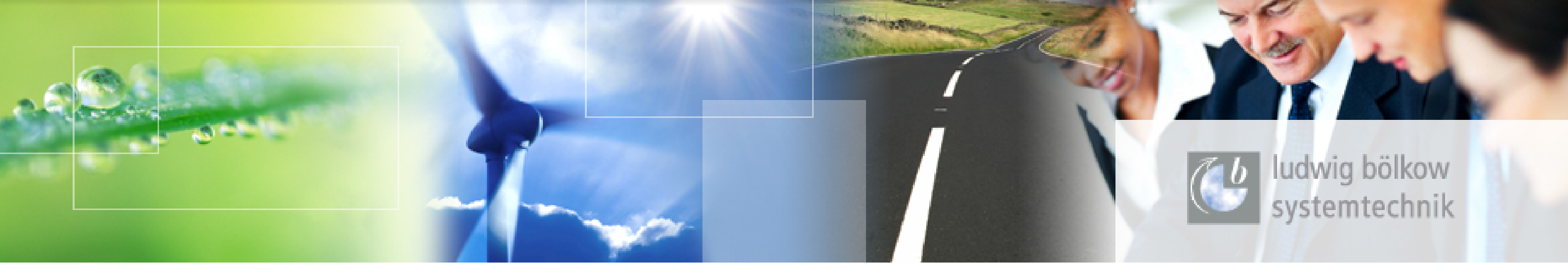

CNG AND LPG FOR TRANSPORT IN GERMANY

ENVIRONMENTAL PERFORMANCE AND POTENTIALS FOR GHG EMISSION REDUCTIONS UNTIL 2020

AN EXPERTISE FOR ERDGAS MOBIL, OMV, AND SVGW

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REPORT

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CONTENTS

TABLES

FIGURES

INFOBOXES

ACRONYMS AND ABBREVIATIONS

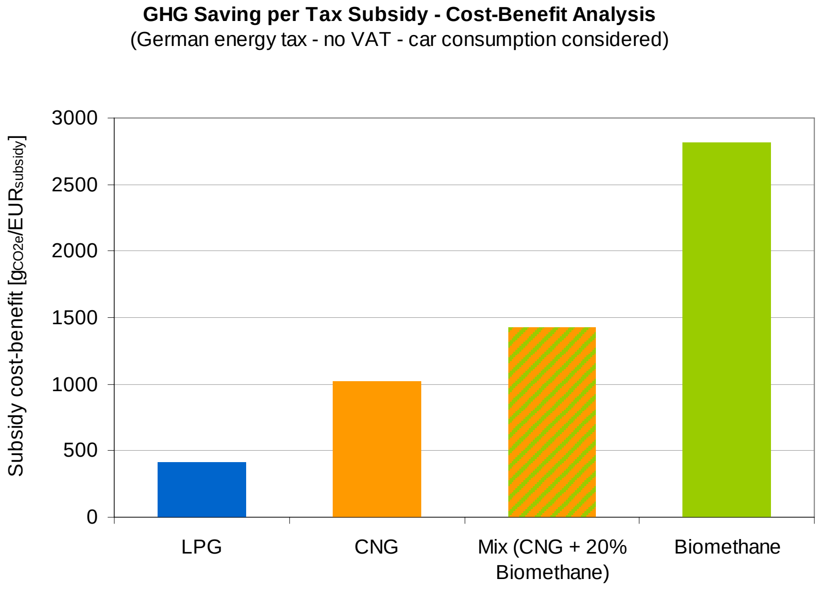
a	year
CCGT	Combined Cycle Gas Turbine
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_{2eq}	Carbon Dioxide Equivalents
DICI	Direct Injection Compression Ignition
DISI	Direct Injection Spark Ignition
DPF	Diesel Particulate Filter
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HHV	Higher heating value
I/O	Input/Output
ICE	Internal Combustion Engine
km	kilometre(s)
kn	knots
LBST	Ludwig-Bölkow-Systemtechnik
LCA	Life-Cycle Assessment
LHV	Lower heating value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MPa	1 Mega Pascal = 10 bar
N/A	Not Available / Not Applicable
NG	Natural Gas
NGL	Natural Gas Liquid(s)
nm	nautical miles
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
pcs.	pieces
PISI	Port Injection Spark Ignition
PM	Particulate Matter
SCO	Synthetic Crude Oil
SO_2	Sulphur Dioxide
tkm	ton kilometres
TTW	Tank-to-Wheel
WTT	Well-to-Tank
WTW	Well-to-Wheel
yr	Year

EXECUTIVE SUMMARY

In the course of the study "CNG and LPG for Transport in Germany" throughout the first half of 2010, LBST has analysed CNG (Compressed Natural Gas) and LPG (Liquid Petroleum Gas) energy pathways for the supply and use as a transport fuel in Germany. The study was commissioned by erdgas mobil (Germany), OMV (Austria), and SVGW (Switzerland). Öko-Institut e.V. (Germany) served as a reviewer and counsel.

Current status

- In Germany, natural gas comes mainly through pipelines from Russia, The Netherlands, Norway, and own German sources, and to a lesser extent also from LNG shipping. In 2009, 0.17% of all natural gas in Germany was used as transportation fuel. LPG comes as a by-product from crude-oil refining and is mainly used as material input for the chemical industry as well as for residential heating purposes. Less than 10% of the LPG is used as a fuel in the transport sector.
- In 2008, German road transport emitted 146 million tons of CO_2 equivalents (t_{CO2eq}).
- Today, a CNG passenger car saves about 3 times more greenhouse gas emissions (GHG) than an LPG passenger car. 68,500 CNG passenger cars save about 0.592 t_{CO2eq} per car and year, i.e. 40,500 t_{CO2e} a year in total. 370,000 LPG passenger cars save about 0.194 t_{CO2eq} per car and year, i.e. 72,000 t_{CO2eq} a year in total.
- Comparing economic costs from German Energy Tax reductions vis-à-vis the benefits in terms of GHG emission reductions (emissions saved per € tax rebate), CNG saves 2.5 times the amount of greenhouse gas emissions on a per-km basis compared to LPG. Pure bio-methane provides the highest cost-benefit with 2.6 times that of CNG and 6.8 times that of LPG.

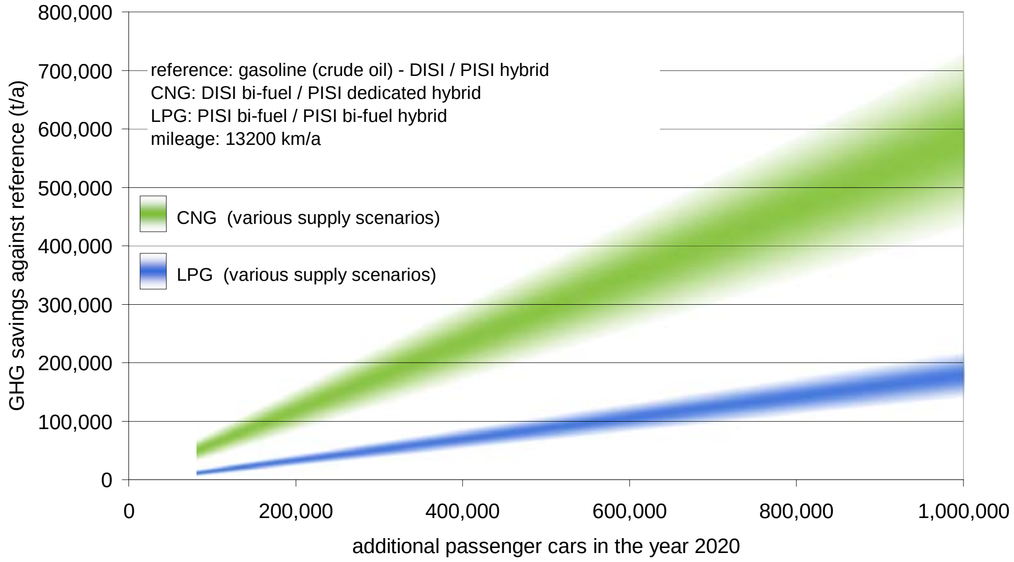


GHG Saving per Tax Subsidy - Cost-Benefit Analysis
(German energy tax - no VAT - car consumption considered)

Greenhouse gas emission reduction

- One million additional CNG vehicles in 2020 provide a 3-5 times greater volume of greenhouse gas emission reductions compared to the introduction of the same amount of LPG vehicles (430-710,000 t_{CO2eq}/yr and 145-215,000 t_{CO2eq}/yr by 2020, respectively). CNG vehicles provide lower per-km well-to-tank GHG emissions compared to LPG vehicles. Secondary impacts from increasing demands of CNG and LPG have not been assessed.
- The leverage of one million additional CNG and LPG vehicles which each reflects 2.1 percentages can contribute with 0.12–0.34 and 0.09–0.19 percentage points respectively to the EU Fuel Quality Directive target of reducing GHG intensity of conventional diesel and gasoline by 6% by 2020. This means the leverage of CNG vehicles is up to 3 times higher than the potential of the LPG vehicles. At the same time these amounts of CNG vehicles may contribute to the EU Renewable Energy Directive (EU-RED) if bio-methane is used. LPG, from today's perspective, is not able to make any contribution on the EU-RED.
- Since LPG is a by-product with limited availability, a high number of LPG vehicles (e.g. 5 to 10 million) in Germany would cause strong repercussions to other LPG consumers (e.g. households and chemical industry) and a drastic increase of import shares. CNG is able to supply a higher number of vehicles while reducing overall GHG emissions from transportation significantly.
- For higher fleet penetrations, the GHG reduction may not scale linearly, since a significant demand increase for CNG or LPG implies higher shares of the fuel coming from non-conventional sources such as oil sands or shale gas.

Greenhouse Gas Reduction Potentials through Additional CNG and LPG Vehicles by 2020



Environmental performance

- CNG vehicles generally offer lower greenhouse gas (GHG) emissions than LPG and gasoline vehicles, mainly attributed to the lower carbon content of the fuel.
- In spite of the EURO 6 vehicle emission limits to come, emissions of particulate matter (PM) will remain the most critical pollutant with both direct injection diesel and spark ignition engines. Using CNG in direct injection engines can significantly reduce PM emissions. CNG and LPG port injection engines both produce almost no PM emissions.
- Hybrid vehicles provide an opportunity for low fuel consumption, leading to low overall well-to-wheel GHG and pollutant emissions. While for hybrid LPG vehicles, the relative savings through hybridisation are about similar to gasoline vehicles; savings are more significant for dedicated CNG engines due to different engine characteristics.
- Future improvement of the efficiency of gas turbines used for natural gas compressors provides potential to decrease GHG emissions for natural gas transport. If these potentials are exploited, increasing transport distances will not necessarily increase the GHG emission attributed to the gas supply logistics in the future.
- With the progressing decline of conventional oil sources, LPG transport distances will increase and more LPG will be produced from non-conventional oil over time.
- Oil sands have been assessed as an additional source of crude-oil for LPG supply. Resulting GHG emissions as well as other environmental impacts are significantly higher compared to LPG from conventional crude-oil refining and natural gas processing.
- Shale gases have been assessed as a supply option for CNG. While greenhouse gas emissions from shale gas production increase only moderately compared to conventional natural gas supply, significant other environmental impacts are associated with its exploration and production.
- Greenhouse gas and pollutant emissions of CNG can be reduced further if methane derived from renewable sources is introduced, e.g. methane derived from biogas (provided that no land-use change occurs) or synthesised from renewable electricity and CO_2.

Main conclusions and perspectives

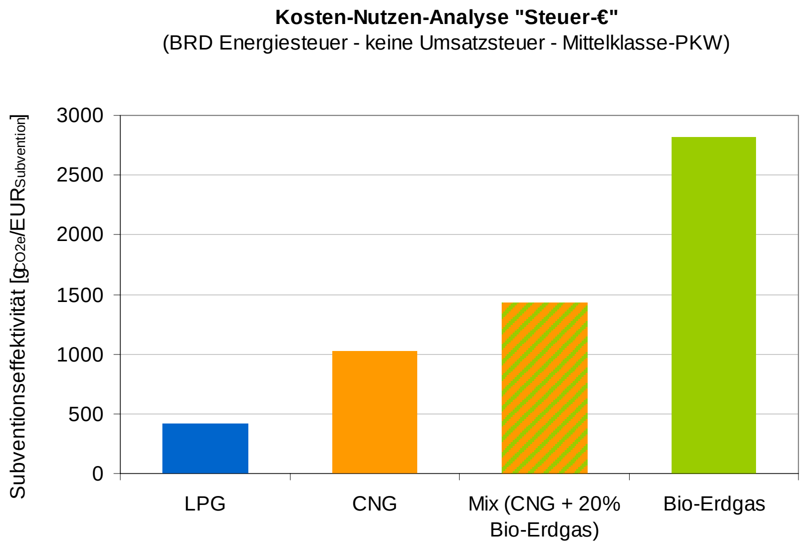
- The EU targets of 6% lower life-cycle greenhouse gas emissions from transport fuels (EU-FQD) and 10% renewable transport fuel in each Member State by 2020 including sustainability criteria for biomass-based fuels (EU-RED) provide a significant political momentum for renewable methane in CNG vehicles.
- CNG is a short term, readily available improvement of the environmental performance of the road transport sector. Concerning air pollutant emission reduction in urban areas, CNG's advantage is highest against diesel-powered light and heavy delivery trucks.
- CNG vehicles have a higher potential for greenhouse gas reduction than LPG vehicles, both in relative as well as in absolute terms.
- On a global level, as a by-product from either natural gas exploration or oil refining, the LPG potential is connected to the limited availability of fossil supplies. Global oil supplies may have peaked already. Natural gas supplies may peak in the next decade. The fossil resource basis of CNG is less constrained than for LPG. In addition, bio-methane from organic sources (upgraded biogas) and methane synthesised from renewable electricity and CO_2 (synthesised natural gas – SNG) are available as a drop-in substitute to stretch the eventually limited fossil resource base of natural gas.

ZUSAMMENFASSUNG

In der Studie „Erdgas und LPG im Verkehrssektor in Deutschland“ hat die Ludwig-Bölkow-Systemtechnik (LBST) CNG (Komprimiertes Erdgas) und LPG (Flüssiggas) Versorgungspfade für die Nutzung als Kraftstoff in Deutschland analysiert. Die Studie wurde von durch erdgas mobil (D). OMV (A) sowie der SVGW (CH) in Auftrag gegeben. Das Öko-Institut e.V. (D) diente im Beirat als fachlicher Berater und Gutachter.

Aktueller Stand

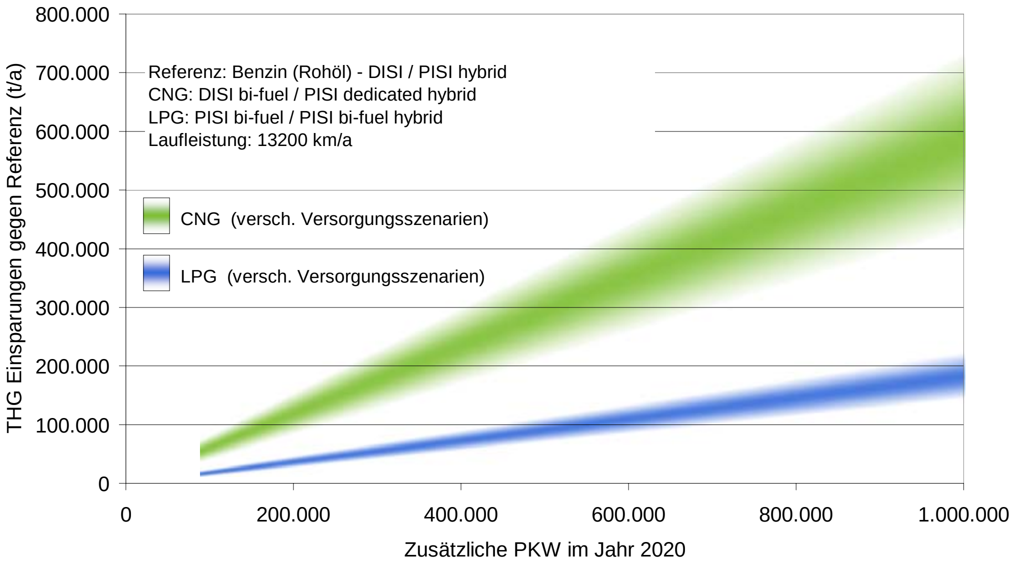
- Deutschland erhält sein Erdgas überwiegend via Pipeline aus Russland, den Niederlanden, Norwegen sowie aus eigenen Quellen sowie zu einem kleinen Teil via LNG-Schiffen. Nur 0,17% des Erdgases wurde 2009 in als Kraftstoff eingesetzt. LPG wird in Deutschland hauptsächlich als ein Nebenprodukt aus der Ölraffinierung gewonnen und in der chemischen Industrie sowie in Haushalten eingesetzt. Weniger als 10% wird als Kraftstoff verwendet.
- 2008 emittierte der deutsche Straßenverkehr 146 Mio. Tonnen Treibhausgase (t_{CO2e}).
- Ein CNG-PKW spart aktuell ca. 3-mal so viel Treibhausgase ein wie ein LPG-PKW. 68.500 CNG-PKW sparen 0.592 t_{CO2eq} je Fahrzeug und Jahr, insgesamt 40.500 t_{CO2e} pro Jahr. 370.000 LPG-PKW sparen ca. 0.194 t_{CO2eq} je Fahrzeug und Jahr, insgesamt 72.000 t_{CO2e} pro Jahr.
- Ein Vergleich der volkswirtschaftlichen Kosten (entgangener „Steuer-€“) auf Grund der reduzierten deutschen Energiesteuersätze vis-à-vis den reduzierten Treibhausgasen zeigt, dass CNG 2,5-mal mehr Treibhausgase pro gefahrenem km einspart als LPG. Reines Bio-Erdgas weist die höchste Kosten-Nutzen-Relation auf; es spart 2,6-mal mehr Treibhausgase ein als CNG und 6,8-mal mehr als LPG.



Szenarien zur Minderung der Treibhausgasemissionen

- Unter der Annahme der Zulassung von 1 Million zusätzlichen CNG-PKW bis 2020 können 3-5-mal mehr Treibhausgase eingespart werden als mit der gleichen Zahl an LPG-PKW (430-710.000 t_{CO2e} pro Jahr gegenüber 145-215.000 t_{CO2e} pro Jahr). CNG-PKW weisen pro km niedrigere Well-to-tank THG-Emissionen auf als LPG-PKW. Sekundäreffekte durch höhere LPG-Nachfrage wurden nicht berücksichtigt.
- Unter der Annahme der Zulassung von 1 Million zusätzlichen CNG- und LPG-PKW bis 2020 können diese mit 0.12–0.34 bzw. mit 0.09–0.19 Prozentpunkten zum THG-Reduktionsziel von 6% beitragen, das die EU-Kraftstoffqualitätsrichtlinie (EU-FQD) bis 2020 für die Minderung der THG-Intensität von konventionellem Benzin und Diesel vorschreibt. Der Hebel zur THG-Minderung ist damit bei CNG-PKW 3-mal höher bei LPG-PKW. Zudem können CNG-PKW zu den Zielen der EU-Erneuerbarenrichtlinie (EU-RED) beitragen, wenn Bio-Erdgas als Kraftstoff eingesetzt wird. LPG kann aus heutiger Sicht keine Beiträge zu EU-RED leisten.
- Da LPG ein Nebenprodukt mit begrenzter Verfügbarkeit ist, würde eine große Anzahl LPG-Fahrzeuge (z.B. 5-10 Millionen) in Deutschland starke Rückwirkungen auf andere LPG-Verbraucher und einen drastischen Anstieg der Importe zur Folge haben. CNG hat ein höheres Potenzial, eine größere Anzahl Fahrzeuge zu versorgen und damit die THG-Emissionen im Verkehr signifikant zu verringern.
- Bei großen Fahrzeugzahlen skaliert die THG-Reduktion nicht zwangsläufig linear mit der Anzahl Fahrzeuge, da ein signifikanter Anstieg der Nachfrage für CNG und LPG höhere Anteile aus nicht-konventionellen Quellen wie Ölsande oder Schiefergas mit sich bringen kann.

Treibhausgas-Einsparpotenziale durch zusätzliche CNG- und LPG-Fahrzeuge bis 2020



Umweltauswirkungen

- CNG-Fahrzeuge emittieren weniger CO_2 im Vergleich zu allen anderen fossilen Kraftstoffen auf Grund des geringeren Kohlenstoffanteils im Kraftstoff.
- Trotz der Einführung der EURO 6 Richtlinien im September 2015 werden Partikelemissionen der kritischste Schadstoff bleiben. Dies betrifft sowohl direkteinspritzende Diesel- als auch Ottomotoren. Mit direkteinspritzenden CNG-Ottomotoren können Partikelemissionen unter optimierten Verbrennungsbedingungen stark reduziert werden. LPG und CNG-Motoren mit Saugrohreinspritzung produzieren praktisch keine Partikel.
- Hybrid-Fahrzeuge bieten die Möglichkeit zu niedrigerem Kraftstoffverbrauch und damit zu niedrigen Treibhausgas (THG)- und Schadstoffemissionen. Während die relative Einsparung durch Hybridisierung von LPG-Fahrzeugen der Einsparung bei Benzinfahrzeugen entspricht, haben Hybrid-CNG-Fahrzeuge aufgrund der Motorcharakteristik einen stärkeren Einsparungseffekt.
- Zukünftige Effizienzsteigerungen in der Anlagentechnik für den Erdgastransport führen auch bei steigenden Transportwegen nicht zwangsläufig zu einem Anstieg der THG-Emissionen in der Versorgungsvorkette.
- Der Rückgang der Verfügbarkeit von Öl aus konventionellen Quellen führt bei LPG zu längeren Transportwegen sowie steigenden Anteilen aus nicht-konventionellem Öl.
- Teersande wurden als eine zusätzliche Rohöl-Quelle für LPG untersucht. Die damit verbundenen THG-Emissionen sowie andere Umweltauswirkungen sind signifikant höher als bei LPG aus der Raffinierung von konventionellem Rohöl oder aus der Erdgasgewinnung.
- Schiefergas (shale gas) wurde als eine zusätzliche Quelle für CNG untersucht. Die resultierenden THG-Emissionen steigen nur moderat, jedoch sind signifikante andere Umweltauswirkungen mit der Exploration und Gewinnung von Schiefergas verbunden.
- Die THG- und Schadstoffemissionen können weiter verringert werden, wenn Methan aus erneuerbaren Energien verwendet wird, z.B. aus Biogas (ohne Landnutzungsänderungen) oder synthetisches Methan aus erneuerbarem Strom (SNG).

Fazit

- Die EU-Ziele von 6% niedrigerer THG-Intensität in Kraftstoffen (EU-FQD) sowie der Einführung von 10% erneuerbaren Kraftstoffen in jedem EU-Mitgliedsland (EU-RED) unter Berücksichtigung von Nachhaltigkeitskriterien für Biomasse stellen ein bedeutendes politisches Moment für Bio-Erdgas in CNG-Fahrzeugen dar.
- CNG stellt eine kurzfristige, verfügbare Verbesserung der Umweltauswirkungen des Straßenverkehrs dar. Mit Blick auf Schadstoffemissionen in urbanen Räumen ist der Vorteil von CNG gegenüber dem Dieselantrieb bei leichten und schweren Nutzfahrzeugen am höchsten.
- CNG-Fahrzeuge haben ein höheres Potenzial zur THG-Minderung als LPG, sowohl spezifisch als auch in absoluten Zahlen.
- Im globalen Maßstab ist das Potenzial von LPG als ein Nebenprodukt aus Erdgasgewinnung und Ölraffinerien auf die Verfügbarkeit fossiler Rohstoffen begrenzt. Die weltweite Ölversorgung ist möglicherweise bereits rückläufig; bei Erdgas wird der Förderhöhepunkt in der nächsten Dekade erwartet. Die fossile Verfügbarkeit von CNG hat weniger Limitierungen als LPG. Des Weiteren steht Bio-Erdgas aus organischen Quellen sowie synthetisches Methan aus erneuerbarem Strom und CO_2 (SNG) als direkte Ergänzung für die begrenzten fossilen Erdgasvorräte zur Verfügung.

1 INTRODUCTION, MOTIVATION AND METHODOLOGY

Compressed natural gas (CNG) and liquefied petroleum gas (LPG) are two alternative fuels available at a large number of fuelling stations in Germany. Though both being gaseous at ambient conditions, these fuels are very different over all aspects from the sources over supply pathways to on-board storage and engine technology. For this reason, also their potential role in the transportation sector and their environmental impacts differ significantly. The purpose of the study at hand is therefore to evaluate the environmental performance and greenhouse gas (GHG) potentials for conventional fuel substitution and GHG emission reduction of LPG and CNG in the German transportation sector until 2020.

The study comprises three main parts. Chapter 2 gives an overview over the past and current use of CNG (compressed natural gas) and LPG (liquefied petroleum gas) with a focus on the transport sector in Germany. Chapter 3 compares the environmental performance (efficiency, greenhouse gas and pollutant emissions) of LPG versus CNG versus fossil-based gasoline today and with an outlook to future trends. Chapter 4 describes potential LPG and CNG scenarios for the reduction of greenhouse gas emissions in German road transport and its dependence on mineral oil.

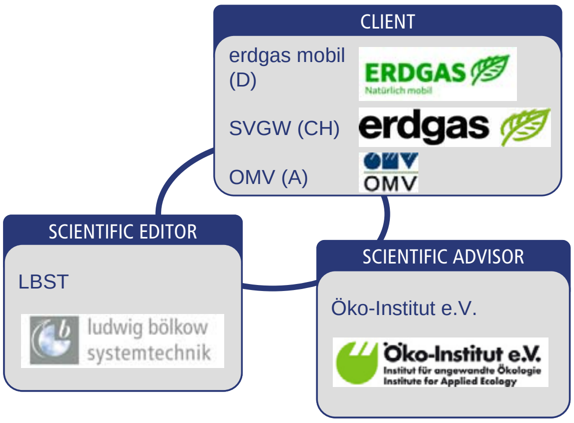
The analysis of environmental performance builds upon the CONCAWE-EUCAR-JRC study "Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context" [CONCAWE 2008]. Compared to the CONCAWE study, the portfolio of pathways has been extended substantially for both LPG and CNG (e.g. including CNG from shale gas, and LPG from crude oil and oil sands). Furthermore, also existing pathways have been revisited, validated and updated, and pollutant emissions have been assessed in view of the upcoming Euro 6 emission limits.

The study has been jointly commissioned by two associations for natural gas as a transport fuel and a natural gas supplier, namely

- erdgas mobil (Germany, erdgasmobil.de),
- SVGW (Switzerland, svgw.ch), and
- OMV (Austria, omv.at).

The study has been carried out by Munich based strategy and technology consultant Ludwig-Bölkow-Systemtechnik GmbH (lbst.de) throughout the first half of 2010.

Dr. Uwe Fritsche of Öko-Institut e.V. (oeko.de) served as scientific advisor to the project.



2 STATUS QUO AND FRAMEWORK CONDITIONS

This section discusses the availability of liquefied petroleum gas (LPG) and natural gas (NG) in Germany in a European context considering global energy supply pathways. To this end, an overview of quantities, origins and uses of LPG and NG in the energy sector is given.

Both petroleum gas and natural gas are so-called 'extractive' resources, i.e. fossil fuels that are exploited from gas or oil wells. The extracted raw fuel needs to be transported to the processing facility. The processing of raw fuel comprises the separation of hydrocarbon products depending on their chain length. The fuel is transported internationally and distributed through local networks to the end users.

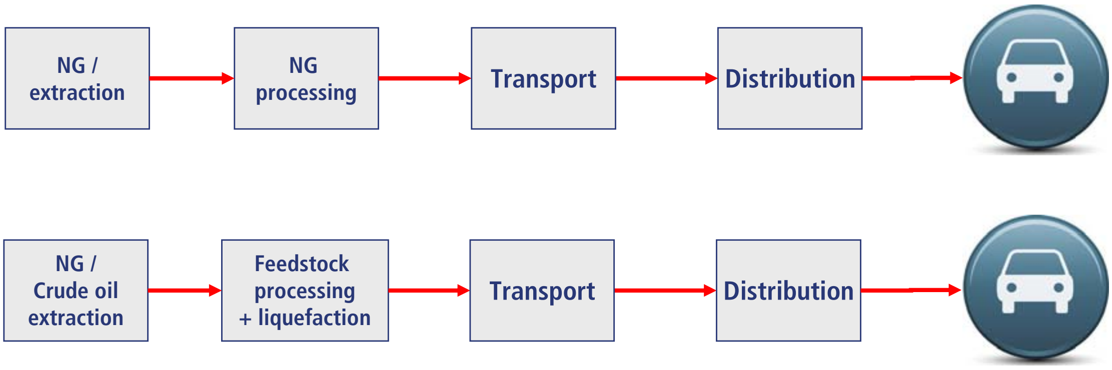


Figure 1: Simplified process scheme from CNG/LPG extraction for use as transport fuel

For a detailed description of environmental performance of the various extraction, processing, transport and distribution pathways for LPG and CNG and their use as a fuel in the transport sector, refer to chapter 3.

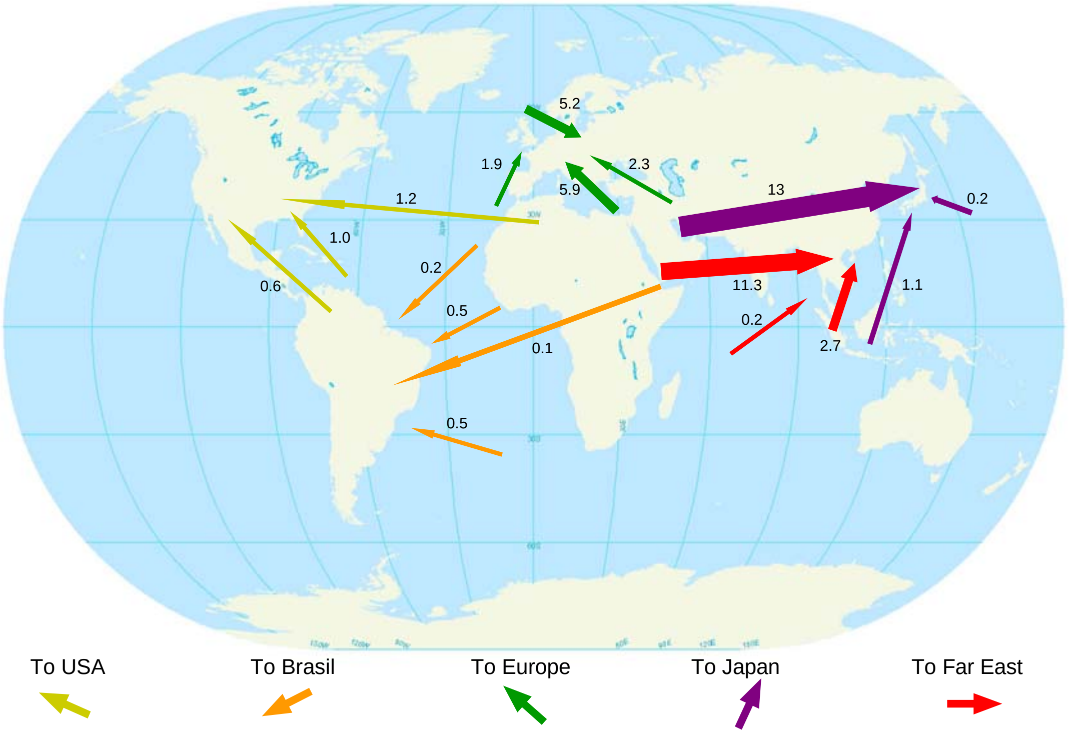
2.1 LPG

LPG stands for 'liquefied petroleum gas'. In the passenger vehicle sector, LPG as a transport fuel is commonly referred to as GPL from the French word 'Gaz de Pétrole Liquéfié'.

There are two sources for petroleum gas. On the one hand, petroleum gas comes as a co-product from natural gas extraction, i.e. the heavy fractions separated from the output stream of natural gas wells separated on-site ('well head'). On the other hand, petroleum gas comes as a by-product from crude oil refining. Petroleum gas is liquefied for the purpose of easier transport handling, and thus trading.

Since LPG accrues as an inevitable co-product, the market for LPG is supply-driven.

Figure 2 depicts the main trading routes of LPG worldwide.



Source: Statistical Review of Global LP Gas 2009

Figure 2: **World wide LPG trade in millions of metric tonnes (LBST based on [WLPGA 2009])**

Table 1 lists the LPG streams in Germany, Europe, and worldwide in the year 2008, compiled by the sector's representative organisation, the World LPG Association.

Table 1: **Availability of LPG in Germany, Europe and worldwide in 2008 [WLPGA 2009]**

[1,000 t]; 1 t = 46 GJ	Production		Import	Export	Use in Transport
	Gas Processing	Refinery			
Worldwide	126,194	115,512	73,500	73,933	20,879 (8.67%)
Europe/Eurasia	9,864	33,087	19,698	17,805	8,191 (18.79%)
Germany	0	2,512	889	557	247 (8.59%)

In Germany, LPG predominantly originates from the refineries. The main areas of application of LPG are household use (30% in 2008) and as an input material for the chemical industry (51% in 2008) [WLPGA 2009] Like CNG, LPG is also used as a transportation fuel. Some 8.6% of LPG in Germany goes into the transport sector. The characteristic, e.g. the octane number, of petroleum gas is similar to the one of gasoline, which is why it is used in spark ignition engines.

2.2 CNG

Natural gas (NG) is a fossil fuel used for various purposes like electricity generation, heating or transportation fuel. The major part of natural gas sources can be found outside of Europe. The main natural gas transportation routes to Europe are mapped in Figure 3.

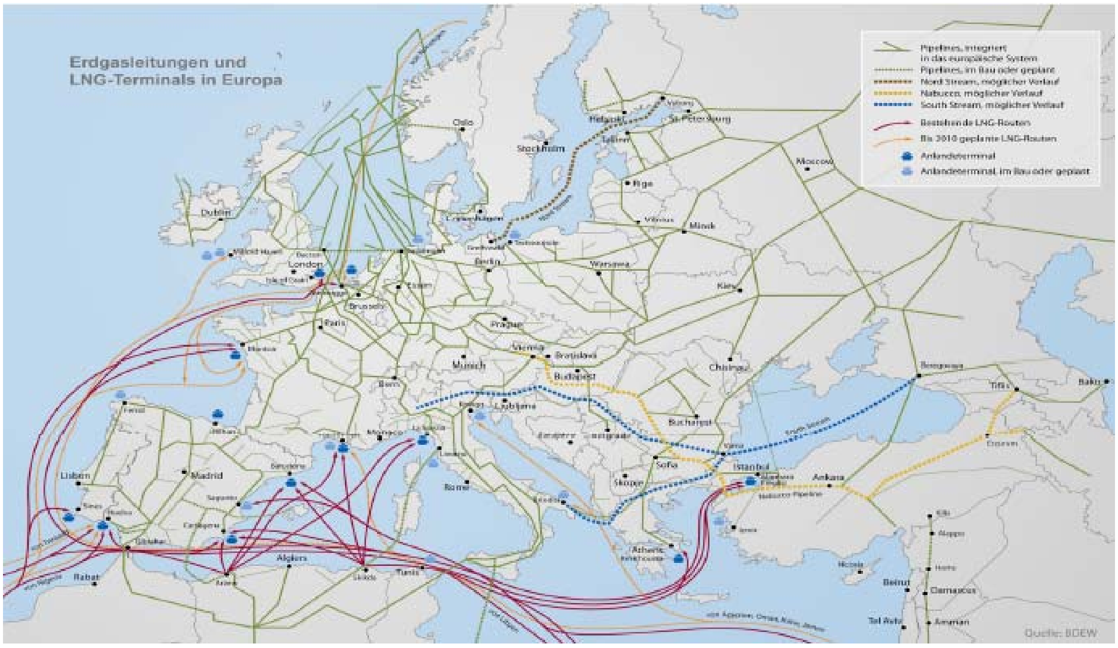


Figure 3: European natural gas pipelines and ship transport [BDEW 2009]

Natural gas is mostly transported through gas pipelines. Increasingly, but still at a low share, natural gas is liquefied for overseas shipping (LNG). The volumes produced and traded worldwide, in Europe, and in Germany are depicted in Table 2.

Table 2: **Availability of natural gas in Germany, Europe and worldwide [IEA 2009a, IEA 2009b, AGEB 2009, BAFA 2009, BMWi 2010]**

[PJ/yr]	Production	Import	Export	Thereof for transport	Share dedicated to transport
Worldwide (2007)	104,587.5	31,717.1	31,093.7	505.8	0.48%
OECD Europe (2007)	9,907.2	14,545.8	5,895.9	26.4	0.14%
Germany (2007)	598.8	3,323.7	450.9	4.1	0.12%
Germany (2008)	545.4	3,480.5	471.3	4.1	0.12%
Germany (2009)	509.9	3,551.3	421.0	6.1	0.17%

Natural gas is mostly used for electricity generation, heating, and cooking purposes as well as basic input material for chemical processes. The share of natural gas used in transport is yet very low worldwide (<< 1%). Exceptions are e.g. Argentina with 1.8 million CNG vehicles as of December 2009 and Italy with more than 7% by market share in 2009. The origins of natural gas in Germany are depicted in Figure 4. Russia and Norway are the major suppliers providing 1/3rd of natural gas consumed in Germany in 2009. The Netherlands and Germany together provide about the same share.

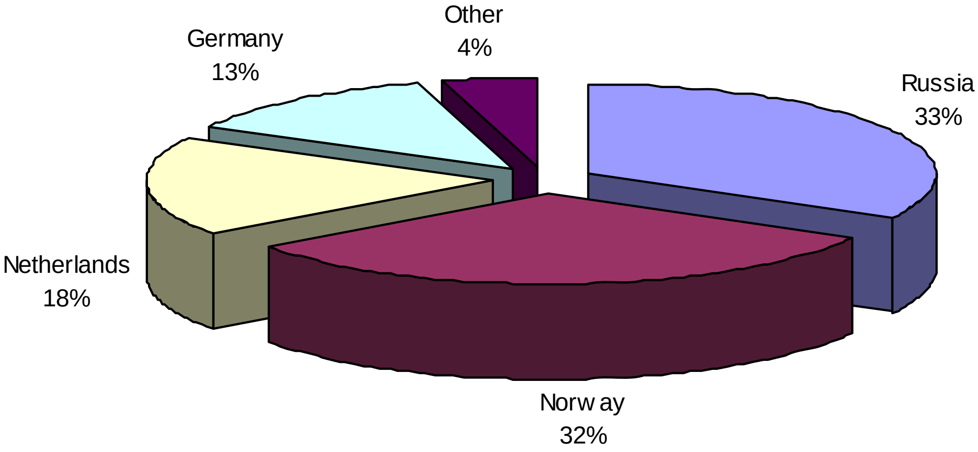


Figure 4: **Origins of natural gas used in Germany in 2009 (all uses) [BAFA 2009]**

For the purpose of this study, particular focus is laid on compressed natural gas (CNG) for the use of natural gas in transport. No literature resource could be found that depicts the origins of CNG dedicated to transport fuel use in Germany. CNG as transport fuel is generally derived from the public natural gas grid and – to a lesser extent – directly from LNG in Germany. Assuming CNG from the grid mix is a fair approximation for the purpose of this study.

The number of CNG vehicles deployed between 2002 and 2009 grew by an average 31%/yr as depicted in Figure 5.

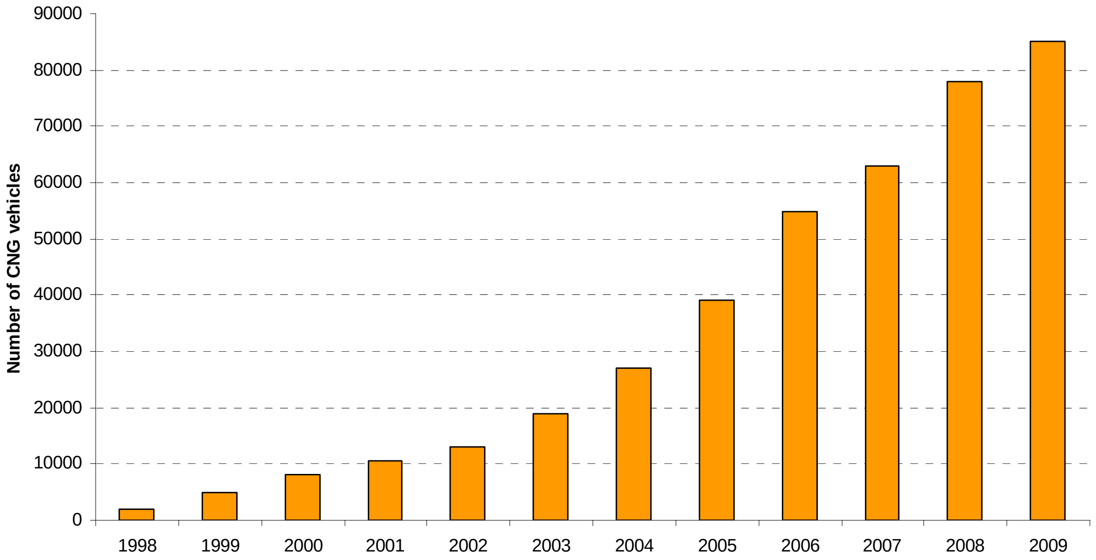


Figure 5: **Number of licensed CNG vehicles in Germany 1996 – 2009 (all uses) [dena 2010]**

By the end of 2009, 86,264 CNG vehicles were licensed in Germany [KBA 2010], most of them being passenger cars. Figure 6 shows the split of CNG vehicles by vehicle type.

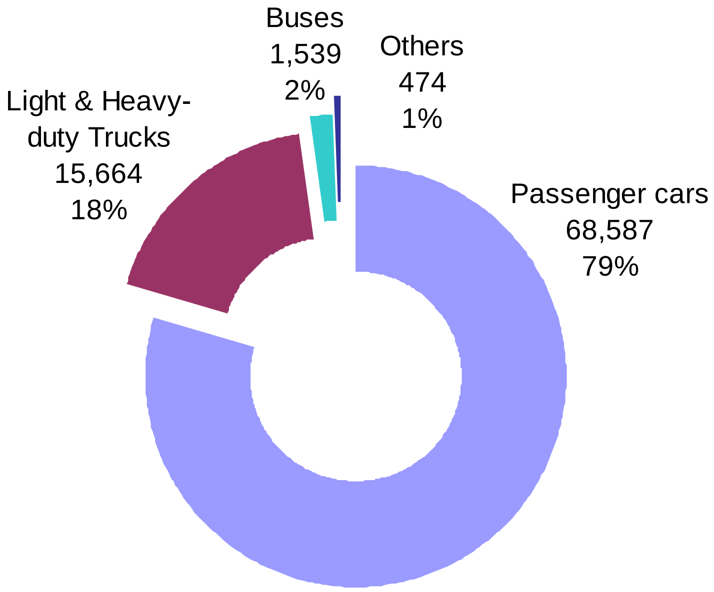


Figure 6: **CNG vehicles in Germany by vehicle type in 2009 [KBA 2010]**

In line with increasing deployment of natural gas vehicles, natural gas consumption has increased in the transport sector (see Figure 7) [1].

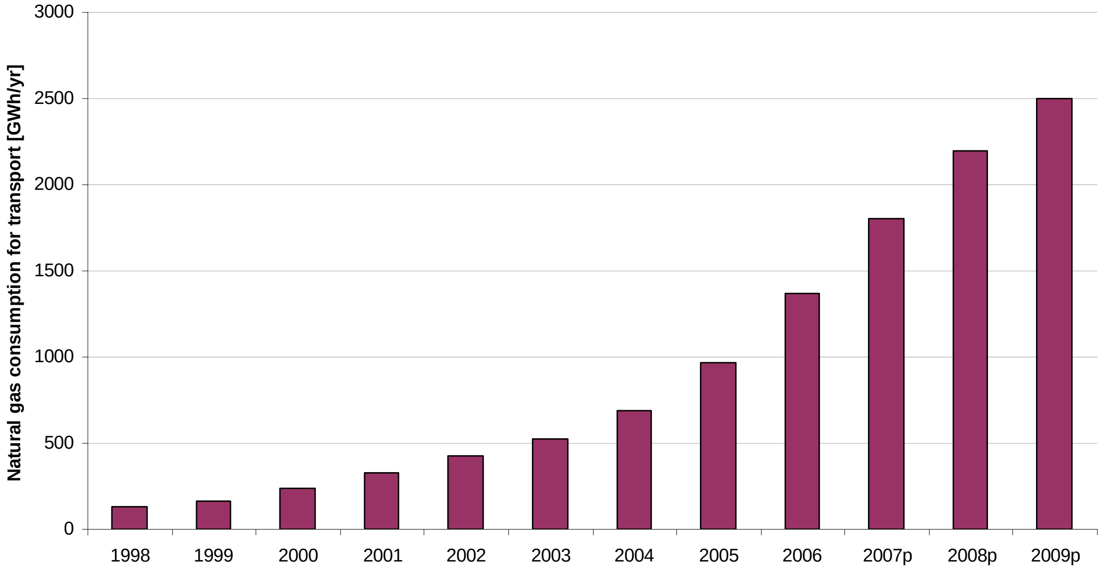


Figure 7: **Natural gas use for transportation in Germany 1998 – 2009 (2007 – 2009 are forecasts) (LBST derived from [BDEW 2009])**

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[1] There is some inconsistency between the different sources for Figure 7 and Table 2: the 4.1 PJ/a specified in Table 2 for 2007 are equivalent to 1,140 GWh/a, which according to Figure 7 is below the 2006 value; however, there no decrease in natural gas use for transportation could be observed.

RESOURCES & STRATEGIES

Oil resources meanwhile are recognised for their supply availability to decline shortly, i.e. this decade already [EWG 2007], [IP 2008], [Guardian 2009]. Still low on the public agenda is the resource situation of the natural gas supply base. World production could enter into decline in the next decade [AWEO 2007], [BMU 2010], [SOS 2010]. In this context, vulnerabilities prevail, like

- the German as well as European own supply base for oil and gas is already declining, i.e. imports from non-European countries are set to rise;
- geopolitical aspects impacting on the security of energy supply, especially with increasing energy dependency from non-European countries;
- the almost total dependency of the transport sector (i.e. road, maritime, aviation) on fossil-based fuels, which is to prevail throughout the short to medium-term future;
- LPG availability is subject to vectorisation of well-head NGL as well as refiners' decision to increase the gasoline fraction.

While there is no single 'silver bullet' answer to the two-fold challenges of a secure and sustainable energy supply, natural gas provides some distinct strategic propositions to foster sustainable development in the transport sector in the short-term:

- Reduced pollutant emissions, especially emissions of local particulate matter (PM) in urban conglomerations.
- Increasing public acceptance and awareness of transport fuel alternatives to petrol and diesel propulsion.
- Phase-in of gaseous fuels in the transport sector with a view to hydrogen as a long-term, sustainable transport fuel for various transport modes next to electricity.
- Diversification and 'greening' of the road transport sector through using methane derived from biogas (though limited and under competition with other uses) and synthesised natural gas (SNG) derived from hydrogen that is produced from renewable electricity (possibly with excess electricity occurring with high shares of renewable power in the grid). Furthermore, hydrogen can be directly admixed to the natural gas grid up to a few percent (by energy content) without the need for infrastructure modifications.
- Diversification and 'greening' of aviation (use of LNG with a view towards liquid hydrogen) and maritime shipping (use of LNG boil-off as well as dedicated LNG with a view to emission control areas expected to be further extended).

GOING RENEWABLE – METHANE FROM BIOGAS

The following table shows how biogas production has been growing throughout the last five years in Germany.

Table: Biogas quantities produced in Germany between 2006 and 2009 (estimated amounts based on installed capacities) derived from [BEE 2010]

Year	2006	2007	2008	2009
Raw biogas (TWh)	22.91	32.03	36.36	40.00

As biogas feedstock livestock manure, municipal waste, and maize are typically used in Germany. With a view to an increased use of bio-methane in the transport sector, dedicated energy crops for biogas production are needed, e.g. maize (whole plant) or double-cropping.

Today, bio-methane is already sold at public fuelling stations. Stadtwerke München (SWM – Municipal Utility Munich) sells natural gas for road vehicles blended with 20% methane from biogas. Energieversorgung Weser-Ems (EWE – Weser-Ems Regional Utility) is selling a 10% admixture of bio-methane at more than 50 CNG refuelling stations. A first refuelling station solely dedicated for dispensing bio-methane has been erected in Jameln, Wendland, Germany by the Raiffeisen- und Warengenossenschaft e.G. In Sweden, E.ON Gas Sverige is selling CNG with a content of at least 50% bio-methane.

In 2009, the European Union voted for a target of 10% of renewable energies in transport fuels by 2020 [EU-RED 2009], for which all renewable energy sources are eligible, i.e. biofuels (including bio-methane), hydrogen, and electricity from renewable energy sources.

As a contribution to the EU targets for renewable energies in transport, power and heat supply, the European Biomass Association [AEBIOM 2009] proposed a share of 1-2% of the transportation fuel in 2020 to come from methane derived from biogas, 2-3% of electricity to be produced from biogas, and a 1% contribution of biogas to heat supply in Europe. To this end, [AEBIOM 2009] suggests that the corresponding biogas quantities could be produced if 35% of the overall manure, 40% of the overall bio-digestible organic waste and water treatment sludge, and energy crops cultivated on 5% of the overall arable land in Europe were used for biogas production. The shares seem reasonable and achievable. Competition in land-uses is avoided with the use of waste streams as input to biogas production.

3 ENVIRONMENTAL PERFORMANCE OF LPG AND CNG

3.1 Methodology

3.1.1 CO_2 equivalents

Greenhouse gases considered in this study are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) [2]. The global warming potential of the various greenhouse gases is expressed in CO_2 equivalents. Table 3 shows the relative global warming potential for a period of 100 years according to the latest update from the Intergovernmental Panel on Climate Change (IPCC) in 2007.

Table 3: Global warming potential of various GHGs [IPCC 2007]

	CO_2 equivalents [g/g]
CO_2	1
CH_4	25
N_2O	298

The combustion of biomass is considered CO_2 neutral because the amount of CO_2 emitted during the combustion of the biomass is the same as the amount of CO_2 which has been removed from the atmosphere during the growth of the plants. In the evaluation only CO_2 generated by the combustion of fossil fuels is considered.

3.1.2 Efficiency method

For a calculation of the energy requirements for the supply of transportation fuel, the so-called "efficiency method" has been applied here similar to the procedure adopted by international organisations (IEA, EUROSTAT, ECE). In this method the efficiency of electricity generation from nuclear power is based on the heat released by nuclear fission which leads to an efficiency of about 33%. In the case of electricity generation from hydropower and other renewable energy sources where the useful energy produced cannot be measured in terms of a calorific value (wind, solar energy) the energy input is assumed to be equivalent to the electricity generated which results in an efficiency of 100%.

3.1.3 System boundaries

The energy requirements and emissions resulting from the construction and decommissioning of the fuel production plants are not considered. Furthermore, the

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[2] Other greenhouse gases are CFCs, HFCs and SF_6 but are not relevant in this context.

energy requirements and emissions resulting from the manufacturing and decommissioning of the vehicles have been neglected.

All calculations of energy use and emissions are based on the lower heating value (LHV).

3.2 Well-to-tank (WTT)

3.2.1 Gasoline and diesel from conventional crude oil

Crude oil is extracted and transported to a refinery. For the supply and use of gasoline in the EU the energy requirements and associated GHG emissions for the supply of crude oil are derived from [CONCAWE 2008]. The air pollutant emissions have been derived from [BP 2000], [OLF 2001], [Shell Nigeria 2001], [UKOOA 2001]. The crude oil input includes the LHV of the delivered crude oil.

Table 4: Energy requirement and emissions from crude oil extraction

	I/O	Unit	Amount
Crude oil	Input	MJ/MJ	1.025
Crude oil	Output	MJ	1.000
Emissions			
CO_2 equivalent	-	g/MJ	3.3
NO_x	-	g/MJ	0.011
Dust/PM	-	g/MJ	0.000
SO_2	-	g/MJ	0.007
NMVOC	-	g/MJ	0.029
CO	-	g/MJ	0.008

The energy requirements and GHG emissions have been derived from [CONCAWE 2008]. The air pollutant emissions have been derived from [ESU 1996].

Table 5: Energy requirements and emissions from crude oil transport

	I/O	Unit	Amount
Crude oil	Input	MJ/MJ	1.000
Heavy fuel oil	Input	MJ/MJ	0.010
Crude oil	Output	MJ	1.000
Emissions			
CO_2 equivalent	-	g/MJ	0.8

NO_x	-	g/MJ	0.015
Dust/PM	-	g/MJ	0.001
SO_2	-	g/MJ	0.015
NMVOC	-	g/MJ	0.001
CO	-	g/MJ	0.002

The heavy fuel oil input is connected with its supply.

The crude oil is converted to gasoline and diesel in a refinery. The energy requirement and GHG emissions for the refinery have been derived from [CONCAWE 2008]. The air pollutant emissions have been derived from [FEA 1999].

Table 6: Gasoline and diesel from crude oil refining

	I/O	Unit	Gasoline	Diesel
Crude oil	Input	MJ/MJ	1.08	1.10
Diesel	Output	MJ	1.00	1.00
Emissions				
CO_2	-	g/MJ	7.0	8.6
NO_x	-	g/MJ	0.0072	0.0089
Dust/PM	-	g/MJ	0.0006	0.0006
SO_2	-	g/MJ	0.0103	0.0131
NMVOC	-	g/MJ	0.0094	0.0117
CO	-	g/MJ	0.0039	0.0047

Gasoline and diesel is transported to a depot via pipeline, barge (distance: 500 km) and rail (distance: 250 km). The share of gasoline transport via pipeline is 60%, the share of inland navigation is 20% and the share of rail is 20%. The electricity consumption for the transport of gasoline via pipeline is about 0.0002 kWh/kWh of gasoline. About 0.012 tkm per MJ of gasoline and diesel are required for the transport of gasoline via barge over a distance of 500 km. Table 7 shows the fuel consumption and the GHG emissions of a typical barge. The diesel consumption and emissions of the barge have been derived from [ESU 1996]. A return voyage (empty) is considered for the fuel consumption of the barge.

Table 7: Fuel consumption and GHG emissions of a barge

	I/O	Unit	Amount
Diesel	Input	MJ/tkm	0.50
Distance	Output	tkm	1.000
Emissions			
CO_2	-	g/tkm	38.0
CH_4	-	g/tkm	0.03
N_2O	-	g/tkm	0.00
NO_x	-	g/tkm	0.3
Dust/PM	-	g/tkm	0.03
SO_2	-	g/tkm	0.031
NMVOC	-	g/tkm	0.04
CO	-	g/tkm	0.17

For the transport of gasoline over a distance of 250 km about 0.0058 tkm per kWh of gasoline and diesel are required. The electricity consumption of the train is about 0.21 kWh per tkm. The electricity requirement of the train is met by the EU electricity mix (10-20 kV level).

The electricity consumption of the depot is about 0.0008 MJ/MJ of diesel. From there the diesel is distributed to the filling stations via truck over an average distance of 150 km. The electricity for the train (10-20 kV level) and the electricity for the depot and the filling station (0.4 kV level) is derived from the EU electricity mix. The electricity requirement of the refuelling station amounts to about 0.0034 MJ/MJ of gasoline or diesel.

3.2.2 Gasoline and diesel from oil sands

This pathway describes crude oil derived from oil sands in Canada.

Surface mining

At first the cover layers of soil (overburden) has to be removed. A part of the overburden is used to construct the containment structures for the tailings (excavation residues). The oil sand is mined with electric or hydraulic shovels and subsequently transported to the crushers. After crushing, the oil sand is converted to a slurry. From the slurry a bitumen froth is extracted in a primary separation step. The bitumen froth is transported to the oil extraction site using centrifugal pumps and pipelines. The bitumen froth typically consists of about 60% bitumen, about 30% water and about 10% fine solids. The tailings from the bitumen froth production are sent to tailings setting basins.

The bitumen is extracted from the bitumen froth using the naphtha solvent or the paraffinic solvent process. The naphtha solvent based process requires inclined plate separators and centrifuges to remove solids and water. A more advanced process with paraffinic solvent adds further process vessels but eliminates high maintenance intensive centrifuges and results in a cleaner product [ACR 2004]. Bitumen produced by the naphtha solvent based dilution centrifuge process as practiced by Suncor and Syncrude contains approximately 0.3 – 0.5% solids and 1 – 2% water. This makes it unsuitable for pipeline transport and for direct sale to traditional refineries. Therefore, its further upgrading is required.

In-situ extraction

The bitumen can be extracted in-situ via the steam assisted gravity drainage (SAGD) process. In case of the SAGD process several horizontal well pairs are drilled over a distance of 1,000 m into the oil sand layer. The top well of a pair is used to inject steam to warm up a zone around and below the injector, reducing the viscosity and mobilizing the bitumen, which is then extracted with the lower well. The steam-to-oil ratio ranges from 1.5:1 to 3.0:1 on a volume basis. The ultimate recovery is expected to be between 40 and 70% [ACR 2004], [Söderbergh 2006].

The surface facilities consist of water treatment plants to produce boiler feed water from steam condensate or brackish water produced from local aquifers. Steam generators or co-generation plants provide steam for injection into the reservoir. The oil is separated from the emulsion produced by blending it with condensate and treating it with chemicals at elevated pressure.

Upgrading

Raw bitumen is a thick tar-like substance, often containing sulphur and heavy metals. It has a density of 970 to 1,015 kg/m^3. Since bitumen is lacking hydrogen, it must be upgraded into higher quality synthetic crude oil (SCO) to make it an acceptable feedstock for conventional refineries. The upgrading to synthetic crude oil (SCO) mainly comprises coking and hydrotreating. The hydrogen required is generated via steam reforming of natural gas or via gasification of residues.

Combined mining and upgrading

The data for the production of synthetic crude oil (SCO) from oil sands have been derived from [Renewbility 2009] and are based on data from Syn-Crude and SunCor in Canada. Bitumen from oil sands is used as fuel and as feedstock for the upgrading process. Until now Syn-Crude only applies via surface mining. Next to surface mining SunCor also applies in-situ-extraction.

Table 8: Energy use and emissions for the production of synthetic crude oil (SCO) from oil sands in Canada

	I/O	Unit	Amount
Oil sands	Input	MJ/MJ	1.279
Crude oil	Output	MJ	1.000
Emissions			
CO_2	-	g/MJ	68.9
CH_4	-	g/MJ	
N_2O	-	g/MJ	
NO_x	-	g/MJ	0.151
Dust/PM	-	g/MJ	
SO_2	-	g/MJ	0.414
NMVOC	-	g/MJ	0.232
CO	-	g/MJ	

Other environmental impacts are the pollution of water with toxic substances endangering drinking water supplies and the disturbance of large areas resulting in a loss of biodiversity. For the bitumen extraction about 2 to 4 barrels of water per barrel of raw bitumen are required. The residue containing toxic substances ("tailings") from the production of synthetic crude oil (SCO) is stored in open ponds. Leaks can lead to the contamination of both ground and surface water [Pembina 2009].

Transport to the EU

The synthetic crude oil is transported to the coast via pipeline over a distance of 5,000 km. The electricity consumption for the transport via pipeline is about 0.0082 MJ/MJ of crude oil and has been derived from [GEMIS 2005]. From the coast the crude oil is transported to the EU via ship over a distance of 6,000 km. The ship is now being fuelled with heavy fuel oil (HFO) with a sulphur content of 3.5%. The specific emissions and energy consumption of the oil tanker (Table 9) have been derived from [ESU 1996].

Table 9: Fuel consumption and GHG emissions of the oil tanker

	I/O	Unit	Amount
Heavy fuel oil (HFO)	Input	MJ/tkm	0.056
Distance	Output	tkm	1.000
Emissions			
CO_2	-	g/tkm	4.3
CH_4	-	g/tkm	
N_2O	-	g/tkm	

	I/O	Unit	Amount
NO_x	-	g/tkm	0.086
Dust/PM	-	g/tkm	0.004
SO_2	-	g/tkm	0.086
NMVOC	-	g/tkm	0.003
CO	-	g/tkm	0.011

In the EU synthetic crude oil (SCO) is processed in a refinery nearby the import terminal. For the refinery and for the distribution of the final fuel the same assumptions have been made as for the pathways where conventional crude oil is converted to gasoline and diesel (chapter 3.2.1).

3.2.3 LPG from natural gas processing

Besides methane (CH_4) the gases stored in natural gas fields contain combustible gases such as ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}). During natural gas processing propane and butane are separated and sold as LPG. The energy requirements and emissions for the supply of LPG from natural gas processing have been derived from [ETSU 1996]. The data indicated in [ETSU 1996] are related to the upper heating value (HHV) and have been converted to numbers based on the lower heating value (LHV)[3]. Table 10 shows the inputs and outputs for the extraction of LPG. The LPG input represents the LPG extracted from the natural gas field.

Table 10: Energy use and emissions for extraction and processing of LPG

	I/O	Unit	Output
Natural gas	Input	MJ/MJ	0.053
LPG	Input	MJ/MJ	1.000
LPG	Output	MJ	1.000
Emissions			
CO_2	-	g/MJ	3.1
CH_4	-	g/MJ	0.015
N_2O	-	g/MJ	0.000
NO_x	-	g/MJ	0.009
Dust/PM	-	g/MJ	0.000
SO_2	-	g/MJ	0.000
NMVOC	-	g/MJ	0.011
CO	-	g/MJ	0.001

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[3] HHV (propane) = 50.0 MJ/kg; LHV (propane) = 46.4 MJ/kg

In case of small scale LPG carriers the LPG is liquefied via compression and stored onboard in pressure vessels. In case of large LPG carriers the LPG is liquefied via cooling down to -48°C (the boiling point of LPG at 0.1013 MPa amounts to about -42°C) and stored onboard in cryogenic tanks.

For the liquefaction of LPG via cooling about 130 MJ of electricity is required per t of LPG [ETSU 1996]. In the UK LPG consists of a mixture of about 90% propane by volume and 10% butane by volume [ETSU 1996]. In Germany LPG comprises 60% propane by volume and 40% butane by volume in winter and 40% propane by volume and 60% by volume in summer. Throughout one year an average mix of 50% propane and 50% butane by volume can be assumed for Germany resulting in about 47% propane and 53% butane by energy (LHV).

Table 11: Fuel properties of LPG

	Unit	Propane	Butane
Lower heating value (LHV)	MJ/kg	46.35 (1) 46.33 (2)	45.74 (1) 45.62 (2)
Density @ 15°C, liquid	kg/l	0.51	0.59
Composition in Germany			
Winter	% by volume	60	40
Summer	% by volume	40	60
Average	%by volume	50	50
	% by energy	47	53

(1) Calculated; (2) Erdgas mobil, 2010

Assuming an LHV of 46.0 MJ/kg (mix of propane and butane as indicated for Germany) the electricity effort for liquefaction would be about 0.0028 MJ per MJ of LPG. It is typically met by a natural gas fuelled combined cycle gas turbine (CCGT) power plant with an efficiency of 55%.

The transport capacity of the LPG carrier “Djanet” by Kawasaki amounts to about 84,000 m³ of LPG [Kawasaki 2000]. Another Kawasaki built LPG carrier “Grace River” has a similar transport capacity of 79,200 m³ of LPG (~45,000 t LPG) [Kawasaki 1/2002].

Figure 8: **LPG carrier "Grace River" [Kawasaki 1/2002]**

The majority of Japanese ports are adapted to unload such large LPG carriers [Kawasaki 2/2002]. The data for "Djanet" have been used for the calculation in [CONCAWE 2008].

Table 12: **LPG Carrier "Djanet" [Kawasaki 2000]**

	LPG carrier
Transport capacity (LPG)	84,310 m^3
Velocity	16.8 kn (31 km/h)
Propulsion power (Kawasaki-MAN B&W 5S70MC Mk VI)	13,646 kW
Fuel	Heavy fuel oil (HFO)

At -42°C and 0.1 MPa the density of propane is about 0.58 t per m^3. At -48°C and 0.1 MPa the density of propane becomes about 0.59 t per m^3. The maximum allowed fill factor is 0.98. As a result about 47,900 t of LPG can be transported at a rated transport capacity of 84,310 m^3 as indicated for the LPG carrier "Djanet". The specific fuel consumption of the ship's main engine (a 2-stroke diesel engine) is about 169 g per kWh of mechanical work ±5% based on a fuel with a LHV of 42.7 MJ/kg. This results in an overall efficiency of about 49.9% [MAN 2003].

For the transport distance two options have been taken into account:

- LPG from remote natural gas fields, one way distance for maritime LPG transport: 5,500 nautical miles (10,186 km).
- LPG from natural gas fields in the North Sea, one way distance for maritime LPG transport: 1,000 km.

The storage of large amounts of LPG at depots generally is carried at cryogenic conditions (< -42°C) [ETSU 1996]. Further on, it has been assumed that the LPG is distributed via truck over an average distance to the refuelling stations. Onboard the truck the LPG is stored at elevated pressure to keep the LPG liquid. According to [SeAH 2003] the geometric volume of an LPG trailer tank amounts to about 43.5 m^3. At a maximum allowable fill factor of 0.85 and a LPG density of 0.5 t per m^3 about 18.5 t of LPG can be carried in one LPG trailer tank as indicated in the data sheet of the manufacturer. The mass of the LPG tank itself amounts to about 8.6 t.

The payload specific fuel consumption is based on an assumed fuel consumption of 35 l diesel fuel per 100 km. In [KFZ-Anzeiger 2003] a Mercedes-Benz Actros 1844 has been tested with an average fuel consumption of 31.6 l diesel per 100 km. The previous model (Mercedes-Benz Actros 1843) consumed 34.9 l diesel per 100 km. In [KFZ-Anzeiger 2001] another truck, the MAN TG 510 A had been tested. Its fuel consumption was 37.0 l diesel fuel per 100 km. In [ETSU 1996] the fuel consumption of a truck with a payload of 25 t amounts to 32.8 l diesel fuel per 100 km also leading to about 0.26 kWh per tkm if the return voyage (empty) is considered. Therefore it can be concluded that 0.26 kWh/tkm is a realistic assumption.

Table 13 shows the fuel consumption and the emissions of a truck with a gross weight of 40 t and a payload of about 27 t which is typically used for LPG transport. The truck meets the Euro 4 emission limits. The emission limits for heavy trucks are indicated in g per kWh of mechanical work. For the conversion into g per km the efficiency of the diesel engine for a driving cycle has been assumed to be 37.5% based on information from a manufacturer of heavy trucks.

Table 13: Fuel consumption and emissions of a 40 t truck

	I/O	Unit	Amount
Diesel	Input	MJ/tkm	0.94
Distance	Output	Tkm	1.0000
Emissions			
CO_2	-	g/tkm	68.6
CH_4	-	g/tkm	0.005
N_2O	-	g/tkm	0.000
NO_x	-	g/tkm	0.341
Dust/PM	-	g/tkm	0.002
SO_2	-	g/tkm	0.000
NMVOC	-	g/tkm	0.040
CO	-	g/tkm	0.146

The LPG is transferred from the LPG trailer into the stationary pressure vessels at the refuelling station by simple pressure difference. Therefore, no additional electricity for compression is required. It has been assumed that the electricity consumption of the LPG refuelling station is the same as for a typical gasoline or diesel fuel refuelling station. According to [TotalFinaElf 2002] the electricity consumption of a gasoline or diesel fuel refuelling station is about 0.0034 MJ per MJ of gasoline or diesel fuel. Analogous to [CONCAWE 2007] and [RED 2009] it has been assumed that the electricity requirement is met by the EU electricity mix (467 g CO_2 equivalent per kWh of electricity). Using the Germany electricity mix (~575 g CO_2/kWh_e according to [UBA 2010a][4]) would result in slightly higher overall GHG emissions. Yet, the increasing renewable energy share in the future will decrease the GHG emissions for electricity supply.

3.2.4 LPG from crude oil refinery

Two options for the supply of crude oil have been assessed: One option based on the use of conventional crude oil (see chapter 3.2.1) and one using synthetic crude oil (SCO) from oil sands (see chapter 3.2.2).

LPG is produced by various processes within a crude oil refinery. LPG can be extracted from the light ends of the atmospheric distillation unit, the light ends of cracking processes (hydrocracker, FCC cracker), the light ends of the visbreaker or a coker, as by-product from the catalytic reformer/platformer, and as by-product from the benzene removal downstream the catalytic reformer/platformer (reformate fractionation and hydrogenation) being used to elevate the octane number of naphtha.

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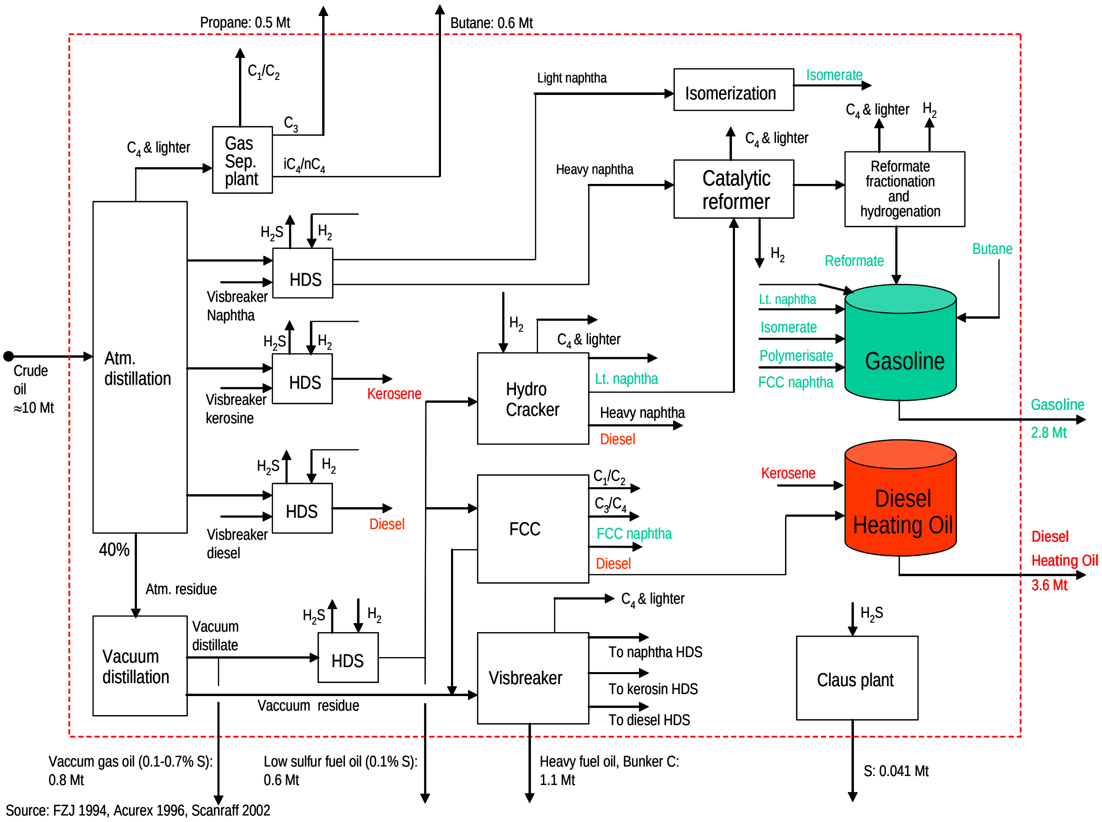
[4] In [UBA 2010a] only CO_2 has been taken into account, the emission of CH_4 and N_2O could add another 30 g/kWh_e



Source: FZJ 1994, Acurex 1996, Scanraff 2002

Figure 9: Crude oil refinery

In a refinery crude oil is converted to gasoline, diesel fuel, LPG, and other products. The refinery data have been derived from [ETSU 1996].

Table 14: Energy requirement and emissions from the production of LPG from crude oil refining

	I/O	Unit	Amount
Crude oil	Input	MJ/MJ	1.087
LPG	Output	MJ	1.000
Emissions			
CO_2	-	g/MJ	7.0
CH_4	-	g/MJ	0.000
N_2O	-	g/MJ	0.000
NO_x	-	g/MJ	0.015
Dust/PM	-	g/MJ	0.000
SO_2	-	g/MJ	0.067
NMVOC	-	g/MJ	0.100
CO	-	g/MJ	0.001

Analogous to [CONCAWE 2008] assumptions for LNG, it has been assumed that LPG is distributed to a refuelling station via truck over a distance of 500 km. The same truck as for LPG from natural gas processing (chapter 3.2.3) has been used for LPG transport and the assumptions for LPG refuelling stations are identical as well.

3.2.5 CNG from piped natural gas

Natural gas is extracted and processed at remote natural gas fields. The energy requirements and GHG emissions are derived from [Shell 2002]. These data have also been used in [CONCAWE 2008]. The air pollutant emissions have been derived from [ETSU 1996] and [GEMIS 2002].

Table 15: Energy requirement and emissions for natural gas production and processing

	I/O	Unit	Amount
NG	Input	MJ/MJ	1.024
NG	Output	MJ	1.000
Emissions			
CO_2	-	g/MJ	1.1
CH_4	-	g/MJ	0.083
N_2O	-	g/MJ	0.000
NO_x	-	g/MJ	0.005
Dust/PM	-	g/MJ	0.000
SO_2	-	g/MJ	0.001
NMVOC	-	g/MJ	0.000
CO	-	g/MJ	0.001

The energy input considers the LHV of the delivered natural gas, i.e. the energy input is the reciprocal value of the efficiency.

Natural gas is transported via pipelines from the natural gas production fields to the EU. Three alternative paths have been assessed:

- Transport distance: 1,000 km (in [CONCAWE 2008] called “EU NG mix”)
- Transport distance: 4,000 km
- Transport distance: 7,000 km

Figure 10 sketches the potential natural gas production sites accessible for German use under these transport distance assumptions.

Figure 10: **1000 km, 4000 km, and 7000 km linear distance from Germany**

For comparison: The distance between the natural gas fields in Siberia and the German border ranges between 4,300 and 5,500 km [Wuppertal 1/2008]. The length of the planned pipeline 'Nabucco' between Baumgarten in Austria and the Iranian border will be about 3,300 km [Nabucco 2009].

The transport of natural gas via pipeline over a distance of 1,000 km requires mechanical work of about 0.26 MJ/tkm. For a transport distance of 4,000 km this mechanical work is about 0.30 MJ/tkm and for 7,000 km about 0.36 MJ/tkm [GEMIS 2002]. The LHV of natural gas is about 50 MJ/kg. Natural gas losses from leakages along the transport route are derived from [Wuppertal 2004]. Methane losses during long distance transport of natural gas via pipeline are low (<1% in case of a distance of 7,000 km). The assumptions in [CONCAWE 2008] are approximately equivalent to those applied for the calculation of the actual data used by [Wuppertal 2/2008] [5].

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[5] The efficiency of gas turbines for natural gas compression in [CONCAWE 2008] is slightly higher (27.8%) than in [Wuppertal 2/2008] (26.4%).

Table 16: Input and outputs for the transport of natural gas via pipeline

	I/O	Unit	1,000 km	4,000 km	7,000 km
NG	Input	MJ/MJ	1.0016	1.0052	1.0092
Mechanical work	Input	MJ/MJ	0.0058	0.0240	0.051
NG	Output	MJ	1.0000	1.0000	1.0000
Emissions					
CH_4	-	g/MJ	0.032	0.104	0.184

The mechanical work is supplied by natural gas fuelled gas turbines. In case of the short distance (1,000 km) a natural gas fuelled gas turbine with an efficiency of 30% has been assumed, and in case of a transport distance of 4,000 km and 7,000 km a gas turbine with an efficiency of about 28% has been assumed. The energy requirement and emissions for the supply of mechanical work for natural gas transport have been derived from GEMIS [GEMIS 2002]. In [GEMIS 2009] the efficiency of the gas turbine is assumed to be 32% for the transport of natural gas from Russia to Germany in 2020, which is close to the 31.5% indicated in [Wuppertal 2/2008] for 2030 (scenario with low natural gas production and low investment). In this study the efficiency of the gas turbine has been assumed to be 32% for the case "2020".

Table 17: Gas turbines used for long distance natural gas transport

	I/O	Unit	1,000 km	4,000 / 7,000 km (2010)	4,000 / 7,000 km (2020)
Natural gas	Input	MJ/MJ	3.333	3.600	3.125
Mechanical work	Output	MJ	1.000	1.000	1.000
Emissions					
CO_2	-	g/MJ	677	713	619
CH_4	-	g/MJ	0.05	0.11	0.09
N_2O	-	g/MJ	0.03	0.03	0.03
NO_x	-	g/MJ	3.527	4.337	3.758
Dust/PM	-	g/MJ	0.050	0.108	0.094
SO_2	-	g/MJ	0.005	0.005	0.005
NMVOC	-	g/MJ	0.101	0.271	0.235
CO	-	g/MJ	1.008	2.168	1.879

The distribution of natural gas typically comprises regional distances of 500 km (high pressure natural gas pipeline grid) and local distances of subsequently 10 km (local natural gas pipeline grid) to the CNG refuelling stations. Methane losses from the distribution of natural gas via the high pressure natural gas grid are about 0.0006% per

100 km [GEMIS 2002]. The mechanical work required is about 0.003 MJ per MJ of natural gas supplied by a gas turbine with an efficiency of 30%.

Table 18: Data on current and future CNG fuelling stations in Germany [ErdgasMobil 2010]

		2010 (typical)	2020 (typical)	2020 (likely)
Nominal installed capacity	Nm^3_{CH4}/h	100	100	200
Filling concept	–	Cascade	Cascade	Cascade
Number of dispensers	pcs.	2	2	e.g. 4
Number of compressors	pcs.	1	1	2
Rated compressor power	Nm^3_{CH4}/h	120	150	300
Suction pressure (absolute)	MPa	0.5	0.5	0.5
Final pressure (absolute)	MPa	30.1	30.1	30.1
Electricity consumption compressor	kWh_e/Nm^3_{CH4}	0.26	0.24	0.24
	MJ_e/MJ_{CH4}	0.026	0.024	0.024

The electricity consumption of CNG refueling station data provided by [ErdgasMobil 2010] is slightly higher than that of the CNG refueling station modeled by [CONCAWE 2008] [6].

Any methane losses at the CNG refuelling station and during CNG dispensing are negligible under approved operating conditions.

3.2.6 CNG from shale gas

For the purpose of this study, CNG from shale gas is considered as a worst case for natural gas extraction in terms of energy and materials input and corresponding environmental impacts. Shale gas is one option of the so-called ‘non-conventional natural gas sources’. Non-conventional natural gas sources comprise coal bed methane (CBM) and shale gas in porous shale layers.

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[6] According to [CONCAWE 2008] the electricity consumption of the CNG refuelling station amounts to about 0.022 MJ per MJ of CNG. The reason is that in [CONCAWE 2008] a final pressure (pressure of the stationary CNG storage) of 25 MPa (absolute) has been assumed instead of 30.1 MPa (absolute) in this study. Own calculations with a suction pressure of 0.5 MPa, a final pressure of 30.1 MPa, an inlet temperature of 288 K, a 3-stage compression with inter-cooling to a temperature of 333 K, a compressor efficiency of 75%, and an electric motor efficiency of 90% result in an electricity consumption of about 0.0235 MJ per MJ of CNG which is close to the one indicated by [ErdgasMobil 2008] for 2020.

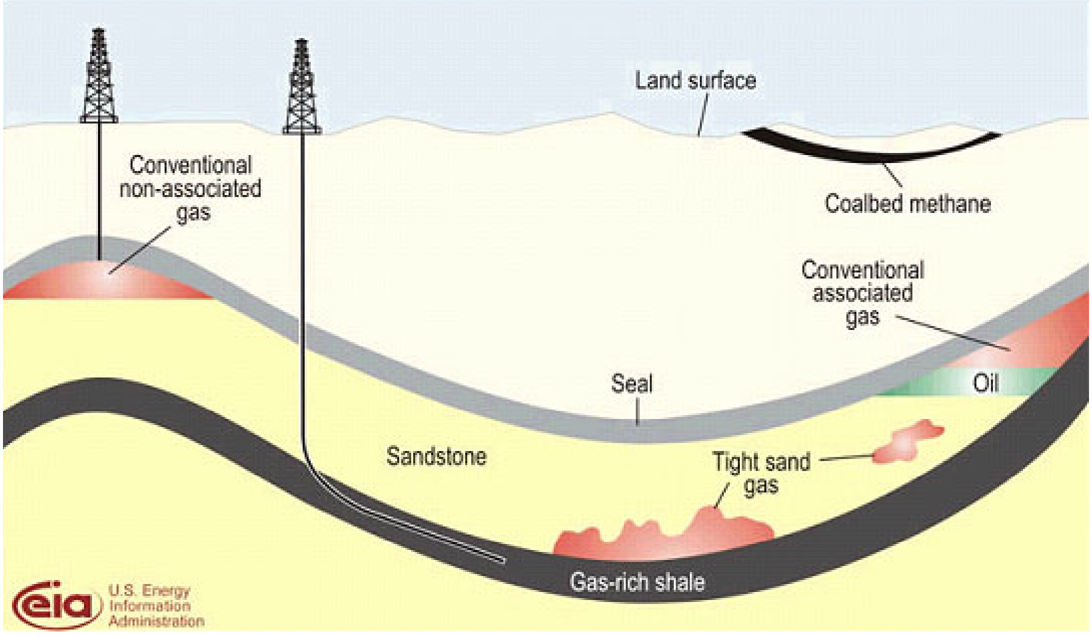

Figure 11: **Schematic presentation of conventional and non-conventional natural gas production**

Main processes to explore shale gas extraction include drilling (about 6 drillings per km²), fracturing of the rock via injection of a mixture of water and chemicals, stripping off the gas, and final disposal of the fluid.

The typical water consumption for fracturing is immense: e.g., during the early exploration phase at 'Barnett Shale' in 1997 about 4,000 m³ of water were used for the fracturing process per drilling site. Collateral damages include shortage and pollution of potable water with toxic and carcinogenic as well as radioactive substances [NYSDEC 2009].

In Europe shale gas can be found in Germany, Poland and the UK. Beginning in 2010, seven projects have been initiated in Europe, thereof one project in Germany.

The data for the calculation of the energy consumption and the GHG emissions from the production of shale gas have been derived from [Armendariz 2009] and [Goodman 2008].

Table 19: Energy use and emissions from the production of shale gas

	I/O	Unit	Amount
Natural gas	Input	MJ/MJ	1.0440
Diesel	Input	MJ/MJ	0.0009
Natural gas	Output	MJ	1.0000
Emissions			
CO_2	-	g/MJ	10.5
CH_4	-	g/MJ	0.202
N_2O	-	g/MJ	n.d.a.
NO_x	-	g/MJ	0.017
Dust/PM	-	g/MJ	n.d.a
SO_2	-	g/MJ	n.d.a
NMVOC	-	g/MJ	0.030
CO	-	g/MJ	n.d.a

n.d.a.: no data available

As a boundary case and because of data availability, it has been assumed that shale gas is produced in the U.S. (Barnett) and transported to Germany as LNG. From the natural gas field the natural gas is transported over a distance of 500 km via pipeline to a liquefaction plant typically located at the coast. The distance for the maritime transport of LNG from the export terminal e.g. in Texas to the import terminal in Belgium is assumed to be 6,000 km (approximately the distance between New York and Belgium). At the import terminal the LNG is vaporised and then injected into the natural gas grid.

The shale gas is distributed over a distance of 500 km (high pressure natural gas pipeline grid) and 10 km (local natural gas pipeline grid) to the CNG refuelling stations. The electricity consumption of the CNG refuelling station is about 0.026 MJ (2010) and 0.024 MJ (2020) per MJ of CNG (see chapter 3.2.5).

3.2.7 CNG via LNG

The natural gas liquefaction plant is located nearby the natural gas field. The energy requirement and emissions for the natural gas extraction are identical to the ones in chapter 3.2.5.

At a feed pressure of 6 MPa the electricity requirement for the liquefaction of natural gas amounts to about 0.036 kWh per kWh of LNG.

Table 20: **Energy use and emissions for natural gas liquefaction**

	I/O	Unit	Amount
NG	Input	MJ/MJ	1.013
Electricity	Input	MJ/MJ	0.034
LNG	Output	MJ	1.000
Emissions			
CO_2	-	g/MJ	0.6
CH_4	-	g/MJ	0.034

The CO_2 emissions result from flared purge gas from natural gas purification. About 0.0025 to 0.02 MJ per MJ of natural gas is flared [Bauer 1996]. Furthermore, methane losses of 0.0017 MJ per MJ of natural gas occur [Masake 1997]. Natural gas liquefaction is a mature technology. Hence, a significant further decrease of electricity consumption cannot be expected.

Here, the electricity requirement for natural gas liquefaction is assumed to be met by a natural gas fuelled combined cycle gas turbine (CCGT) power plant with an efficiency of 55%.

Table 21: **Energy use and emissions of a natural gas fuelled gas turbine (CCGT) power plant**

	I/O	Unit	Amount
NG	Input	MJ/MJ	1.818
Electricity	Output	MJ	1.000
Emissions			
CO_2	-	g/MJ	100
CH_4	-	g/kWh	0.007
N_2O	-	g/kWh	0.005
NO_x	-	g/MJ	0.153
Dust/PM	-	g/MJ	0.001
SO_2	-	g/MJ	0.001
NMVOC	-	g/MJ	0.001
CO	-	g/MJ	0.153

For loading of an LNG carrier 0.0007 to 0.001 kWh of electricity per kWh of LNG are required. This number has been derived from the electricity requirement indicated by [Bauer 1996] as being equivalent to an energy loss of 0.2 to 0.3% on a primary energy basis. The CO_2 emissions result from flared natural gas according to [Dautrebande 2001].

The electricity requirement of the export terminal is met by a natural gas fuelled combined cycle gas turbine (CCGT) power plant.

The LNG carrier is partly fuelled with vaporised LNG and partly with heavy fuel oil. Table 22 shows the energy use and emissions for the maritime transport of LNG.

Table 22: Energy use and emissions for the transport of LNG via LNG carrier over a distance of 5,500 nautical miles (10,186 km)

	I/O	Unit	Amount
LNG	Input	MJ/MJ	1.037
Heavy fuel oil	Input	MJ/MJ	0.031
LNG	Output	MJ	1.000
Emissions			
CO_2	-	g/MJ	4.5
CH_4	-	g/MJ	0.000
N_2O	-	g/MJ	0.000
NO_x	-	g/MJ	0.008
Dust/PM	-	g/MJ	0.002
SO_2	-	g/MJ	0.030
NMVOC	-	g/MJ	0.000
CO	-	g/MJ	0.002

The import terminal in the EU can be simulated as having the identical energy needs as the export terminal. Yet, in contrast to the export terminal the electricity requirement is met by the EU electricity mix.

For the distribution of natural gas from imported LNG the following cases have been assessed in [CONCAWE 2008]:

- Vaporisation at the import terminal, injection into the natural gas pipeline grid and distribution to the CNG refuelling stations via pipeline over a distance of 500 km (high pressure natural gas pipeline grid) and 10 km (local natural gas pipeline grid).
- Distribution as LNG via a 40 t truck to the CNG refuelling stations over a distance of 500 km, vaporisation at the CNG refuelling station. The payload of the truck amounts to 19 t of LNG.

As LNG is vaporised at the import terminal and inserted into the natural gas pipeline grid the same CNG refuelling station is used as in case of piped natural gas (chapter 3.2.5).

In case of trucked LNG [CONCAWE 2008] has applied a different CNG refuelling station concept which uses the combustion of natural gas to heat the LNG vaporiser as state-of-the-art technology. Alternatively an ambient air vaporiser can be applied.

Electricity consumption of the LNG pump is about 0.0034 MJ/MJ of CNG [Messer 1998].

3.2.8 CNG (bio-methane) from upgraded biogas

Biogas mainly consists of 50 to 75% methane and 25 to 50% CO_2. Biogas can be upgraded to almost pure (>0.96%) methane via pressurised water scrubbing, pressure swing adsorption scrubbing with amines and membrane separation. Today, mainly pressurised water scrubbing is used to remove the CO_2 from the biogas. Bio-methane is distributed to the CNG refuelling stations via the natural gas grid.

For biogas generation a mixture of energy crops (maize whole plant, wheat whole plant and small amounts of wheat grain) and manure as indicated in [DBFZ 2009] have been assumed anticipating no land use change.

The fertiliser and diesel fuel requirement for the cultivation of whole plant maize have been derived from [KTBL 2006]. For the cultivation of whole plant wheat and wheat grain the same assumptions as in [CONCAWE 2008] have been applied.

Table 23 shows the input and output data for the cultivation of the energy crops for the production of biogas via anaerobic fermentation.

Table 23: Cultivation of energy crops used as biogas feedstock

	Unit	Maize whole plant	Wheat whole plant	Wheat grain
Yield	t_{FS}/(ha yr)	44	25.7	5.2
Dry matter content	%	35	35	86.5
LHV	MJ/kg_{DS}	18	17.1	17.0
Diesel	MJ/(ha yr)	3576	3716	3716
CaO fertiliser	kg/(ha yr)	560	-	-
K_2O fertiliser	kg/(ha yr)	96	71.1	16.4
P_2O_5 fertiliser	kg/(ha yr)	96	31.9	21.6
N fertiliser	kg/(ha yr)	108	109.3	109.3
Pesticides	kg/(ha yr)	3.5	2.3	2.3
Seeding material	kg/(ha yr)	25	120	120
Digestate	m^3/(ha yr)	15 (1)	- (2)	- (2)
Emissions				
N_2O	g/MJ_{crop}	0.016	0.012	0.024

FS: fresh substance; DS: dry substance; (1) In [KTBL 2006] only a part of the fertiliser requirement is met by the digestate. A part of the digestate from the biogas plant is exported leading to a credit at the fermentation stage (2) The fertiliser input above is the gross fertiliser input. The nutrients in the digestate from the biogas plant saves fertiliser and lead to a credit which is taken into account as credit at the fermentation stage.

Whole plant maize, whole plant wheat, wheat grain and cattle manure are transported to the biogas plant via 40 t truck.

Table 24: Assumptions for feedstock transport

	Unit	Whole plant maize	Whole plant wheat	Wheat grain	Cattle manure
Distance	km	5.09	5.09	5.09	2.02
Dry matter content	%	35	35	86	10

The technical data for the biogas plant have been derived from [DBFZ 2009]. The capacity of the combined biogas and upgrading plant amounts to 5 MW of pure methane.

Heat for the fermenter is supplied by a biogas fuelled condensing boiler. The electricity required by the fermenter and the upgrading plant is derived from the EU electricity mix.

The maximum bio-methane output amounts to 5 MW. The heat demand of the fermenter is met by a biogas fuelled condensing boiler. Upgrading to almost pure methane is carried out via pressurised water scrubbing. The electricity demand is met by electricity from the EU electricity mix. The digestate is returned back to the fields as fertiliser. The nutrient content of the digestate has been derived from the Thüringer Landesanstalt für Landwirtschaft [TLL 2009].

Table 25: **Combined biogas and upgrading plant (5 MW_{CH4})**

	I/O	Unit	Amount	Comment
Cattle manure	Input	MJ/MJ	0.043	0.51 t
Maize whole plant	Input	MJ/MJ	1.099	3.14 t
Wheat whole plant	Input	MJ/MJ	0.482	1.45 t
Wheat grain	Input	MJ/MJ	0.196	0.24 t
Electricity	Input	MJ/MJ	0.114	568 kW
LPG	Input	MJ/MJ	0.047	9.19 Nm^3/h
Bio-methane	Output	MJ	1.000	5,000 kW
N fertiliser	Output	kg/MJ	0.00098	
K_2O fertiliser	Output	kg/MJ	0.00158	
P_2O_5 fertiliser	Output	kg/MJ	0.00071	
Emissions				
CO_2	-	g/MJ	3.0	From LPG use
CH_4	-	g/MJ	0.20	CH_4 losses: 1%
N_2O	-	g/MJ	0.0000	
NO_x	-	g/MJ	0.0023	
Dust/PM	-	g/MJ	0.0000	
SO_2	-	g/MJ	0.0000	
NMVOC	-	g/MJ	0.0001	
CO	-	g/MJ	0.0014	

Bio-methane is injected into the local natural gas grid and distributed to the CNG refuelling stations. No energy is required for the local distribution of natural gas. The electricity consumption of a CNG refuelling station is about 0.026 MJ (2010) and 0.024 MJ (2020) per MJ of CNG (see chapter 3.2.5).

Table 26 shows the overall use of non-renewable energy and the GHG emissions for the supply of CNG from upgraded biogas (bio-methane).

The reason for the negative value for N_2O at the biogas generation and upgrading stage are credits for exported nutrients from the biogas digestate which are used as fertiliser. The CO_2 absorbed from the atmosphere and bound in the final fuel is emitted during the combustion in the vehicle (TTW part). Credits for avoided CH_4 emissions from avoided storage of untreated manure have not been taken into account. However, the amount of manure input is low in the pathways considered in this study.

Table 26: Use of non-renewable energy and GHG emissions “well-to-tank” for the supply of CNG from upgraded biogas

	Energy [MJ/MJ$_{CNG}$] (non-renewable)	GHG [g/MJ$_{CNG}$]			
		CO_2 equivalent	CO_2	CH_4	N_2O
Cultivation	0.14	21.02	8.6	0.02	0.040
Transport	0.00	0.12	0.1	0.00	0.000
Biogas generation and upgrading	0.29	15.67	12.8	0.22	-0.009
Distribution	0.00	0.00	0.00	0.00	0.000
Refuelling station	0.07	3.37	3.14	0.01	0.000
Total WTT GHG emitted	-	40.19	24.7	0.25	0.031
CO_2 absorbed from the atmosphere bound in the fuel	-	-55.00	-	-	-
Total pathway WTT	0.50	-14.81	-	-	-

Negative emissions at the biogas generation and upgrading stage result from credits for saved fertiliser due to returning the fermentation digestate back to the fields.

For the biogas generation and upgrading plant a layout with maximum output of biomethane has been selected (economic optimisation). For this the heat demand of the fermenter is met by a biogas fuelled condensing boiler and the electricity demand of the fermenter and biogas upgrading plant is met by electricity from the EU electricity mix. Provision of electricity and heat from onsite biogas fuelled combined heat and power (CHP) plant would lead to overall lower GHG emissions (see e.g. [Wuppertal 2010]), however, regulatory framework does not incentivise optimisation of plant layout for least greenhouse gas emissions.

ORGANIC RESIDUES – FEEDSTOCK FOR METHANE FROM BIOGAS

There is still a potential for biogas from organic residues which offer low overall greenhouse gas (GHG) emissions for the supply of the feedstock. But biogas plants using organic residues as feedstock generally are smaller plants and are rather used for electricity generation than for the generation of bio-methane as transportation fuel. One reason is that the fixed feed-in tariff according to the German Renewable Energy Sources Act ("Erneuerbare-Energien-Gesetz" – EEG) encourage to operate a biogas plants to generate electricity.

In 2010, for a biogas plant with a gas engine with a capacity of up to 150 kW_e the feed-in tariff amounts to about 11.55 cent per kWh of electricity if organic residues are used. If the excess heat is used for district heating (bonus for CHP: "KWK-Bonus") the feed-in tariff increases by 3.0 cent per kWh of electricity to 14.55 cent per kWh of electricity. If the efficiency of the gas engine were assumed to be 30% the fixed feed-in tariff would amount to about 3.5 cent per kWh of biogas without CHP bonus and about 4.4 cent per kWh of biogas with CHP bonus. If the biogas were upgraded to pure methane and injected into the natural gas grid the bio-methane would have to compete with the price of natural gas.

The feed-in tariff for a larger biogas plant with a capacity of 5 MW_e amounts to 8.17 cent per kWh of electricity if organic residues are used. If agricultural residues such as manure or energy crops are used as feedstock, the feed-in tariff increases by 3.0 cent per kWh of electricity to 11.17 cent per kWh of electricity. Including CHP bonus the feed-in-tariff would amount to about 14.17 cent per kWh of electricity. If the efficiency of a larger gas engine were assumed to be 40% the feed-in-tariff would amount to about 3.3 cent, 4.5 and 5.7 cent per kWh of methane respectively.

If bio-methane is produced additional investments for the upgrading plant are required. On the other hand no investment for the gas engine is required if only pure methane is generated and the heat is supplied by a boiler. For large plants (> 1 MW_e) the investment for gas engine and the investment for a biogas upgrading plant are approximately the same for the same biogas input. For small plants (e.g. 200 kW_e) the investment for the gas engine is lower than that for an upgrading plant with the same biogas input. Therefore, the generation of bio-methane for the supply of transportation fuel is more envisaged for large biogas plants than for small biogas plants. Large (> 5 MW CH_4) biogas plants require large amounts of feedstock which are generally not available as residue at the location of the plant.

3.2.9 Results "Well-to-Tank"

Table 27 through Table 31 show the GHG emissions from the supply of gasoline, diesel, LPG and CNG.

Table 27: GHG emissions "Well-to-Tank" from supply of gasoline and diesel fuel

	GHG	CO2	CH4	N2O
	g CO2eq/MJ	g/MJ	g/MJ	g/MJ
Gasoline from conventional crude oil				
Crude oil production	3.60	3.6	0.00	0.000
Transport to the refinery	0.93	0.9	0.00	0.000
Refinery	7.01	7.0	0.00	0.000
Distributioin	0.57	0.6	0.00	0.000
Refuelling station	0.44	0.4	0.00	0.000
Total WTT GHG emitted	**12.55**	12.5	0.00	0.000
Gasoline from oil sands				
Synthetic crude oil (SCO) production	20.68	20.7	0.00	0.000
Transport to the refinery	0.72	0.7	0.00	0.000
Refinery	7.01	7.0	0.00	0.000
Distributioin	0.57	0.6	0.00	0.000
Refuelling station	0.44	0.4	0.00	0.000
Total WTT GHG emitted	**29.43**	29.4	0.00	0.000
Diesel from conventional crude oil				
Crude oil production	3.67	3.7	0.00	0.000
Transport to the refinery	0.94	0.9	0.00	0.000
Refinery	8.60	8.6	0.00	0.000
Distributioin	0.57	0.6	0.00	0.000
Refuelling station	0.44	0.4	0.00	0.000
Total WTT GHG emitted	**14.22**	14.2	0.00	0.000
Diesel from oil sands				
Synthetic crude oil (SCO) production	21.04	21.0	0.00	0.000
Transport to the refinery	0.74	0.7	0.00	0.000
Refinery	8.60	8.6	0.00	0.000
Distributioin	0.57	0.6	0.00	0.000
Refuelling station	0.44	0.4	0.00	0.000
Total WTT GHG emitted	**31.39**	31.3	0.00	0.000

Table 28: GHG emissions "Well-to-Tank" from supply of LPG

	GHG	CO2	CH4	N2O
	g CO2eq/MJ	g/MJ	g/MJ	g/MJ
LPG from natural gas processing, 1000 km				
Extraction and processing	3.46	3.1	0.02	0.000
Liquefaction	0.31	0.3	0.00	0.000
Maritime transport to EU	0.24	0.2	0.00	0.000
Distributioin	1.30	1.3	0.00	0.000
Refuelling station	0.44	0.4	0.00	0.000
Total WTT GHG emitted	**5.75**	5.3	0.02	0.000
LPG from natural gas processing, 5500 nautical miles (10186 km)				
Extraction and processing	3.46	3.1	0.02	0.000
Liquefaction	0.31	0.3	0.00	0.000
Maritime transport to EU	2.46	2.5	0.00	0.000
Distributioin	1.30	1.3	0.00	0.000
Refuelling station	0.44	0.4	0.00	0.000
Total WTT GHG emitted	**7.97**	7.5	0.02	0.000
LPG from crude oil refining				
Crude oil production	3.62	3.6	0.00	0.000
Transport to the refinery	0.91	0.9	0.00	0.000
Refinery	7.01	7.0	0.00	0.000
Liquefaction	0.36	0.3	0.00	0.000
Distributioin	1.30	1.3	0.00	0.000
Refuelling station	0.44	0.4	0.00	0.000
Total WTT GHG emitted	**13.63**	13.6	0.00	0.000
LPG from crude oil refining, crude oil from oil sands				
Synthetic crude oil (SCO) production	20.79	20.8	0.00	0.000
Transport to the refinery	0.73	0.7	0.00	0.000
Refinery	7.01	7.0	0.00	0.000
Liquefaction	0.36	0.3	0.00	0.000
Distributioin	1.30	1.3	0.00	0.000
Refuelling station	0.44	0.4	0.00	0.000
Total WTT GHG emitted	**30.62**	30.6	0.00	0.000

Table 29: GHG emissions “Well-to-Tank” for supply of CNG (2010)

	GHG	CO2	CH4	N2O
	g CO2eq/MJ	g/MJ	g/MJ	g/MJ
CNG from piped natural gas, 1000 km				
Extraction and processing	3.32	1.2	0.09	0.000
Pipeline (1000 km)	1.93	1.1	0.03	0.000
Distribution (500 km plus 10 km)	0.59	0.6	0.00	0.000
Refuelling station	3.37	3.1	0.01	0.000
Total WTT GHG emitted	**9.21**	6.0	0.13	0.000
CNG from piped natural gas, 7000 km				
Extraction and processing	3.85	1.3	0.10	0.000
Pipeline (7000 km)	15.01	10.2	0.19	0.000
Distribution (500 km plus 10 km)	0.57	0.6	0.00	0.000
Refuelling station	3.37	3.1	0.01	0.000
Total WTT GHG emitted	**22.81**	15.2	0.30	0.001
CNG from imported LNG from shale gas in the USA				
Extraction and processing, pipeline	17.99	12.3	0.23	0.000
Liquefaction	6.74	5.4	0.05	0.000
Maritime transport to EU	7.10	7.0	0.00	0.000
Distribution (500 km plus 10 km)	0.57	0.5	0.00	0.000
Refuelling station	3.37	3.1	0.01	0.000
Total WTT GHG emitted	**35.77**	28.4	0.29	0.001
CNG from piped natural gas, 4000 km				
Extraction and processing	3.52	1.2	0.09	0.000
Pipeline (4000 km)	7.51	4.8	0.11	0.000
Distribution (500 km plus 10 km)	0.57	0.5	0.00	0.000
Refuelling station	3.37	3.1	0.01	0.000
Total WTT GHG emitted	**14.97**	9.7	0.21	0.000
CNG via LNG, vaporisation, distribution via pipeline				
Extraction and processing	3.53	1.2	0.09	0.000
Liquefaction	5.82	4.7	0.04	0.000
Maritime transport to EU	7.43	7.4	0.00	0.000
Distribution (500 km plus 10 km)	0.57	0.5	0.00	0.000
Refuelling station	3.37	3.1	0.01	0.000
Total WTT GHG emitted	**20.72**	17.0	0.14	0.001
CNG via LNG, distribution via truck				
Extraction and processing	3.51	1.2	0.09	0.000
Liquefaction	5.78	4.7	0.04	0.000
Maritime transport to EU	6.24	6.2	0.00	0.000
Distribution (truck, 500 km)	3.78	1.2	0.10	0.000
Refuelling station	1.51	1.5	0.00	0.000
Total WTT GHG emitted	**20.82**	14.8	0.24	0.000
CNG from piped natural gas, 4000 km, 20% bio-methane				
Extraction and processing	2.82	1.0	0.07	0.000
Pipeline (4000 km)	6.00	3.8	0.08	0.000
Bio-methane supply	7.36	4.3	0.05	0.006
Distribution (500 km plus 10 km)	0.46	0.4	0.00	0.000
Refuelling station	3.37	3.1	0.01	0.000
Total WTT GHG emitted	**20.01**	12.7	0.21	0.007
CO2 absorbed and bound in the fuel	-11.00			
Total pathway WTT	**9.01**			

Table 30: GHG emissions "Well-to-Tank" for supply of CNG (2020), fossil sources only

	GHG	CO2	CH4	N2O
	g CO2eq/MJ	g/MJ	g/MJ	g/MJ
CNG from piped natural gas, 1000 km				
Extraction and processing	3.32	1.2	0.09	0.000
Pipeline (1000 km)	1.93	1.1	0.03	0.000
Distribution (500 km plus 10 km)	0.59	0.6	0.00	0.000
Refuelling station	3.11	2.9	0.01	0.000
Total WTT GHG emitted	**8.95**	5.7	0.13	0.000
CNG from piped natural gas, 7000 km				
Extraction and processing	3.77	1.3	0.10	0.000
Pipeline (7000 km)	13.65	8.9	0.19	0.000
Distribution (500 km plus 10 km)	0.57	0.6	0.00	0.000
Refuelling station	3.11	2.9	0.01	0.000
Total WTT GHG emitted	**21.11**	13.6	0.29	0.001
CNG from imported LNG from shale gas in the USA				
Extraction and processing, pipeline	17.99	12.3	0.23	0.000
Liquefaction	6.74	5.4	0.05	0.000
Maritime transport to EU	7.10	7.0	0.00	0.000
Distribution (500 km plus 10 km)	0.57	0.5	0.00	0.000
Refuelling station	3.11	2.9	0.01	0.000
Total WTT GHG emitted	**35.51**	28.2	0.29	0.001
CNG from piped natural gas, 4000 km				
Extraction and processing	3.48	1.2	0.09	0.000
Pipeline (4000 km)	6.86	4.2	0.11	0.000
Distribution (500 km plus 10 km)	0.57	0.5	0.00	0.000
Refuelling station	3.11	2.9	0.01	0.000
Total WTT GHG emitted	**14.03**	8.8	0.20	0.000
CNG via LNG, vaporisation, distribution via pipeline				
Extraction and processing	3.53	1.2	0.09	0.000
Liquefaction	5.82	4.7	0.04	0.000
Maritime transport to EU	7.43	7.4	0.00	0.000
Distribution (500 km plus 10 km)	0.57	0.5	0.00	0.000
Refuelling station	3.11	2.9	0.01	0.000
Total WTT GHG emitted	**20.46**	16.7	0.14	0.001
CNG via LNG, distribution via truck				
Extraction and processing	3.51	1.2	0.09	0.000
Liquefaction	5.78	4.7	0.04	0.000
Maritime transport to EU	6.24	6.2	0.00	0.000
Distribution (truck, 500 km)	3.78	1.2	0.10	0.000
Refuelling station	1.51	1.5	0.00	0.000
Total WTT GHG emitted	**20.82**	14.8	0.24	0.000

Table 31: GHG emissions "Well-to-Tank" for supply of CNG (2010) involving 20% admixture of bio-methane (by energy)

	GHG	CO2	CH4	N2O
	g CO2eq/MJ	g/MJ	g/MJ	g/MJ
CNG from piped natural gas, 1000 km, 20% bio-methane				
Extraction and processing	2.66	0.9	0.07	0.000
Pipeline (1000 km)	1.54	0.9	0.03	0.000
Bio-methane supply	7.36	4.3	0.05	0.006
Distribution (500 km plus 10 km)	0.47	0.5	0.00	0.000
Refuelling station	3.11	2.9	0.01	0.000
Total WTT GHG emitted	**15.15**	9.5	0.15	0.006
CO2 absorbed and bound in the fuel	-11.00			
Total pathway WTT	**4.15**			
CNG from piped natural gas, 4000 km, 20% bio-methane				
Extraction and processing	2.79	1.0	0.07	0.000
Pipeline (4000 km)	5.49	3.3	0.08	0.000
Bio-methane supply	7.36	4.3	0.05	0.006
Distribution (500 km plus 10 km)	0.46	0.4	0.00	0.000
Refuelling station	3.11	2.9	0.01	0.000
Total WTT GHG emitted	**19.21**	11.9	0.21	0.007
CO2 absorbed and bound in the fuel	-11.00			
Total pathway WTT	**8.21**			
CNG from piped natural gas, 7000 km, 20% bio-methane				
Extraction and processing	3.02	1.0	0.08	0.000
Pipeline (7000 km)	10.92	7.1	0.15	0.000
Bio-methane supply	7.36	4.3	0.05	0.006
Distribution (500 km plus 10 km)	0.46	0.4	0.00	0.000
Refuelling station	3.11	2.9	0.01	0.000
Total WTT GHG emitted	**24.87**	15.8	0.28	0.007
CO2 absorbed and bound in the fuel	-11.00			
Total pathway WTT	**13.87**			

In case of CNG from bio-methane CO_2 is absorbed from the atmosphere during growth of the plants and bound in the product fuel. The carbon bound in the product fuel will be emitted during the combustion in the vehicle ("Tank-to-Wheel").

3.3 Tank-to-Wheel (TTW)

For the purpose of this study, a typical European compact size 5-seater sedan like the "VW Golf" has been used as reference vehicle for the calculation of the fuel consumption "tank-to-wheel" (TTW) in accordance with extensive works done at European level by automobile and energy industry stakeholders [CONCAWE 2008].

Today's fuel consumption of the LPG-powered vehicle has been assumed equal as for the gasoline fuelled vehicle.

Due to the higher octane number of methane (the main component of natural gas) compared to gasoline a higher compression ratio can be applied (the compression ratio can be increased from 9.5:1 to 12.5:1) leading to a higher efficiency of dedicated natural gas engines [CONCAWE 2008]. As presented in Figure 12 the efficiency of dedicated CNG engines is significantly higher than that of gasoline fuelled engines over wide operating ranges. Specifically hybrid vehicles offer the advantage to operate the engine in areas where the efficiency is high.

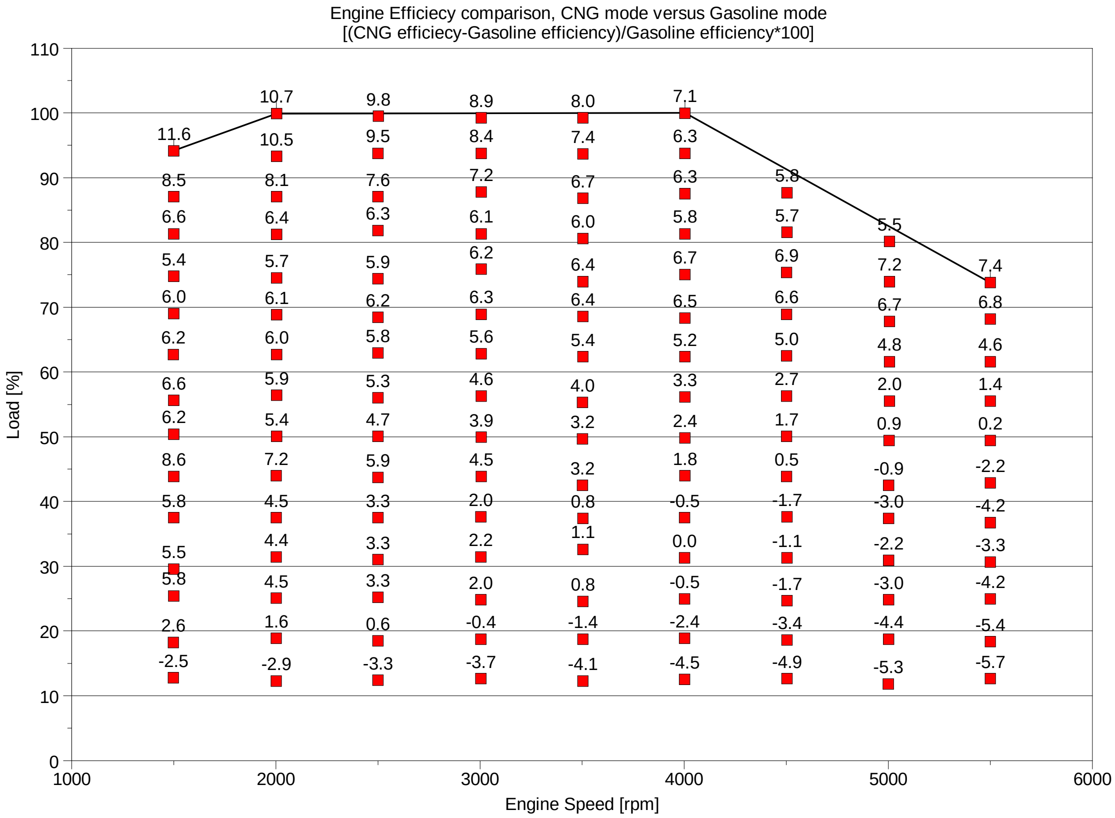

Figure 12: Efficiency difference between gasoline and CNG engines

For CNG fuelled hybrid vehicles only the dedicated CNG ICE configuration was considered by [CONCAWE 2008]. The availability of the electric engine allows the acceleration criteria to be met with the ICE displacement of 1.6 l.

Table 32: **Fuel consumption "tank-to-wheel" based on "VW-Golf" class vehicle based on [CONCAWE 2008]**

	Time horizon	Used in		Non-hybrid		Hybrid	
		WtW	Scenario	MJ/km	l_{GE}/(100 km)	MJ/km	l_{GE}/(100 km)
Gasoline PISI 1.6 l	2002 (mix today)		X	2.235	6.9	-	-
Gasoline DISI 1.6 l	2002 (mix today)		X	2.088	6.5	-	-
LPG bi-fuel PISI 1.6 l	2002 (mix today)		X	2.235	6.9	-	-
CNG bi-fuel PISI 1.6 l	2002 (mix today)		X	2.269	7.1	-	-
Gasoline PISI	2010-2020	X		1.900	5.9	-	-
Gasoline PISI 1.6 l 14 kW	2010-2020	X	X	-	-	1.617	5.0
Gasoline DISI	2010-2020	X	X	1.879	5.8	-	-
Gasoline DISI 1.6 l	2010-2020			-	-	1.630	5.1
Diesel DICI DPF	2010-2020	X		1.657	5.1	-	-
Diesel DICI DPF 1.9 l	2010-2020	X		-	-	1.456	4.5
LPG bi-fuel PISI	2010-2020	X	X	1.900	5.9	1.617	5.0
CNG bi-fuel PISI	2010-2020	X		1.883	5.9	-	-
CNG bi-fuel DISI*	2010-2020	X		1.883	5.9	-	-
CNG dedicated PISI 1.6 l	2010-2020	X	X	1.872	5.8	1.394	4.3
CNG dedicated DISI*	2010-2020	X	X	1.872	5.8	1.394	4.3

GE: Gasoline Equivalent
PISI: Port Injection Spark Ignition
DISI: Direct Injection Spark Ignition
DICI: Direct Injection Compression Ignition
DPF: Diesel Particulate Filter
* Assumption: same fuel consumption as PISI because of no sufficient data available

In [CONCAWE 2008] a "2002" configuration has been defined. The "2002" configuration can be considered as the mix of passenger vehicles of the "Golf class" currently on the road. The "2010" configuration in [CONCAWE 2008] refers to the passenger vehicle configuration in the time frame 2010 to 2020.

For comparison, the latest "VW Golf" with 77 kW DISI engine (model "VW Golf 77 kW TSI 7-shift dual-clutch gearbox") consumes about 5.8 l gasoline per 100 km which is the same which has been assumed in [CONCAWE 2008] for the gasoline DISI 2010 vehicle. The latest "VW Golf" with a 77 kW DICI diesel engine (model "VW Golf 77 kW TDI 7-shift dual-clutch gearbox") consumes 4.7 l diesel per 100 km which corresponds to 5.3 l gasoline equivalent per 100 km. Both vehicles meet the Euro 5 emission limits. Given the more stringent Euro 6 emission limits there is a likelihood that the energy consumption of the diesel version may even increase (i.e. there is a trade off between low NO_x emissions and lower consumption).

Future reductions in energy consumption of vehicles are seen in hybridization of the drive-train.

According to current EU regulations [EC 2007], passenger vehicles[7] have to fulfil the following emission limits “EURO 6” with effect from 1 September 2015 (Table 33).

Table 33: Emissions limits “Euro 6” applicable for cars from 2015

	CO [g/km]	CH_4 [g/km]	NMVOC [g/km]	NO_x [g/km]	PM [g/km]
Spark Ignition (PI)	1.000	0.032	0.068	0.060	0.005
Compressed Ignition (CI)	0.500		0.090 (THC)	0.080	0.005

In case of diesel engines no dedicated NMVOC emission limits are indicated.

The Euro 6 emission limits have been used for the calculation of the particulate matter (PM) emissions of the vehicles except for the vehicles with PISI engines where measurement data from [FVT 2008] have been used. In contrast to diesel engines PISI engines generally emit only very small amounts of PM even without any particulate matter filter. The reason for the introduction of PM emissions limits for spark ignition (Otto) engines is that spark ignition engines with direct injection (DISI) can emit PM. Thus, for DISI engines the PM emissions have been derived from the Euro 6 emission limits as for the diesel (DICI) engines. However, the operation for DISI at stoichiometric and homogeneous conditions can avoid the formation of particulate matter.

Particulate matter (PM) is the most serious air pollution problem in many cities and towns and it appears to be the component of air pollution most consistently associated with adverse health effects. Diesel exhaust particulates exert their effect by way of specific activities of chemical agents, i.e. poly-aromatic hydrocarbons which are attached to the PM. Furthermore, the diesel particulates interact with pollen grains and increase their allergic potential [D’Amato 2008]. Diesel engines adapted to meet the Euro 4 limits emit particulates which are even more dangerous to human health than older diesel engines because of a different structure of the particulates [MPI 2008].

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[7] EU vehicle category ‘M’

LIGHT & HEAVY-DUTY TRUCKS

Light and heavy-duty trucks are predominantly powered by diesel fuel. Approximately 14,000 light and heavy-duty trucks are running on CNG in Germany today, compared to about 4,600 LPG-fuelled ones [Shell 2010]

LDVs and HDVs that run on methane offer the advantage of negligible particulate matter emissions without any exhaust treatment. In addition, methane powered trucks have lower noise emissions compared to diesel HDV engines [Shell 2010]. Light and heavy-duty vehicles thus lend themselves for CNG conversion if used in urban areas. Ideal candidates for use of methane in light and heavy-duty vehicles are fleets, such as city buses and municipal garbage collection trucks.

Major truck manufacturers like Daimler and Volvo are co-operating with original equipment manufacturers (OEMs) like UK-based Hardstaff. Recently, a truck retrofitted to run on liquefied methane (liquefied natural gas or liquefied bio-methane) has been presented by another OEM, the Netherlands-based Rolande. The higher density of the liquefied fuel is set to allow for truck operating ranges of 1,200 km on a single filling [Rolande 2010].

3.4 Well-to-wheel (WTW)

Figure 13 shows the main components of the pathways for the supply and use ('well-to-wheel') of LPG from natural gas processing and from crude oil refining. In case of LPG from NG processing, electricity for LPG liquefaction is provided by a NG combined cycle gas turbine (CCGT) power plant, because the liquefaction plant is located remotely and nearby the natural gas field (no grid connection). In case of LPG from crude oil refining, the electricity requirement is met by the European electricity grid, because refineries have grid connection.

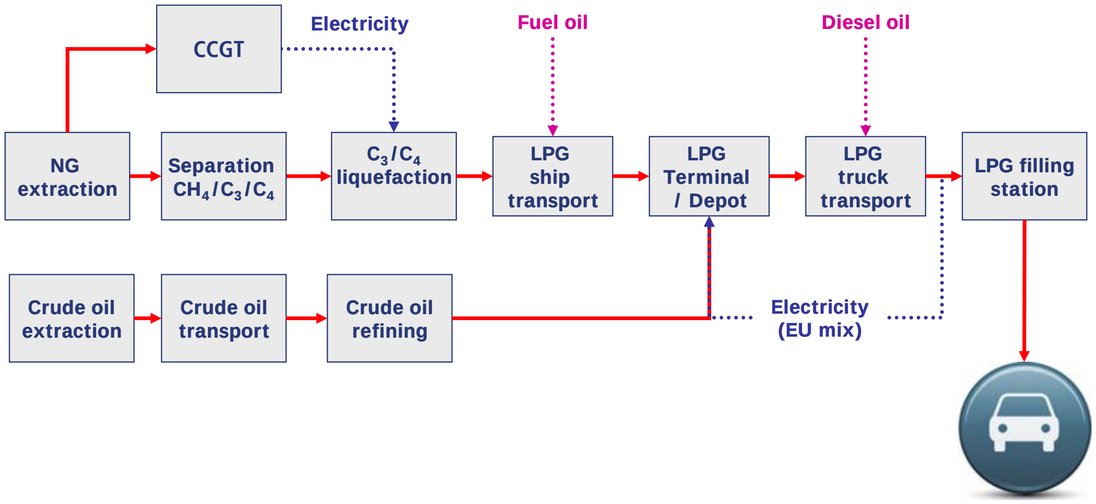


Figure 13: Detailed overview of LPG pathways well-to-wheel

Figure 14 shows the main components of the pathway for the supply and use ('well-to-wheel') of CNG from natural gas.

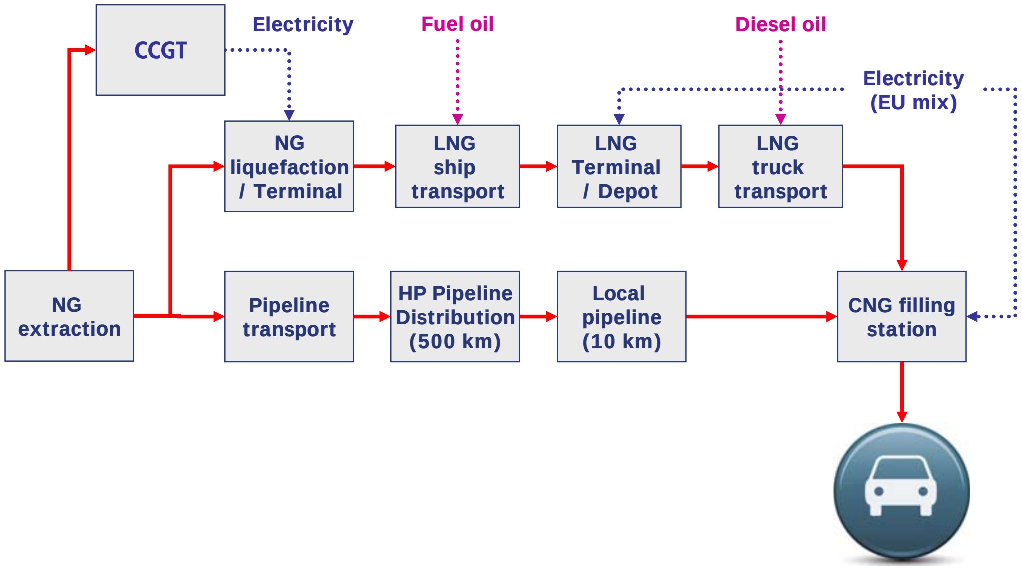
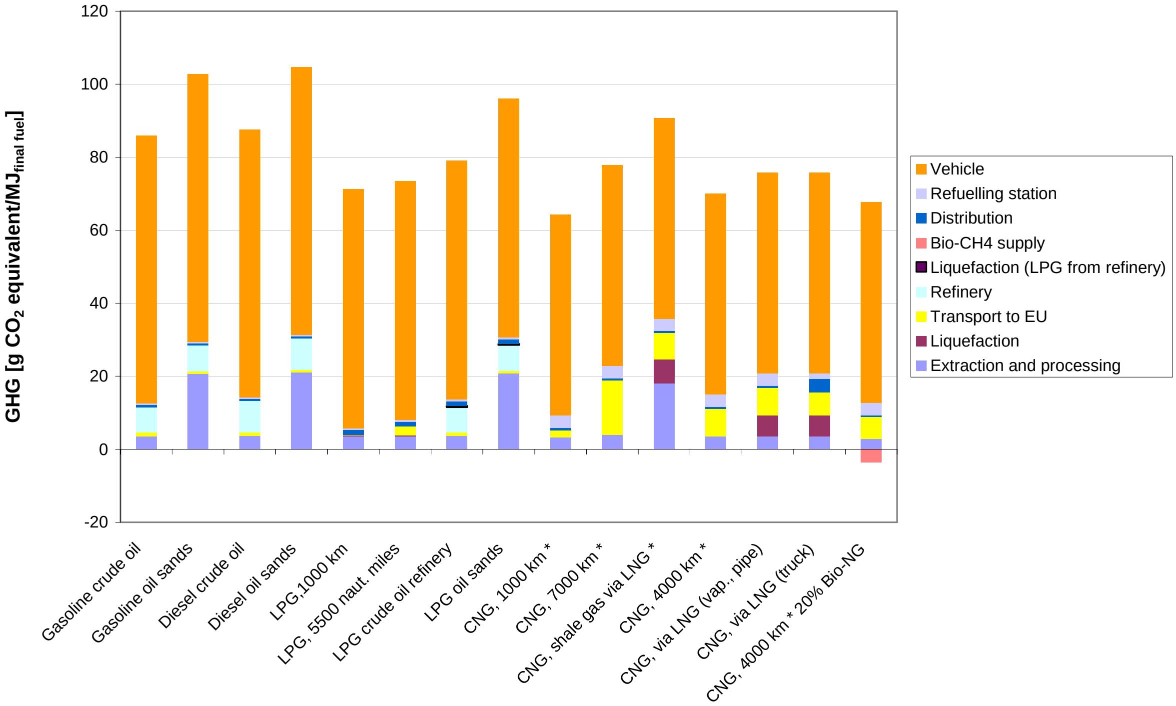


Figure 14: Detailed overview of CNG pathways well-to-wheel

Figure 15 shows the GHG emissions "well-to-wheel" (WTW) for the supply and use (combustion e.g. in a vehicle) of LPG and CNG per MJ of final fuel compared with crude oil based gasoline and diesel for 2010.

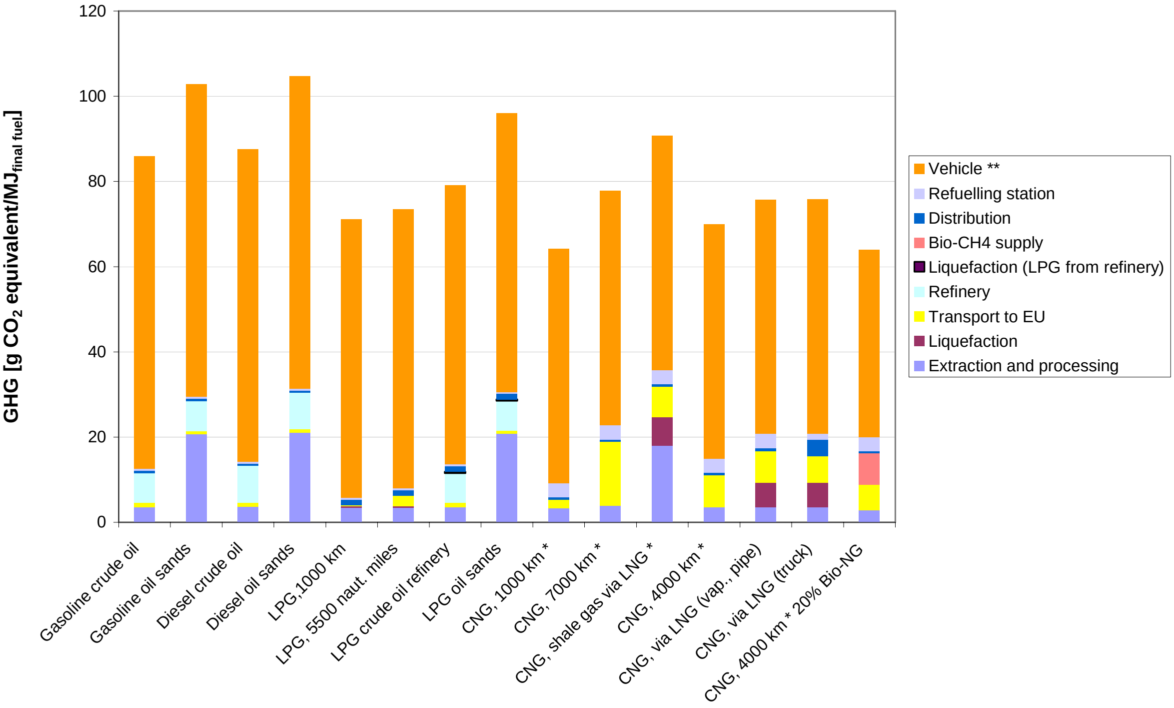


* plus distribution via the high pressure natural gas grid (500 km) and the local natural gas grid (10 km)

Figure 15: **GHG emissions from the supply and use (WTW) for pathways involving LPG and CNG compared to gasoline and diesel fuel (2010) per MJ of final fuel**

The negative greenhouse gas emissions are from the CO_2 absorbed from the atmosphere during growth of the plants and are emitted during the combustion in the vehicle (the vehicle GHG emissions are always the same for CNG). It has been assumed that no land use change occurs. Therefore, no CO_2 emissions from land use change have been taken into account.

Figure 16 shows the net GHG emissions for the supply and use (combustion) per MJ of final fuel.

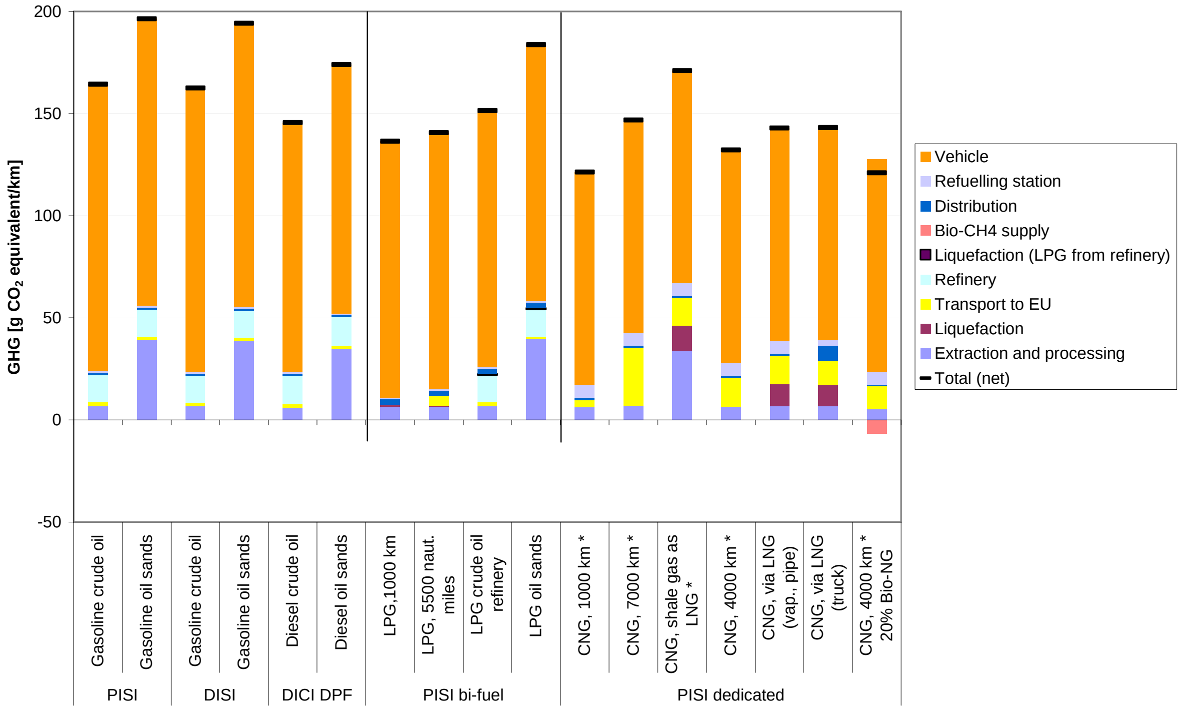


* plus distribution via the high pressure natural gas grid (500 km) and the local natural gas grid (10 km)
** Share of bio-methane derived CNG is CO_2 neutral

Figure 16: Net GHG emissions from the supply and use (WTW) for pathways involving LPG and CNG compared to gasoline and diesel fuel (2010) per MJ of final fuel

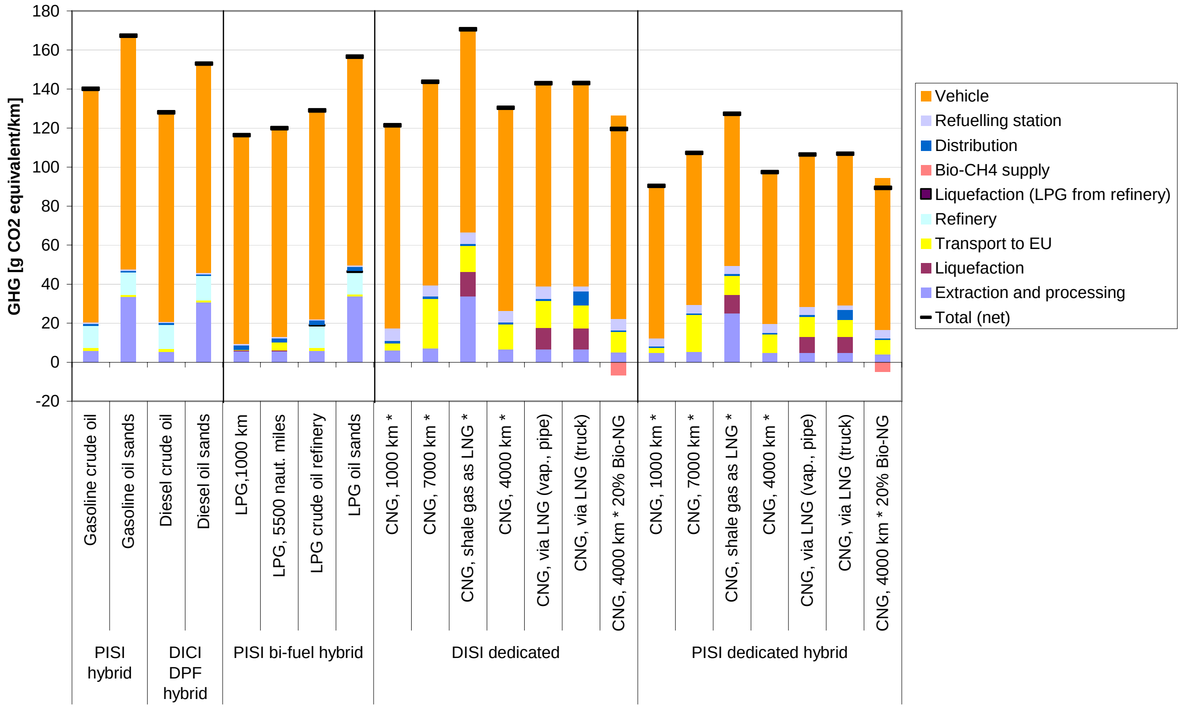
The fuel consumption of the vehicles adapted to the various fuels is different. Therefore, the fuel consumption of the vehicle has to be taken into account for a comprehensive assessment.

Figure 17 and Figure 18 show the GHG emissions "well-to-wheel" (WTW) for the supply and use of LPG and CNG per km compared with crude oil based gasoline and diesel fuel for 2010 and 2020, respectively. The crude oil is derived from conventional oil production and as synthetic crude oil from oil sands.



* plus distribution via the high pressure natural gas grid (500 km) and the local natural gas grid (10 km)

Figure 17: WTW GHG emissions for pathways involving LPG and CNG compared to gasoline and diesel fuel (2010) (non-hybrid vehicles only)

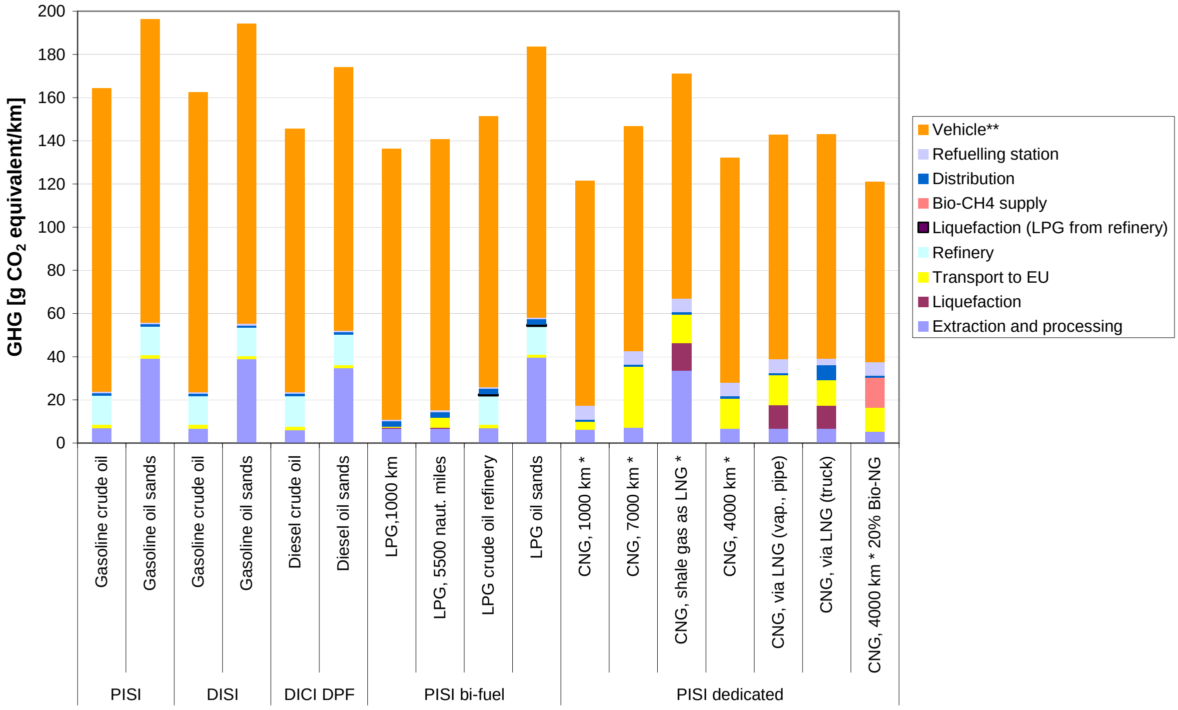


* plus distribution via the high pressure natural gas grid (500 km) and the local natural gas grid (10 km)

Figure 18: **WTW GHG emissions for pathways involving LPG and CNG compared to gasoline and diesel fuel (2020) (hybrid and non-hybrid vehicles)**

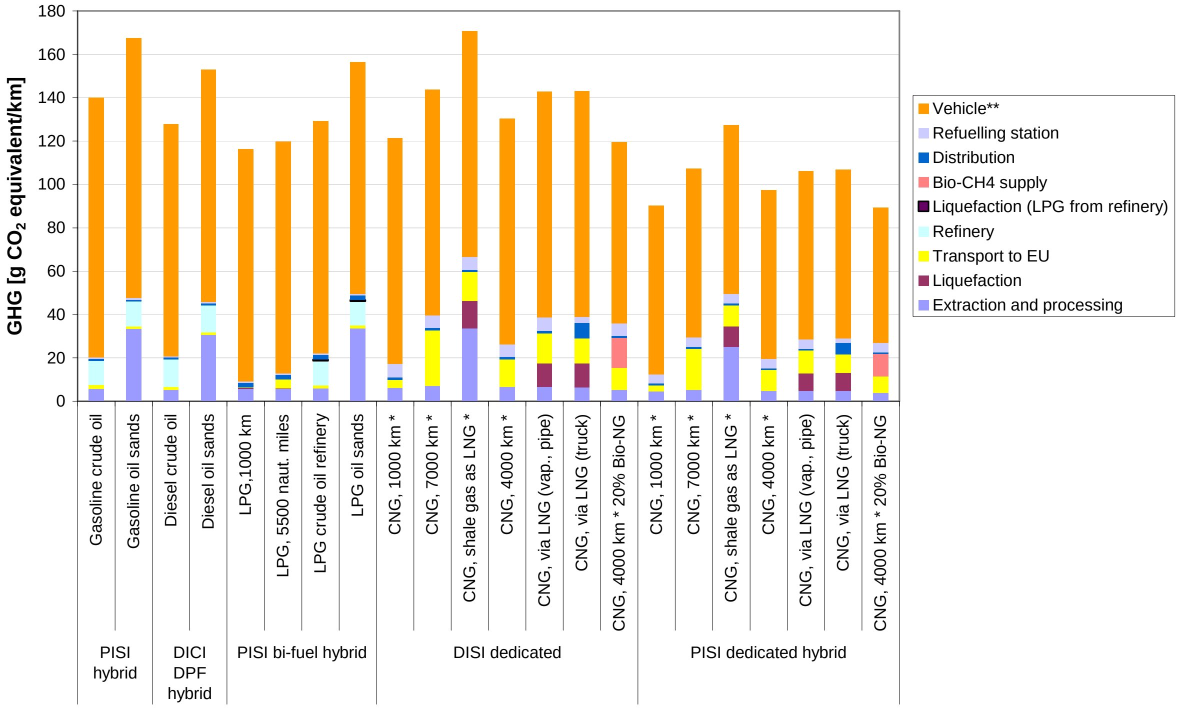
The negative GHG emissions are from the CO_2 absorbed from the atmosphere during growth of the plants and are emitted during the combustion in the vehicle (the vehicle GHG emissions are always the same for CNG). The black mark shows the net GHG emissions (net total).

Figure 19 and Figure 20 show the net GHG emissions GHG emissions “well-to-wheel” (WTW) for the supply and use of LPG and CNG per km compared with crude oil based gasoline and diesel fuel for 2010 and 2020, respectively.



* plus distribution via the high pressure natural gas grid (500 km) and the local natural gas grid (10 km)
** Share of bio-methane derived CNG is CO_2 neutral

Figure 19: **Net WTW GHG emissions for pathways involving LPG and CNG compared to gasoline and diesel fuel (2010) (non-hybrid vehicles only)**



* plus distribution via the high pressure natural gas grid (500 km) and the local natural gas grid (10 km)
** Share of bio-methane derived CNG is CO_2 neutral

Figure 20: **Net WTW GHG emissions for pathways involving LPG and CNG compared to gasoline and diesel fuel (2020) (hybrid and non-hybrid vehicles)**

The admixture of 20% bio-methane leads to net GHG savings of about 8% if the natural gas supply case with 4,000 km long distance pipeline transport is used as base case.

The difference between “2010” and “2020” is in the use of different vehicles with lower fuel consumption and the higher efficiency of the gas turbines for long distance natural gas transport (4,000 km and 7,000 km) via pipeline.

4 POTENTIALS FOR GHG REDUCTION UNTIL 2020

The following chapter describes development scenarios for CNG and LPG vehicles until 2020 and the associated reduction of greenhouse gas (GHG) emissions. The effect of vehicle penetration scenarios on GHG reductions under different framework conditions found in literature is discussed.

4.1 Basic assumptions

In order to derive absolute greenhouse gas emission savings from a certain market penetration of alternative vehicles, the most important input assumptions are the specific (per-km) well-to-wheel (WTW) greenhouse gas emissions of the alternative vehicles and the vehicles they replace, and their annual mileage. While the WTW emissions of different vehicle types and fuel supply chains were assessed in detail in the previous chapter, assumptions on the annual mileage need to be derived from other studies. Some prominent and recent studies for Germany are e.g.:

- The "Renewbility" study on the analysis of material flows for sustainable mobility in the context of renewable energy until 2030, performed by the German Aerospace Centre (DLR) and the Institute for Applied Ecology (Öko-Institut) [Renewbility 2009]. The study relies partly on data derived from "Traffic Prognosis 2025 (Verkehrsprognose 2025)" study performed by BVU and Intraplan Consult in 2007 for the German Federal Ministry of Transport, building and urban development (BMVBS) [BVU/ITP 2007]. The annual mileage was calculated from the overall mileage and the car stock.
- The "Passenger car scenarios until 2030" by Shell [Shell 2009].
- The "Energy scenarios for the energy summit 2007" performed by EWI/Prognos for the German Federal Ministry of Economics and Technology [EWI/Prognos 2007].

Figure 21 shows the assumptions for the annual mileage of these studies. As a result of the discussions within the project group and advisory council, it was decided to use the data of the Renewbility study for the calculation of GHG emission savings, i.e. annual mileages of 12,800 km by 2010, and 13,200 km by 2020.

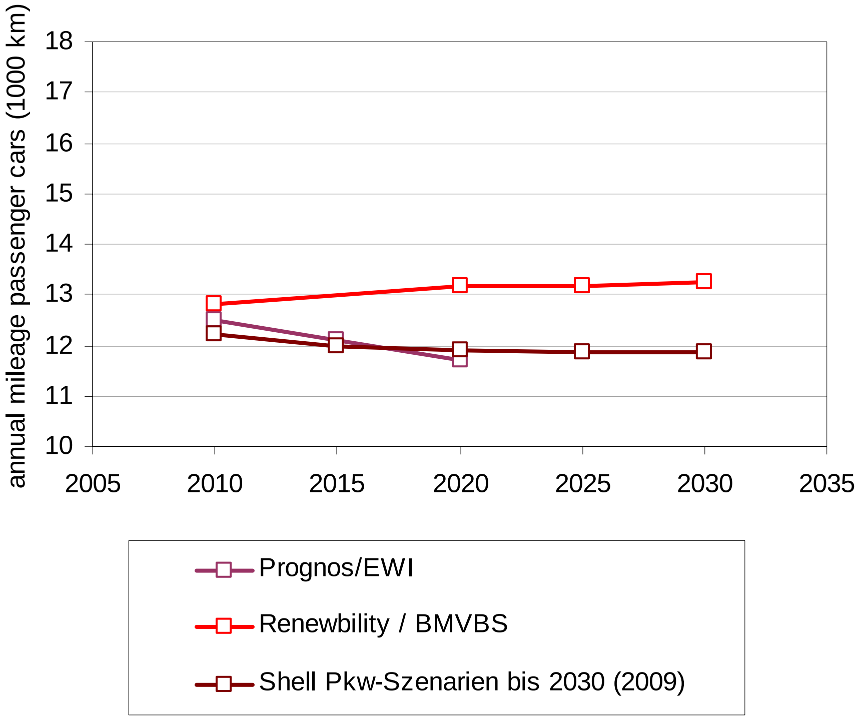


Figure 21: **Development of annual mileage of passenger cars Germany**

For the calculation it was further assumed that every alternative fuel vehicle would substitute a gasoline vehicle of a similar engine technology, without alterations in driving behaviour or annual mileage. Bi-fuel vehicles were assumed to be operated completely on LPG or CNG.

4.2 Current GHG emission savings from fuel switch to CNG and LPG

In 2008, German road transport emitted 146 million tons of CO_2 equivalents (t_{CO2e}) in total (tank-to-wheel – TTW) [UBA 2010b], more than two thirds of which originate from passenger vehicles. Out of the 47.5 million passenger vehicles in Germany, about 68,500 are using CNG and about 370,000 are using LPG as a fuel. The emissions savings from these vehicles depend on the underlying fuel supply chain and the vehicle technology. For the 2010 case, it is assumed that the vehicles substituted are gasoline vehicles using PISI technology, the gasoline being produced by conventional crude oil refining. For CNG vehicles, bi-fuel PISI vehicles are assumed. The natural gas is transported over a distance of 1,000 km, which today is the most common transport distance (compare Figure 4). For current LPG vehicles, the bi-fuel PISI technology is assumed. As of today, in Germany LPG is exclusively produced from oil refining; the origin of the imported LPG fraction is, however, unknown.

Table 34 shows the resulting emissions savings using the well-to-wheel (WTW) values for the supply chains and vehicles described as shown in Figure 17 and Table 32. Today’s

CNG vehicles save about 40,500 tons of CO_2 equivalent green house gas emissions per year compared to conventional vehicles, while the LPG vehicles save about 72,000 tons$_{CO2e}$ per year. Hence, even though LPG vehicles outnumber CNG vehicles by more than a factor of 5 today, LPG only saves about 75% more CO_2 equivalent emissions than CNG.

Table 34: Status quo of GHG savings (annual mileage by 2010: 12,800 km)

Technology	GHG savings per car (2010)	# of cars (2010)	Overall GHG savings (2010)
CNG (bi-fuel PISI; 1,000 km transport distance)	0.592 t_{CO2eq} / a	68,500	40,527
LPG (bi-fuel PISI; crude oil refining)	0.194 t_{CO2eq} / a	370,000	71,765

4.3 Cost-benefit analysis (Tax €) of current GHG emission savings

In Germany, the introduction of alternative transport fuels is – among other policy instruments like target setting – supported with a reduction in energy taxes. Table 35 gives an overview of current German Energy Tax rates, formerly known as 'mineral oil tax'.

Table 35: Energy tax rates for transport fuels in Germany in 2010 (excl. VAT) and normalised to functional unit 'per km' (mid-sized car)

Transport fuel	Energy tax rate [BMF 2010]		Energy tax rate by energy use [EUR/km]*	GHG WTW 2010 [g_{CO2e}/km]
Gasoline crude oil	654.50	EUR/1000l	0.03864	163.2
Diesel crude oil	470.40	EUR/1000l	0.02172	145.1
LPG (crude oil refining)	180.32	EUR/1000kg	0.00746	150.3
CNG (1,000 km transport dist.)	13.90	EUR/MWh	0.00723	131.0
Mix (CNG + 20% Bio-methane)	13.90	EUR/MWh	0.00723	118.3
Bio-methane	13.90	EUR/MWh	0.00723	74.7

* Gasoline: PISI; Diesel: DICI DPF; all others: Bi-fuel PISI

From Table 35 it can be observed that transport fuels are taxed differently. In order to facilitate a fair comparison, the different energy tax rates have been normalised to a common functional unit, i.e. per km driven in a mid-sized car (2010 fuel consumption).

Gasoline has the highest per-km tax rate; the difference of all other fuels to the gasoline rate can be considered a subsidy. The effectiveness of German Energy Tax subsidies vis-à-vis resulting greenhouse gas emission savings is calculated in the following cost-benefit analysis. Taking gasoline from crude oil as reference for energy taxation and furthermore considering today's greenhouse gas emission savings from using LPG, CNG, bio-methane or a mixture of CNG and bio-methane against the gasoline reference, results in cost-benefits as depicted in Figure 22.

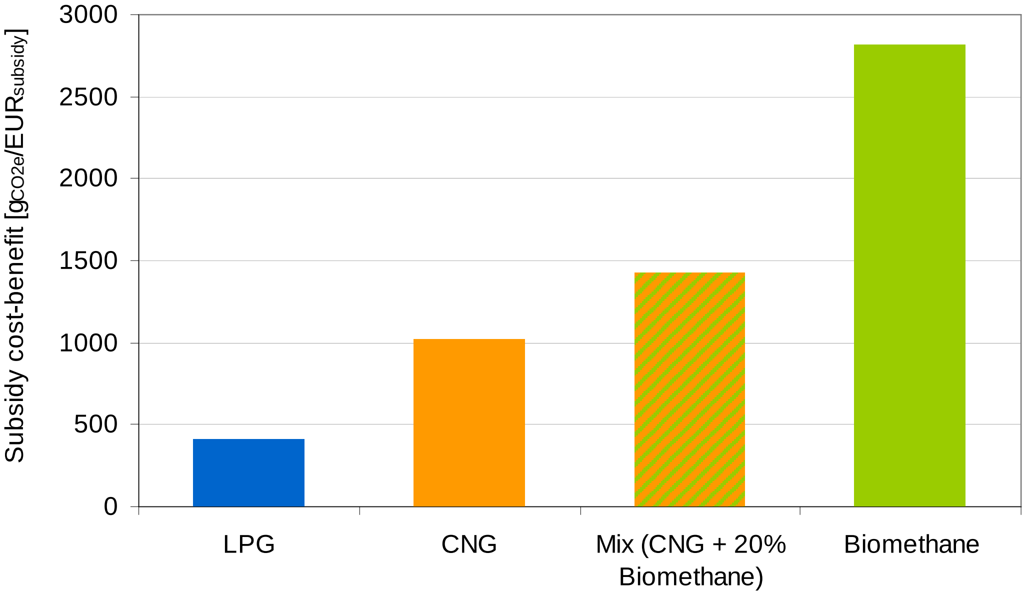


Figure 22: **Cost-benefit analysis in terms of greenhouse gas emission savings per Euro tax subsidy (German Energy Tax, no VAT, mid-sized car)**

Pure bio-methane provides the highest cost-benefit in terms of greenhouse gas emission reductions per Euro subsidy with 2.6 times that of CNG and even 6.8 times that of LPG. Per Euro subsidy, CNG saves 2.5 times the amount of greenhouse gas emissions on a per-km basis compared to LPG. The corresponding mitigation costs are 2,416 $€_{subsidy}/t_{CO2e}$ for LPG, 975 $€_{subsidy}/t_{CO2e}$ for CNG, 700 $€_{subsidy}/t_{CO2e}$ for the CNG admixed with 20% bio-methane, and 355 $€_{subsidy}/t_{CO2e}$ for pure bio-methane.

4.4 Prospective GHG reductions until 2020 and beyond

Progressing towards 2020, both vehicle technologies as well as the typical fuel supply pathways will change.

In line with the general trend towards hybridisation and direct injection spark-ignition engines, the standard of the conventional vehicles to be substituted by CNG and LPG will develop further; hence, instead of PISI technology, either DISI or hybridised PISI engines are assumed for the 2020 scenarios. Also for CNG vehicles, either DISI or hybridised PISI engines are assumed to become the standard by 2020, and hybridised LPG vehicles will be available as well.

Regarding the fuel supply chains, due to the ongoing decline of European natural gas resources, more and more of the CNG and also the NG-derived LPG will have to be transported over longer distances, increasing the energy use and GHG emission in the supply chain. It is assumed that by 2020, CNG will be transported by pipeline across a distance of 4,000 to 7,000 km (see Figure 10), and also LNG will be a common supply pathway. LPG will either be produced from oil refining (as in 2010), or come from NG processing with a ship transport distance of 5,500 nm (10,186 km). Also LPG produced during refining of non-conventional oil from oil sands will become a common pathway.

Figure 23 shows the specific GHG emission reduction achievable against the reference vehicles (gasoline from crude oil; hybrid or non-hybrid) for different pathways and vehicle technologies. It can be seen that in all cases the bandwidth of GHG emissions reduction by CNG vehicles is higher than by LPG vehicles. This is mainly due to the attributed GHG well-to-tank emissions for fuel production and supply chain, and the lower carbon content of CNG. Furthermore, hybridisation yields higher efficiency improvements for dedicated CNG engines than for LPG engines. Secondary impacts (i.e. 'rebound effects' that may occur when LPG is substituted by other fuels, e.g. in chemical industry or residential heating) have not been assessed here.

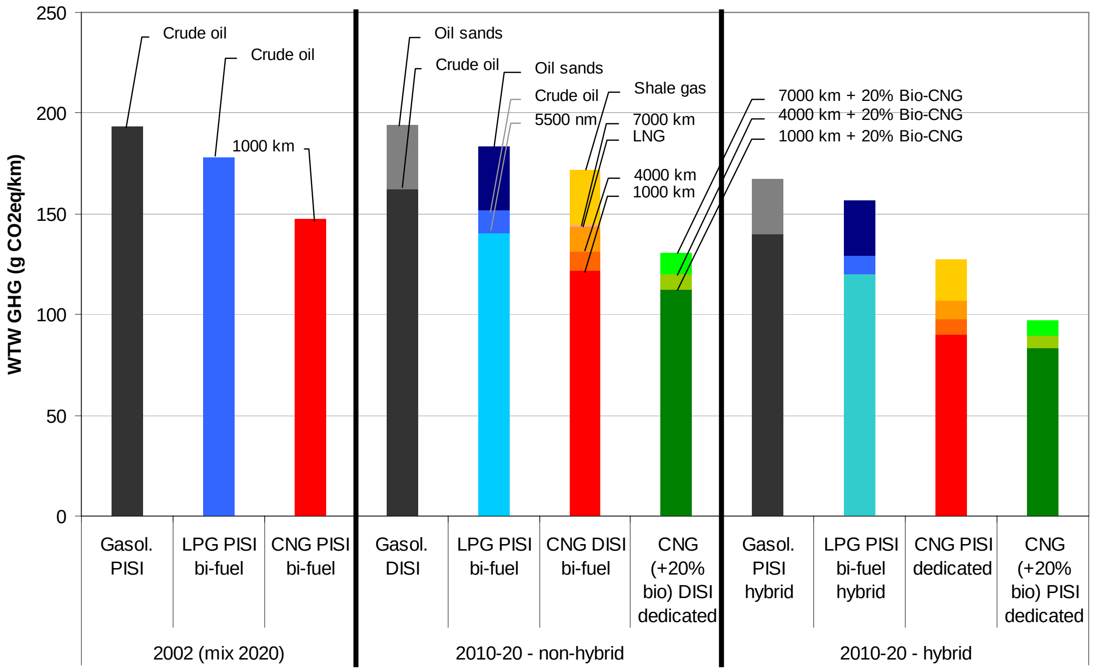


Figure 23: Specific GHG emission reductions against the reference vehicle

In order to estimate the resulting absolute GHG savings for additional CNG and LPG vehicles against the reference vehicles, scenarios for the time around 2020 were analysed. Furthermore, the shares of sources for both CNG and LPG were varied to span the event horizon for the year 2020. The scenarios are as follows:

- LPG with today's supply mix: In this scenario it is assumed that as today, LPG used in Germany mainly originates from crude oil refining.
- LPG with supply over longer transport distances: It is assumed that the oil refining in Germany is decreasing sharply and hence a 50% share of the LPG comes from natural gas processing and is transported over long distances.
- CNG with today's mix plus 20% bio-methane: It is assumed that the CNG mix used in Germany by 2020 is the same as today. Hence, today's distribution of distances is used[8] (see Figure 4) [BAFA 2009]. It is furthermore assumed that the decline of the European natural gas sources will be compensated by lower natural gas consumption across all sectors, and substantial feed in of bio-methane. Consequently, a 20% share of CNG from bio-methane is assumed.
- CNG with supply over longer transport distances: In this scenario it is assumed that by 2020, the decline of the European natural gas sources will be compensated by a higher share of natural gas from farther distant origins. The shares are derived from the base case scenario from a recent Eurogas study [Eurogas 2010][9]. It is furthermore assumed that no relevant contribution from bio-methane will be made to the CNG mix.

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[8] 1,000 km transport distance is assumed for natural gas from Norway, The Netherlands and Germany; 4,000 km for Russia; and 7,000 km/LNG for other sources.

[9] 1,000 km transport distance was assumed for NG EU27 and Norway. The contracted imports and possible prolongations from outside Europe were split to the 4,000 and 7,000 km transport distances in a 70/30 ratio. The additional supplies to be defined were assumed to be LNG.

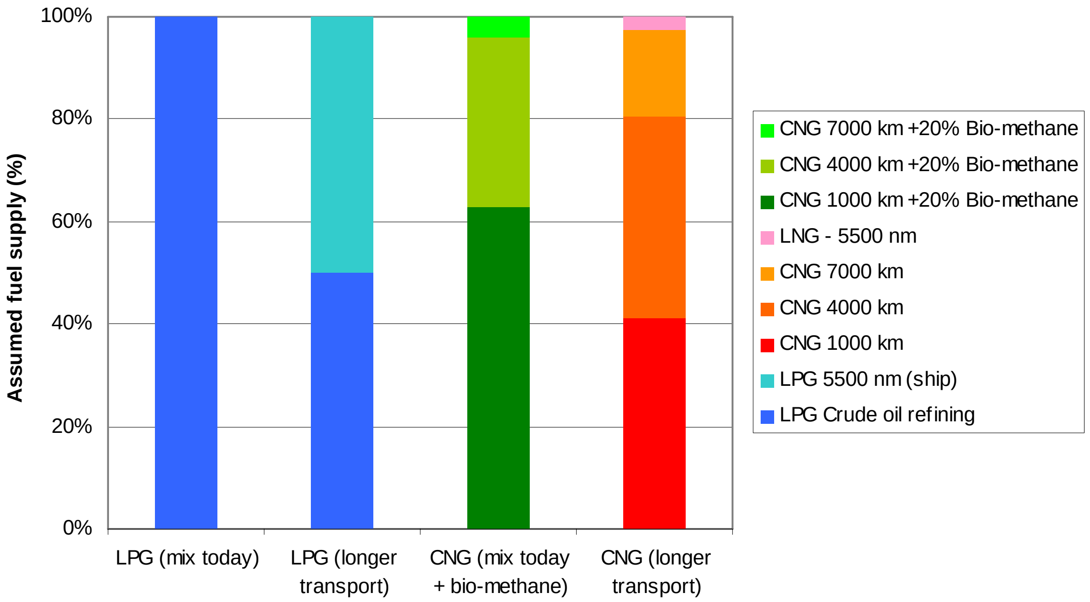

Figure 24: **Scenario assumptions of shares for LPG and CNG in Germany by 2020**

Figure 24 shows the resulting composition for the four scenarios. Note that in order to be consistent with the previous figure, the bio-methane contribution has not been added as a separate source but instead the mixed pathways from Chapter 0 are shown here.

The resulting absolute GHG savings from additional CNG and LPG vehicles against the reference vehicles are shown in Figure 25 (hybrid) and Figure 26 (non-hybrid), assuming an annual mileage of 13,200 km, and for a variable number of vehicles. It can be seen that depending on the scenario, introducing one million additional LPG vehicles can save 145-205,000 t_{CO2eq} per year by 2020, assuming hybrid vehicles replacing hybrid vehicles, and slightly more assuming non-hybrid vehicles replacing non-hybrid vehicles. In contrast, one million additional CNG vehicles can save 580-710,000 t_{CO2eq} per year assuming hybrid vehicles and 430-620,000 t_{CO2eq} assuming non-hybrid vehicles. It can be concluded that for the scenarios investigated, CNG as a fuel can save 2 to 5 times as much GHG emissions as LPG vehicles for the same number of vehicles.

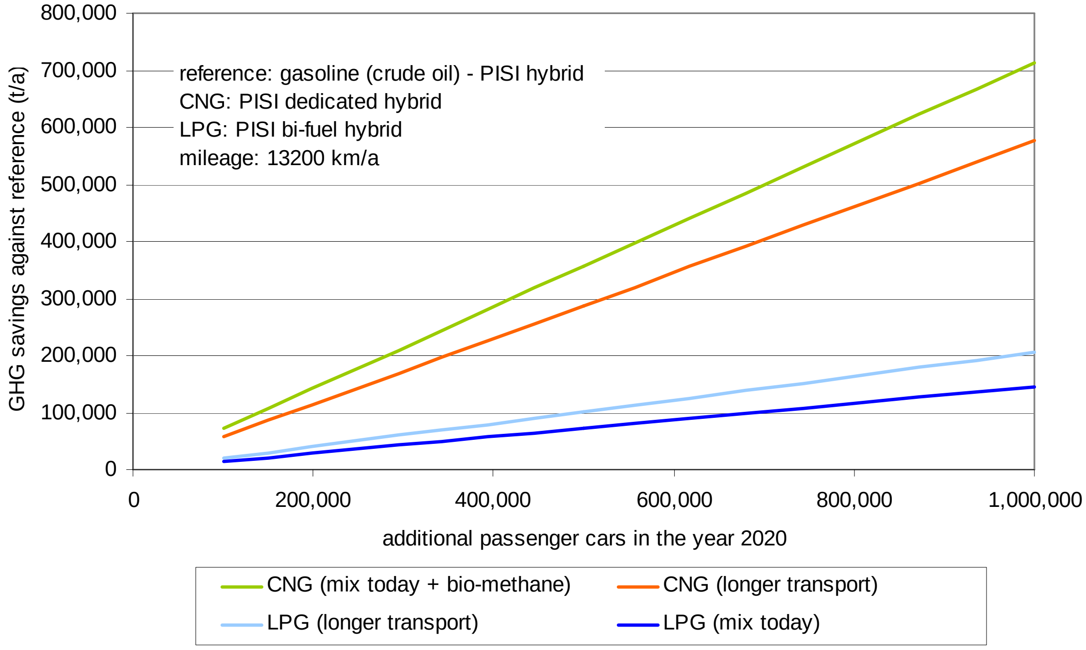

Figure 25: **Additional GHG savings through CNG and LPG vehicles by 2020 (hybrid)**

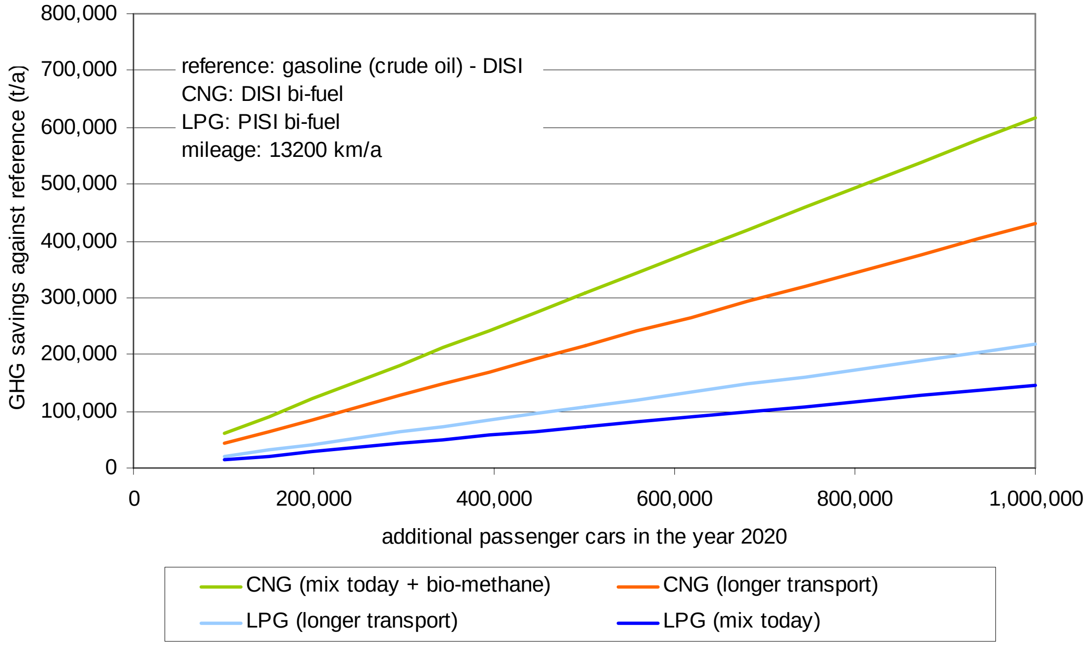

Figure 26: **Additional GHG savings through CNG and LPG vehicles by 2020 (non-hybrid)**

The assumption of one million CNG cars by 2020 is close to the development expected by dena [dena 2010]. According to Table 32, this number of vehicles would consume between 18.4 and 24.9 PJ/a fuel (assuming 13,200 km/a; lower bound: PISI dedicated hybrid; upper bound: DISI bi-fuel). According to Table 2, Germany consumed a total of about 3,640 PJ of natural gas in 2009. Hence, one million CNG vehicles would represent only 0.5 to 0.68% of the 2009 demand. On the other hand, one million LPG vehicles would consume about 21.3 to 25.7 PJ/a (lower bound PISI bi-fuel hybrid, upper bound PISI bi-fuel). According to Table 1, the LPG used in Germany in 2009 is equivalent to 131 PJ. Hence, one million LPG vehicles would represent 16 to 20% of today's LPG consumption.

Since LPG is a by-product of either crude oil refining or natural gas processing, it must be assumed that the production cannot be extended significantly both locally and globally. The expected decline in worldwide crude oil production implicates a decline in LPG production from refining; to what extent this can be compensated by increasing natural gas production has not been assessed here. Even though a certain part of the LPG consumption of chemical industry might be substituted by other fuels, supplying several million additional LPG vehicles will in any case massively increase the overall LPG consumption in Germany and thereby imply substantial changes in the LPG supply. Transport distances would increase and a partial switch to alternative sources would become even more necessary. On the CNG side, the situation is less limited, since the overall natural gas turnover is much higher (reducing the impact CNG vehicles have on overall consumption). Furthermore, bio-methane CNG can fill in once the supplies face hard limits.

However, it must be noted that for high penetration numbers (e.g. 5 to 10 million vehicles), the GHG reduction effect may not scale linearly, since a significant demand increase for CNG or LPG will have a feedback on the supply; i.e. a shift to longer distances and higher shares of fuel coming from non-conventional sources, such as oil sands or shale gas, which generally increases their GHG footprint and other environmental impacts. In this case, from GHG emission point of view, CNG coming from shale gas performs possibly better than LPG from oil sands – however, local impacts in the mining area may be quite severe in both cases. Also in case of LNG transport the GHG reduction for CNG vehicles remains significant.

A conclusion is therefore that CNG fuel has a significantly higher potential to reduce GHG emissions from the transportation sector than LPG fuel. This is due to CNG's higher specific GHG reduction for various current and future pathways, the higher energy efficiency increase achieved by hybridisation of CNG engines, the potential to use bio-methane, and the limitations that exist for the supply of LPG.

4.5 Contribution to comply with European regulations

The so-called "Fuel Quality Directive" 2009/30/EC of the European Parliament and of the Council of 23 April 2009 [EU-FQD 2009] claims:

> *"Suppliers should, by 31 December 2020, gradually reduce life cycle greenhouse gas emissions by up to 10 % per unit of energy from fuel and energy supplied. This reduction should amount to at least 6 % by 31 December 2020, compared to the EU-average level of life cycle greenhouse gas emissions per unit of energy from fossil fuels in 2010, obtained through the use of biofuels, alternative fuels and reductions in flaring and venting at production sites. …"*

From the well-to-tank calculations in Chapter 3.2, it is possible to estimate the contribution of LPG and CNG to the compliance of the claimed 6% per-energy-unit reduction against 2010 of fossil fuel for the 1 million additional vehicles case. In order to estimate the per-energy GHG reduction of the fuel mix, the fuel mix including CNG / LPG must be calculated and the savings of CNG / LPG against conventional gasoline and diesel on a life cycle (here: well-to-wheel) basis.

The overall TTW GHG emissions from road transportation by 2008 were 146 million tons CO_2 equivalent. Assuming a TTW GHG intensity of gasoline and diesel of 264 g/kWh (final energy – supply chain not considered), the final energy consumption in road transportation was about 553 TWh or 1991 PJ. Depending on the type of vehicle technologies used, the specific final energy consumption per km of one million CNG or LPG vehicles (reflecting about 2.1% of the overall passenger vehicle stock) in the time horizon 2010-2020 is between 1.394 and 1.900 MJ/km (see Table 32). Assuming an annual mileage of 13,200 km, this is equivalent to an overall final energy consumption between 18.3 and 25.0 PJ, representing between 0.92 and 1.26% of the 2008 overall final energy in road transportation.

Depending on the supply pathway, the alternative fuels have between 8.8% (LPG from crude oil) and 27.1% (CNG 4,000 km + 20% bio-methane) lower life cycle GHG emissions per energy unit than conventional gasoline or diesel[10]. Hence, the overall life cycle GHG reduction per energy of all transportation fuels according to 2009/30/EC amounts to between 0.09 and 0.34% per million alternative vehicles (assuming no land use change for the bioenergy feedstock). This is equivalent to 1.6 to 5.6% of the mentioned 6% target.

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[10] Note that the numbers differ from Figure 23 because EC directive 2009/30 demands a reduction per energy unit, NOT per km driven; i.e. the vehicle efficiencies as included in Figure 23 are not relevant here.

Table 36: Calculation of contribution to 2009/30/EC (Fuel Quality Directive)

Case	Fuel	Supply pathway	TTW energy use (MJ/km)	Final energy cons. of 1 mill. vehicles) (PJ)	Share of overall final energy	WTW GHG p. energy (g/MJ)	GHG saving p. energy against gasoline/diesel	GHG intensity reduction fuel mix
Reference	Gasol./Diesel	Crude oil refining				85.9 -87.6		
2020 hybrid	CNG	4,000 km	1.394	18.3437	0.92%	69.0	20.4%	0.19%
		7,000 km	1.394	18.3437	0.92%	75.5	13.0%	0.12%
		4,000 km + 20% biomethane	1.394	18.3437	0.92%	63.2	27.1%	0.25%
	LPG	5,500 nm	1.617	21.2782	1.07%	73.4	15.3%	0.16%
		Crude oil refining	1.617	21.2782	1.07%	79.1	8.8%	0.09%
2020 non-hybrid	CNG	4,000 km	1.883	24.7785	1.24%	69.0	20.4%	0.25%
		7,000 km	1.883	24.7785	1.24%	75.5	13.0%	0.16%
		4,000 km + 20% biomethane	1.883	24.7785	1.24%	63.2	27.1%	0.34%
	LPG	5,500 nm	1.9	25.0022	1.26%	73.4	15.3%	0.19%
		Crude oil refining	1.9	25.0022	1.26%	79.1	8.8%	0.11%

Following this calculation approach, Table 36 shows the results for the LPG and CNG pathways considered by 2020, and Figure 27 visualises the resulting life cycle GHG reduction and contribution to fulfilment of the targets. The overall transportation energy demand is based on the 2008 numbers; therefore, assuming hybrid vehicles results in lower energy consumption and hence a lower share of CNG/LPG in the fuel mix than if non-hybrid vehicles are assumed[11]. It can be seen that one million CNG vehicles can contribute by 2.0 to 5.6% to the 6% target (i.e. 0.12 to 0.34 percentage points to the overall transportation fuel consumption), while one million LPG vehicles can only contribute by 1.6 to 3.2% (i.e. some 0.09 to 0.19 percentage points respectively). Having in mind the different level of limitations of the fuels as discussed in the previous chapter, also here it becomes obvious that CNG can contribute more to GHG reduction in transportation than LPG.

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[11] A limitation of this approach is the assumption of 2008 energy consumption remaining constant until 2020.

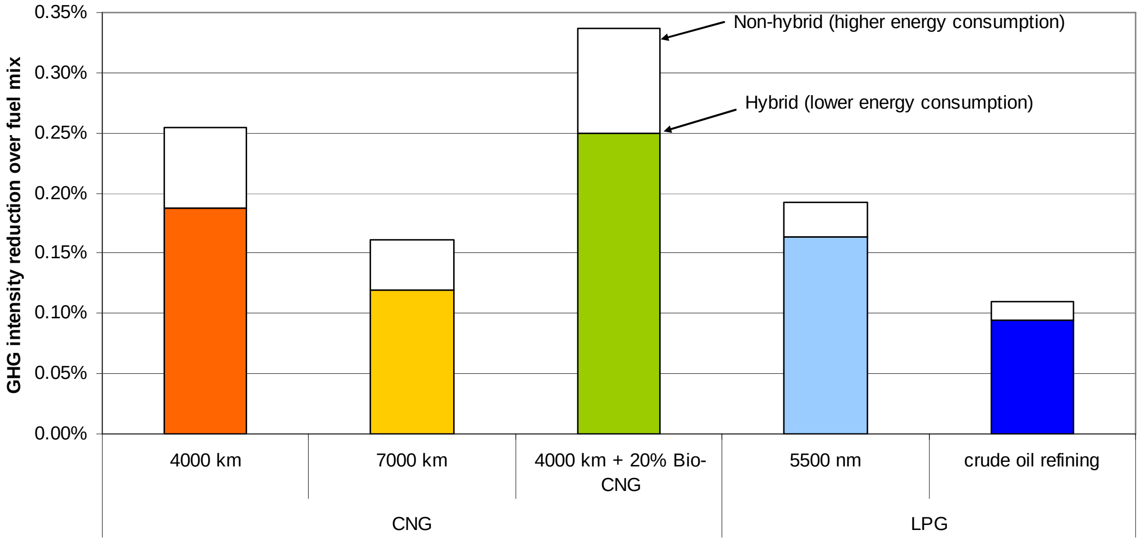

Figure 27: **Reduction of GHG intensity per 1 million CNG/LPG vehicles compared to gasoline and diesel fuel (Directive 2009/30/EC requires GHG intensity reduction in transportation of 6%)**

Another criterion to be met by 2020 is the EU target of 10% renewable transport fuel in each Member State by 2020 as depicted in the European Renewable Energy Directive (EU-RED 2009/28/EC) and accompanying sustainability criteria for biomass-derived fuels. Through the use of renewable methane (bio-methane and SNG), CNG has a short-term potential to contribute significantly to these targets, while for LPG a convenient renewable substitute is not at hand according to the recently released presentation of the CONCAWE-EUCAR-JRC consortium's "Biofuels Programme" [JEC 2010]. Table 37 gives a summary of CNG/LPG compliance to contribute to EU policies.

Table 37: **Compliance of hydro-carbon based alternative transportation fuels with EU policies**

Transportation fuel		EU policy contribution		Annotation
		RED	FQD	
Methane	CNG	–	✓	
	Bio-methane	✓	✓	
	SNG	✓*	✓	*If non-fossil CO_2 is used
LPG	Crude oil refining by-product LPG	–	✓	
	NG extraction by-product LPG	–	✓	

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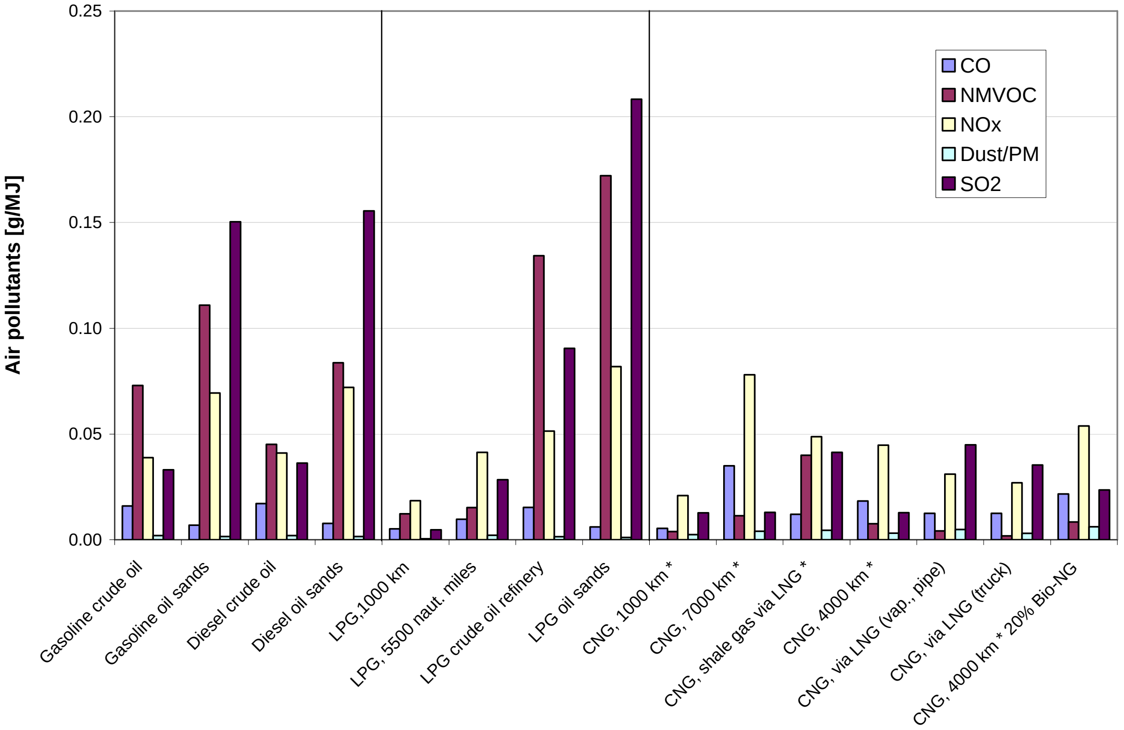
6 APPENDIX

Figure 28 shows the emissions of air pollutants "well-to-tank".



Note: No data available for dust/PM and SO_2 emissions from shale gas production.

Figure 28: Air pollutant emissions from the supply of various transportation fuels ("well-to-tank") 2010

It has to be noted that no data for dust/PM and SO_2 emissions from the production of shale gas are available. The supply of gasoline, diesel and LPG from oil sands leads to high emissions of SO_2. The reason is the high emission of SO_2 at the production of synthetic crude oil (SCO) from oil sands. Another significant source of SO_2 emissions is the maritime transport due to the high sulphur content of the heavy fuel oil used in the ship engines.

Main sources of NO_x emissions are ship engines used for maritime transport and gas turbines used for natural gas compression for long distance transport of natural gas via pipeline.

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