only where other sectors can benefit from natural gas supply as well.**
- **Tax and subsidy policies need to be sustainable in the long run in order to facilitate these investments. While NGV programmes can alleviate pressure on government budgets by replacing fuels that are (more) subsidised, taxation of motor fuels also provides an important source of revenue for governments in many countries.**
- **NGV programmes are driven by a variety of factors, including the improvement of local air quality in densely populated areas, freeing up more valuable oil (products) for exports, reducing government spending on subsidies, stimulate economic development by promoting local production of vehicles, improving security of supply by replacing an imported fuel with a domestically improved fuel and overall gas market development.**
- **The simultaneous development of gas markets, public transportation and the economy in general in many non-OECD countries provide momentum for NGV programmes.**
- **For various reasons, the potential to replace large quantities of diesel fuel by promoting the use of natural gas by HDVs has been underutilised and thus far, very little action has been undertaken to construct "gas highways".**

Having discussed the current state of markets, the economics of NGVs, the technology, its benefits and challenges, as well as the policies and market development in a selected number of countries, this paper will look to the future, aiming to identify the future prospects of NGVs.

Consumption of natural gas by NGVs is expected to remain strongest in the regions that are also currently leading in NGV market development, Asia-Pacific and Latin America (IGU, 2009). In these regions, NGVs are expected to reach very significant shares of total gas consumption while in other regions such as Europe and North America, the share is expected to remain extremely limited. Consumption of natural gas by NGVs is expected to rise in conjunction with overall gas demand, leading to a modest growth in its share in all regions except Latin America (Table 15).

If these projected demand figures[42] become reality, the consequences of this rather concentrated demand of CNG/LNG for these gas markets are substantial. Or rather, the prerequisites for this growth to materialize are significant. IGU estimates that 104 million equivalent[43] NGVs will be on the road (which corresponds to just over 3% of the vehicle park based on *ETP 2010* Baseline projections[44]) and over 133 000 fuel stations will be operational by 2030. This means that around 93 million vehicles need to be put on the road in two decades at

[42] IGU's forecasts are based on an assumed oil price of USD 120 in 2020 and USD 150 in 2030.

[43] The word "equivalent" is important here as it means that one truck or bus counts as 10-15 cars.

[44] IGU (2009) mentions a share of 7% based on a different assumption on the total amount of vehicles.

an average conversion cost or price premium of USD 1 000 per vehicle, at current cost levels,[45] implies an investment in vehicles of USD 93 billion, without considering the costs of replacing vehicles within this period. Naturally, the investments made by vehicle owners are highly likely to be recovered by fuel cost savings, but the investment will nevertheless still need to be made. Assuming an average cost of fuel stations of USD 350 000, the total investment required for the additional 117 000 fuel stations equals about USD 41 billion. This investment can either result from a private company where a profitable business case can be made or by government incentives where the business case is not profitable. Perhaps the largest investment is in the gas market development as some of the countries are on a path to combine NGV programmes with investments in transmission and particularly distribution networks. As discussed in some of the case studies, these investments can be very substantial indeed. It is likely that they will only materialise in situations where synergy with other sectors, such as power production, industry or residential customers, is present.

Table 15: Expected regional NGV gas consumption

Region	NGV gas consumption (bcm)				Share regional gas demand (%)			
	2015	2020	2025	2030	2015	2020	2025	2030
Asia-Pacific	24	46	67	91	4	6	8	9
Europe	2	4	6	10	0	1	1	2
Eastern-Europe/Eurasia	6	10	14	17	1	1	2	2
ME & Africa	9	17	26	35	2	3	4	4
Latin America	15	25	34	44	9	14	17	19
North America	3	5	6	8	0	1	1	1
Total	59	107	152	206	100%	100%	100%	100%

Source: NGV gas consumption based on IGU 2009 – sub-scenario 2 (Region specific average consumption per equivalent NGV in each region business as usual scenario; includes biomethane), share in regional gas demand calculated using IGU data and WEO 2009 Reference Scenario.

Liberalisation of markets and price reforms are also a pressing issue in many countries that are engaged in programmes to increase the use of natural gas in transportation. This is not a coincidence as natural gas replaces fuels that are often heavily subsidized in an effort to protect the domestic market from changes in global commodity prices. In that sense, using CNG for automotive purposes can bring relief to government budgets that are under pressure from "under recoveries", although CNG itself may also be subject to (implicit) subsidies. In these cases, a financially sustainable taxation and subsidies policy is required to drive a stable growth for NGV markets as the stakeholders involved need long-term security in order to decide to invest in this technology.

As the case studies have illustrated, NGV programmes usually have more than just one single motivation. Although one driver can be dominant, usually it will be a mix of factors that cause a government and/or other stakeholders to actively encourage the growth of NGV markets. The possible drivers include the improvement of local air quality in densely populated areas, freeing up more valuable oil (products) for exports, reducing government spending on subsidies, stimulate economic development by promoting local production of vehicles, improving security of supply by replacing an imported fuel with a domestically improved fuel and overall gas market development. The simultaneous development of gas markets, public transportation and the economy in general in many non-OECD countries provide momentum for NGVs.

[45] This may overstate costs as they are likely to decline with economies of scale.

The past decade has seen very substantial growth in number of vehicles, fuel stations and gas consumption in transportation. So far, with little exceptions, this growth has been concentrated mainly in LDVs (*e.g.* three-wheelers, cars, taxis) and transit buses. For various reasons, the potential to replace large quantities of diesel fuel by promoting the use of natural gas by HDVs has been underutilised. The reasons for this vary from inertia (the lack of willingness to change the *status quo*), lobbying by stakeholders with interests in liquid fuels, minor price differentials between diesel and natural gas, low availability of NGV models and, very importantly, the lack of infrastructure. While "blue corridors" could provide a cost-effective way of constructing CNG/LNG refuelling infrastructure and plans certainly exist in regions such as (Eastern)Europe, Latin America and Asia, very little action has been undertaken to actually construct these "gas highways".

Abbreviations and acronyms

AFV	alternative fuel vehicles
bcm	billion cubic meters
BTL	biomass-to-liquids
CBG	compressed biogas
CHP	combined heat and power
CNG	compressed natural gas
EEV	enhanced environmentally friendly vehicle
ESC	European Stationary Cycle
ETC	European Transcient Cycle
EV	electric vehicle
FT	Fischer-Tropsch
HC	hydrocarbon
H-CNG	hydrogen/CNG blend
HD-NGV	heavy-duty natural gas vehicle
HDV	heavy-duty vehicle
LBG	liquefied biogas
LCNG	liquid-to-compressed natural gas
LCV	light commercial vehicle
LDV	light-duty vehicle
Lge	litre of gasoline equivalent
LNG	liquefied natural gas
MBtu	million British thermal unit
mcm	million cubic metres
MDV	medium-duty vehicle
NGV	natural gas vehicle
NMHC	non-methane hydrocarbon
OEM	original equipment manufacturer
PM	particulate matter
RME	Rapeseed Methyl Ester
SNG	synthetic natural gas
THC	total hydrocarbons
TSO	transmission system operator
TTW	tank-to-wheel
WTT	well-to-tank
WTW	well-to-wheel

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