Life Cycle Assessment of a Demonstration Project

Vehicle Use of Hydrogen-Blended Natural Gas

Master's Thesis of

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Abstract

Hydrogen is often considered as the way out of the environmental and economical problems associated with the use of fossil fuels. However, one of the main implementation barriers is the missing infrastructure. The introduction of hydrogen-blended compressed natural gas (HCNG) as a fuel for natural gas vehicles could serve as a bridging technology by using the existing natural gas infrastructure for the distribution of hydrogen.

The unique conditions on site the large petrochemical complex in Stenungsund, Sweden—a hydrogen surplus and the connection to the natural gas grid—initiated a discussion about demonstrating the vehicle use of HCNG by using an already projected natural gas filling station near the industrial area. The hydrogen surplus used in this context will be replaced by natural gas. The intended aim of this demonstration project is learning in dealing with hydrogen as a fuel for vehicles.

The purpose of this thesis is to assess and compare the environmental aspects of using natural gas, HCNG with 15% and 30% hydrogen by volume, and hydrogen as vehicle fuels within the scope of the proposed demonstration project. Life Cycle Assessment is used to analyse and quantify the potential environmental impacts from the use of the considered fuels in two different types of light-duty vehicles with internal combustion engines.

The results show that the environmental benefits of performing the demonstration project are limited since there are no overall benefits connected to the use of HCNG and hydrogen compared to the use of natural gas. In general, the results reveal that the potential environmental impact from the fuel supply chain considerably increases towards a hydrogen share of 100% in the fuel.

Besides these environmental considerations, however, it has to be taken into account that potential environmental impacts as direct project results cannot be consulted alone, when assessing the demonstration project and deciding whether it should be performed or not. Learning should be maximised and, therefore, the assessment of the demonstration project has to be extended by focusing on the dynamics of technological change, which can be given as a suggestion for further studies.

Preface

During my studies in the Environmental Engineering programme as well as my work as a student research assistant at the Department of Life Cycle Engineering, both at the University of Stuttgart, I gained insight into Life Cycle Assessment (LCA), a powerful yet complex environmental assessment tool, representing my ideal conception of the precautionary approach to environmental protection.

My impulse to learn more about this method as well as to study at least one semester abroad finally provided the chance to carry out my diploma thesis within this subject at the Division of Environmental Systems Analysis (ESA) at Chalmers University of Technology, Göteborg.

Thanks to an outstanding supervision at ESA, I finally got to know many methodological aspects of an LCA as well as some of its weak points and pitfalls. Moreover, methodological extensions aroused my interest, especially with regard to the dynamics of technological change. My interest is still unbroken, and hopefully I will have the opportunity to get back to it after my studies.

I gained a lot of experiences during my time in Sweden, both professional and personal, and it was not always an easy way to go. My sincere thanks go to my supervisor Karl Jonasson and my examinator Björn Sandén for all their advice and support in this respect. Furthermore, my special thanks go to my parents. It was their support and encouragement that made all this possible and let me look back now on a successful time in Sweden. Last but not least, I want to thank all the people, who also enabled and encouraged me to realise this project. However, I would be nothing without the other half of my soul—my origin of love. This thesis is dedicated to you.

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List of Abbreviations

APS	Arizona Public Service
ATVA	Advanced Vehicle Testing Activity
CH_4	Methane
CHP	Combined heat and power
CI	Compression-ignition
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CUTE	Clean Urban Transport for Europe
DME	Dimethyl ether
EGR	Exhaust gas recirculation
ETA	Electric Transportation Applications
FCV	Fuel cell vehicle
FT	Fischer-Tropsch
FTP-75	Federal Test Procedure
GHG	Greenhouse gas
GWP	Global warming potential
HC	Unburned hydrocarbons
HCNG	Hydrogen-blended compressed natural gas
HCNG-*xx*	HCNG with *xx* percent hydrogen by volume
ICE	Internal combustion engine
IMEP	Indicated mean effective pressure
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IVL	Swedish Environmental Research Institute

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LNG	Liquefied natural gas
MR	Measuring and regulating
NGG	Nordic Gas Grid
NGV	Natural gas vehicle
NMHC	Non-methane hydrocarbons
NO_x	Nitrogen oxides
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
PSA	Pressure Swing Adsorption
PVC	Polyvinyl chloride
RON	Research octane number
SI	Spark-ignition
SULEV	Super Ultra Low Emission Vehicle
TDC	Top dead centre
ULEV	Ultra Low Emission Vehicle
WTW	Well-to-wheel

1 Introduction

"... I believe that water will one day be used as fuel, that the hydrogen and oxygen of which it is constituted will be used, simultaneously or in isolation, to furnish an inexhaustible source of heat and light, more powerful than coal can ever be. ... I believe, then, that once the coal deposits have been exhausted, we will warm our homes and ourselves with water. Water is the coal of the future."

This passage is cited from Jules Verne's science fiction novel "Mysterious Island" written in the 1870s (Verne 2004). It shall point out that considerations about using hydrogen as an energy carrier have taken place long before our actual debate. Many studies have been carried out since hydrogen was first isolated by Henry Cavendish in 1766, among others regarding hydrogen as a fuel in internal combustion engines (ICEs). Nowadays, the transition to a sustainable energy system based on hydrogen, termed as the 'hydrogen economy', is regarded by many scientists as an upcoming future of our society.

In general, a transition away from fossil fuels within this century is of prime importance. From an environmental point of view, the widely use of fossil fuels as a primary energy source results in large emissions of pollutants affecting the natural and human environment in various ways. In particular, the emission of greenhouse gases (GHGs) and their contribution to the global warming are frequently discussed issues, last but not least since the Kyoto Treaty has entered into force in February 2005. A further increase of the atmospheric concentration of carbon dioxide (CO_2)—recognised as the most important GHG—has to be avoided in order to tackle the problem of climate change (IPCC 2001b). This, however, can only be achieved to a large extent through carbon capture and storage (CO_2 sequestration) and, above all, by reducing the combustion of fossil carbon.

From an economical point of view, the substitution of fossil fuels is not less important, especially in the case of oil. About 35% of the world's total primary energy supply is covered by oil alone. Among the countries within the Organisation for Economic Co-operation and Development (OECD), the share is even 41% (IEA 2004). A considerable increase of the worldwide oil demand is expected mainly due to developing countries that enter the market (IEA 2002). However, oil is expected to run out within this century. Moreover, recent studies show that the peak of oil extraction will be reached around 2007 and output will decline thereafter (ASPO 2005). As the demand exceeds the supply and oil becomes scarce, the pressure on the oil market will increase and the price will rise. This will affect oil-importing countries as well as the regional stability in the Middle East—holding almost 62% of the worldwide proved oil reserves (BP 2005). Reducing the risks of a geopolitical dependence on oil thus means finding alternatives to cover the growing energy demand.

In this regard, the transport sector plays an important role since it depends on oil to roughly 98% and the demand will grow the most rapidly of all end-use sectors, especially in the developing countries (IEA 2002). Furthermore, road transport directly contributes to the total CO_2 emissions related to fossil fuel combustion by some 20% worldwide and close to 30% in the OECD. Moreover, it stands for 18% of the total primary energy supply worldwide and 23% in the OECD (IEA 2004). Due to the high growth potential and the associated environmental as well as economic impacts, it becomes more and more important to find ways of dealing with the rising energy consumption and pollution from road transport. One way is to change transport patterns, or to improve engine and exhaust gas aftertreatment technologies. Another way is to change to fuels that give improved combustion characteristics in the engines. One of the main alternatives in this respect is natural gas (Tunestål et al. 2002).

Natural gas is often considered as the most promising alternative fuel for the short term due to its environmental and economical benefits compared to other fossil fuels. On the one hand, the carbon emission per unit combustion energy is much smaller, and natural gas has also fewer impurities and aromatics (Dicks 1996). Furthermore, natural gas reserves are more abundant than oil reserves and, in addition, distributed more evenly world-wide. Last but not least, various developed countries already have a natural gas infrastructure, transmitting natural gas via large pipeline systems, and noticeable transfer of natural gas between countries exists (BP 2005).

In the transport sector there are several options for the application of natural gas. It can be used directly as an automotive fuel, either liquefied (LNG) or compressed (CNG). It can serve as a feedstock for the production of other fuels, e.g. methanol, Fischer-Tropsch (FT) diesel or dimethyl ether (DME) and, last but not least, it can partly be substituted in time by climate neutral energy carriers like biogas. Thus, a switch from oil based to natural gas based fuel chains may be a good way to reduce both the carbon emissions from current fuel chains and to keep a high degree of flexibility regarding future developments (Hekkert et al. 2005).

Besides these environmental and economical benefits, however, it must be kept in mind that, like other fossil resources, the deposits of natural gas are also exhaustible. Moreover, Ramesohl et al. (2003) carried out an energy system analysis, which revealed that even with a shift to natural gas alone in the transport sector, the reduction of total GHG emissions would be still far from the target of a sustainability scenario.[1] They concluded that the average fleet consumption also has to decline as well as sustainable energy carriers have to be found.

As mentioned at the beginning, hydrogen is often considered as the key to this energy problem. The combustion of hydrogen results in hardly any tailpipe emissions, and when hydrogen is used in fuel cells there is actually no direct pollution at all. Furthermore, fuel cells are much more efficient than ICEs. However, hydrogen as an energy carrier has to be produced from other resources and, therefore, a main issue for a future energy system is to find a way for the sustainable and sufficient production of hydrogen.

Besides the question how to deliver hydrogen in a sustainable manner and in sufficient quantities, a key question that often remains open is how to integrate the new hydrogen option into tomorrow's changing energy and transport infrastructure. In general, the transition to new fuel chains requires large investments and long time frames for adjustments since adaptation of fuel supply, retail stations and vehicles is required. Thus, a clear and prospective strategy is needed. Such a strategy should also consider changes that are flexible regarding future innovations in the energy sector in order to prevent technological 'lock-in' phenomena. Furthermore, in the development of a transition strategy it is important to make a

[1] The sustainability target is based on the sustainability scenario by the German Environmental Agency, which calls for an 80% reduction of total GHG emissions between 2000 and 2050.

trade-off between environmental benefits, costs and implementation barriers that are to be expected (Ramesohl et al. 2003; Hekkert et al. 2005).[2]

According to Hekkert et al. (2005), implementation barriers are mainly determined in two dimensions: the technical radicality and the organisational complexity (required network change) of an innovation. The first dimension is defined as to which extent skills and expertise of organisations need to be adjusted to apply the new technology. The second dimension concerns the change in the structure of the production and implementation network around an innovation. The aspired use of compressed hydrogen in fuel cell vehicles (FCVs) requires a basic and, thus, radical change of vehicle technology, which is still complicated by the immaturity of the hydrogen technology. One of the main implementation barriers, however, is the missing infrastructure for a hydrogen distribution, which prevents a widespread adoption of any kind of innovation concerning the application of hydrogen as a vehicle fuel.

In this context, natural gas could be a promising stepping stone for the introduction of hydrogen. As mentioned above, natural gas fuel chains are supposed to have a high degree of flexibility regarding future developments. This also includes the production of hydrogen via steam reforming of natural gas, and the possibility of substituting natural gas as a feedstock in a sustainable manner by biogas. Moreover, hydrogen can be used together with natural gas as a fuel. Since both are gaseous fuels, hardly any adaptations of natural gas infrastructure and technology are needed, as long as natural gas is blended with small fractions of hydrogen only. Furthermore, several studies showed that common natural gas vehicles (NGVs) can be operated on hydrogen-blended compressed natural gas (HCNG) without affecting their reliability and with some benefits concerning engine efficiency and tailpipe emissions.

Therefore, HCNG could be a viable solution for the chicken-or-the-egg problem of which comes first—the fuel cell vehicles or the hydrogen infrastructure to fuel them—since existing natural gas networks could be used for the distribution of HCNG. According to Munshi et al. (2004), HCNG does not only take advantage of

[2] A more extensive approach regarding transition strategies is given by Sandén (2004) introducing the methodology of technology path assessment for sustainable technology development.

existing investments in natural gas infrastructure, but also allows customers to early use hydrogen with nearly commercial technology. Furthermore, it allows governments and agencies to promote the use of hydrogen to a greater number of people, and helps the hydrogen industry to develop volume and transportation solutions while reducing costs.

However, the transition to a hydrogen energy system by using HCNG as an intermediate step is only one way of many to approach technological change and the outcome remains uncertain. According to Karlström and Sandén (2004), this strategy can be seen as part of a complex innovation process that has to account for environmental and economic factors as well as for technical and societal ones, both in a short and in a long term. Moreover, it is difficult for such a new technology to enter a market that is adjusted to the use of gasoline and diesel.

Demonstration projects are one instrument to foster emerging technologies and to form one step in an innovation process. The demonstration of a new technology, like HCNG, should primarily help to maximise learning that can be fed back into the development process and support decisions on technology choice. Furthermore, it should help to bring actors from industry, politics and society together that play an important role not only for the demonstrated technology, but also for related technologies and political framework processes (Karlström and Sandén 2004).

1.1 Purpose and outline

The purpose of this study is to assess and compare the environmental aspects of using natural gas, HCNG and hydrogen as vehicle fuels. Moreover, the assessment includes a rudimentary discussion of the results with respect to the dynamics of technological change.

More precisely, this study deals with the assessment of a hydrogen demonstration project in Stenungsund, Sweden, located about 50 km north of Gothenburg. In Stenungsund there is a large petrochemical complex with a surplus production of up to some 1,000 kg pure hydrogen per hour. Furthermore, the petrochemical complex is connected to the Swedish natural gas grid.

These local conditions initiated a discussion about using hydrogen together with natural gas in order to provide HCNG at an already existing natural gas filling station to customers with common NGVs. So far, a pre-study was carried out by Engstand (2004), investigating the local and organisational conditions as well as legal and economical issues.

In the run-up to this study, it was discussed to carry out a Life Cycle Assessment (LCA) for the supply and vehicle use of HCNG in general by preferably considering all kind of hydrogen shares between 0 and 100%, including CNG and pure hydrogen. However, there is no direct proportional relationship between the hydrogen share and the operating characteristics of the vehicle. Moreover, only certain HCNG blends are applicable and, last but not least, appropriate vehicle data is hard to come by. Therefore, the LCA is limited to two different vehicle types operated on CNG, HCNG with 15 and 30% hydrogen by volume as well as on pure hydrogen. Furthermore, the assessment is focused on light-duty vehicles according to the design of the considered filling station.

LCA studies can be used to assess different technologies with regard to their present environmental impacts, but they seldom pay much attention to the dynamics of technological change. Therefore, a brief introduction of technological change is given in order to show the fundamental idea behind demonstration projects and to put the LCA study into perspective. This approach includes a rudimentary discussion of the LCA results in this context in order to give suggestions for further studies.

The first sections of the theory chapter describe the considered fuels in this study. Each of these sections close with a discussion of the fuel characteristics regarding common vehicle applications. The last section of the theory chapter provides an insight into methodological considerations about technological change and, in particular, about demonstration projects.

The method part begins with a general introduction of the applied environmental assessment tool LCA. According to the procedural layout of an LCA study, the method is successively described with a discussion of the methodological decisions that are made at each stage. The LCA results are subsequently interpreted and discussed. Finally, the conclusions are drawn from the findings of this study.

Besides several data tables, the appendix includes an extensive documentation of the collected data that is used in the LCA study.

2 Theory

The first three sections of this chapter discuss the considered fuels in this study—natural gas, hydrogen and hydrogen-blended natural gas. First of all, general information is given about sources, production methods and other relevant aspects of the fuels. Furthermore, the current state of fuel usage and projects in Sweden is highlighted. Finally, their properties as vehicle fuels are discussed regarding common utilisation, storage issues and influences on operating characteristics such as performance, efficiency and emissions.

The last section of this chapter provides a brief introduction of the dynamics of technological change, including the conceptual model of a technology life cycle. The intention of this section is to lead over to the role of demonstration projects as a standard instrument to foster emerging technologies in order to provide the base for an appropriate discussion of the LCA results in this context.

2.1 Natural gas

2.1.1 General information

Natural gas is a mixture of different gases in a varying composition. The main component of natural gas is methane, which typically accounts for 70–95 percent of the total volume. Other constituents may include non-methane hydrocarbons such as ethane, propane and butane, and in some cases traces of higher hydrocarbons as well as inert gases like nitrogen and helium. Furthermore, natural gas also consists of carbon dioxide, hydrogen sulphide and sometimes water (Akansu et al. 2004; AFDC 2005a).

Natural gas emerged in connection with oil and coal from the conversion of organic matters by microorganisms. During the formation it diffused out of the bedrock and migrated into a reservoir rock, the present deposits (Voß 2003). The distribution of the proved natural gas reserves is shown in figure 2-1.

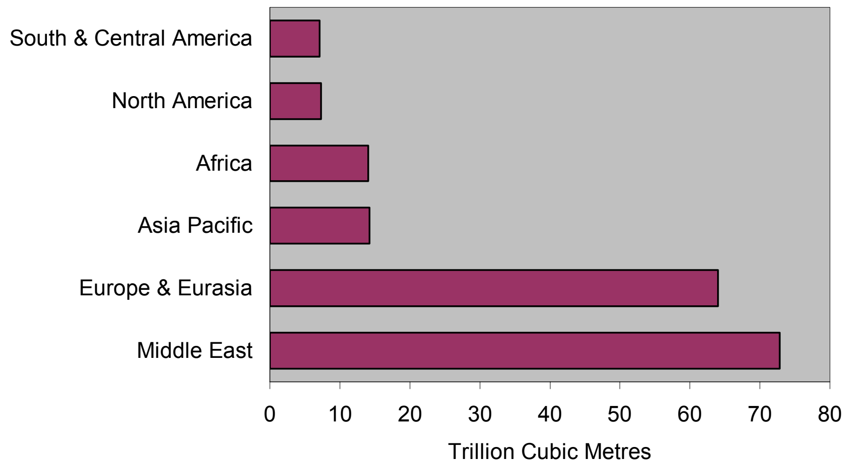

Figure 2-1: *Proved natural gas reserves at end 2004 (BP 2005)*

After the exploration of a potential natural gas deposit, production wells are drilled, which unearth oil and gas either by the pressure of the deposit or, more often, by supporting lifting systems. The extracted natural gas is rarely suitable for pipeline transportation or commercial use due to its constituents that may cause differences in physical properties, or corrode and block pipelines and valves. Therefore, all natural gas is processed in some manner to remove unwanted liquids, solids and other physical contaminants that would interfere with pipeline transportation or marketing of gas. Additional treatment is usually required to remove hydrogen sulphide and carbon dioxide. Natural gas in commercial distribution systems is composed almost entirely of methane and ethane (Pastore 1998).

Natural gas is transported either via pipelines over distances up to some 7,000 km or liquefied via special tankers, especially for intercontinental transports. It is used in a variety of ways, mainly for electricity and heat production, but also as a raw material and vehicle fuel (Voß 2003).

Natural gas can normally be replaced by biogas. Biogas is formed by the bacterial decomposition of organic matter in an anaerobic environment. Like natural gas, it mainly consists of methane (45–85%) and up to 45% carbon dioxide. It can also contain traces of water vapour, oxygen, hydrogen sulphide, nitrogen and ammonia, depending on the production conditions and processing techniques. Especially the high share of carbon dioxide necessitate the refinement of biogas in order to achieve the same quality as natural gas (Jarvis 2004; Eltrop 2005).

2.1.2 Natural gas in Sweden

Natural gas has been used in Sweden since 1985. All natural gas that is used today is still imported from Denmark. It is extracted from Danish oil and gas fields in the North Sea, and transported to the gas-processing site in Nybro, Denmark. The composition of the processed natural gas with a density ρ of 0.84 kg/Nm^3 and a net calorific value H_u of 47.62 MJ/kg is shown in table 2-1. The data represents the product specifications provided by Nova Naturgas (2005).

Table 2-1: Composition of processed natural gas (Nova Naturgas 2005)

	Mole-%
Component	
Methane	88.32
Ethane	6.40
Propane	2.64
Butane	0.97
Pentane	0.21
Heavier alkanes	0.05
Carbon dioxide	1.10
Nitrogen	0.31

Since 1985, the Swedish high-pressure transmission network has been gradually developed. At present, the basic grid is more than 300 km long and covers the west coast of Southern Sweden as shown in figure 2-2 (see also appendix B.1).

***Figure 2-2:** Swedish transmission network (Nova Naturgas 2005)*

Natural gas currently accounts for less than 2% of Sweden's total energy consumption. However, in the municipalities that have access to natural gas, it is up on the European level of 20% of the total energy consumption. In Sweden, around 40% of the natural gas is used in industrial plants, where it serves both as raw material and as fuel for heating. The same proportion is used for combined heat and power (CHP) generation and for the district heating sector. The remaining 20% are mostly used by households and, to a minor degree, in vehicles (Nova Naturgas 2005).

Biogas is mainly used as an energy source for the production of heat and electricity. After processing, it can be fed to the natural gas grid and purchased by the final consumer. This 'green gas' principle is already established in several Swedish cities (amongst others in Gothenburg, Helsingborg and Laholm) and will be further extended (Jarvis 2004).[3]

Today, there are about 51 filling stations across Sweden providing vehicle gas (natural gas and biogas), and another 18 are planned to be finished until 2007 (BRG 2005).

2.1.3 Vehicle application

Natural gas is normally used like gasoline in spark-ignition (SI) engines. The conversion of gasoline engines, thus, is very simple and straightforward. But also diesel engines can be easily converted to gas operation. Unlike diesel, however, natural gas hardly ignites in a compression-ignition (CI) engine due to its higher self-ignition temperature (see appendix A). Using natural gas in a retrofitted diesel engine therefore requires a separate source of ignition. This can be realised e.g. by using a glow plug or diesel fuel pilot injection. Another possibility is the conversion of the CI engine into an SI engine (Duan 1996; Verstegen 1996).

Today, all light-duty NGVs that are offered by original equipment manufacturers (OEMs) are based on gasoline engines. Most of them are bi-fuel NGVs with two separate fuelling systems that enable the vehicle to use either natural gas or gasoline. On the other hand, dedicated NGVs are designed to run on natural gas only and, consequently, tend to demonstrate better performance and lower emissions. In addition, the vehicle does not have to carry two types

[3] The term 'green gas' refers to the fact that biogas is considered as an CO_2 neutral energy carrier, since its combustion only releases as much CO_2 as ingested by the biomass used to produce biogas.

of fuel, which results in an increased loading space and reduced weight (Lottsiepen and Thamm 2004; AFDC 2005b).

For medium or heavy-duty operations, diesel engines are normally chosen and converted to natural gas engines in order to keep the compatibility with the engine mountings and transmission of the vehicle. But also the high compression ratio of diesel engines can be advantageous when using natural gas in a retrofitted diesel engine as described in the following (Nylund and Lawson 2000).

A drawback of NGVs is generally linked to the fuel storage. Natural gas has a higher net calorific value H_u than gasoline and diesel, but the volumetric energy density is much lower due to the low density ρ of natural gas (see appendix A). Therefore, natural gas is usually stored pressurised at 200 bar and ambient temperature on board an NGV. One litre of compressed natural gas (CNG) tank volume holds the equivalent of roughly 0.2 litre gasoline. In other words, the range of NGVs is normally restricted due to the higher storage volume and weight that is needed to store the same amount of energy compared to gasoline and diesel (Bradley et al. 1996; Nylund and Lawson 2000).

In the following, the performance and emission characteristics of NGVs are focused on light-duty vehicles, which implies the combustion of stoichiometric air/fuel mixtures in gasoline-based engines, i.e. mixtures with the chemically correct proportion of air and fuel.[4]

Performance and efficiency

Without further adjustments of engine parameters, a power loss up to some 20% can be expected when switching from gasoline to natural gas (Bradley et al. 1996; Duan 1996). Considering a constant engine speed n and piston displacement V_H, the power P_i that is developed in an internal combustion engine (ICE) is determined by the indicated mean effective pressure p_{mi} (IMEP).

$$P_i = k \cdot n \cdot p_{mi} \cdot V_H \qquad (2.1)$$

with $k = 0.5$ (four-stroke cycle engine)

[4] In contrast, *lean* air/fuel mixtures imply the combustion of fuel with excess air, whereas *rich* air/fuel mixtures are characterised by excess fuel.

IMEP again is determined by the energy of the air/fuel mixture H_G that is captured in the cylinder after the inlet valve closes, and by the efficiency of the cycle η_i.

$$p_{mi} = \eta_i \cdot \lambda_a \cdot H_G \tag{2.2}$$

with λ_a = air efficiency, i.e. ratio of the effective charge and the theoretically possible charge of the cylinder; controlling variable for power regulation in gasoline engines (quantity regulation)

The energy of the air/fuel mixture H_G is somewhat lower for natural gas than for gasoline considering stoichiometric mixtures ($\lambda = 1$) due to a lower density of the mixture ρ_G and a higher stoichiometric air/fuel ratio L_{st} (see appendix A).

$$H_G = \frac{H_u \cdot \rho_G}{L_{st} \cdot \lambda + 1} \tag{2.3}$$

with λ = relative air/fuel ratio, i.e. ratio of the effective air/fuel ratio and the stoichiometric air/fuel ratio L_{st}

The cycle efficiency η_i is influenced by the lower flame speed when switching from gasoline to natural gas (see appendix A), which increases the combustion duration and consequently results in a reduction of the cycle efficiency η_i. In other words, the lower burn rate leads to a combustion that is spread over a greater crank angle interval (Bradley et al. 1996).

An improvement on engine performance can be achieved by some simple modifications. Advanced ignition timing according to the lower burn rate leads to a complete combustion within the correct portion of the engine cycle, i.e. the pressure peak of the combustion is optimally reached around 8 degrees crank angle after the top dead centre (TDC) of the piston. This measure increases the efficiency and, hence, the power output of a natural gas engine. Furthermore, natural gas has a higher knock resistance than gasoline, expressed by a higher research octane number (RON; see appendix A), which allows combustion at higher compression ratios, and also improves both engine efficiency and power output (Duan 1996).[5]

In general, the performance of a natural gas engine is highly dependent on the combustion system and drive concept. Normally, a dedicated natural gas engine has an efficiency that is slightly higher than a comparable gasoline engine, whereas the power and torque output is slightly lower. As indicated above, however, most NGVs can not optimally use the advantage of higher compression ratios in order to increase the engine performance, since they are equipped with bi-fuel engines and, hence, limited by the lower knock resistance of gasoline. As a result, the power output of bi-fuel engines generally decreases by some 10% when switching to natural gas (Nylund and Lawson 2000; Hekkert et al. 2005).

Emissions

According to Duan (1996), the emissions of carbon monoxide (CO), unburned hydrocarbons (HC) and oxides of nitrogen (NO_x) from a natural gas engine against the air/fuel ratio follow the similar pattern of gasoline engines as shown in figure 2-3.

The group of unburned hydrocarbons consists of methane (CH_4) and non-methane hydrocarbons (NMHCs). Unlike the unburned hydrocarbons from gasoline, the unburned hydrocarbons from natural gas mainly consist of methane (approximately 85%). Methane has a very stable molecular structure and is, therefore, more difficult to convert in a conventional gasoline catalyst. As a result, methane emissions from gasoline vehicles converted to natural gas can be relatively high (Duan 1996; Verstegen 1996).

CO and HC emissions are the result of an incomplete combustion of the fuel caused, for example, by ‘dead spots’ in the combustion chamber, improper air/fuel mixtures or cold wall quenching, i.e. part of the air/fuel mixture stops burning close to the wall of the combustion chamber. CO production is strongly a function of the air/fuel ratio, so much so that all other factors like temperature, available oxygen and others affecting CO production are negligible in comparison. HC production, instead, is mainly influenced by oxidation mechanisms. These mechanisms are strong functions of

[5] The knock phenomena in spark ignition engines results from the self-ignition of part of the unburned gas ahead of the propagating flame front. The engine can be damaged due to high cylinder pressure rise and pressure waves if knock occurs.

temperature, i.e. higher temperatures support higher oxidation rates and consequently lead to reduced HC emissions (Verstegen 1996; Tennant 2003).

Due to the lower carbon content of natural gas, the CO emissions from a natural gas engine are generally lower than those from a comparable engine running on gasoline. Theoretically, the same conclusion could be drawn for HC emissions, particularly with regard to the good carburation of gaseous fuels. On the other hand, the slow reaction and low burning velocity of natural gas might also lead to a combustion that could not be completed before the exhaust valve opens and, thus, contribute to higher emissions. Therefore, HC emissions are very dependent on the base engine and running conditions (Duan 1996).

The formation of NO_x during the combustion process primarily depends on the following three combustion parameters: (i) the reaction temperature, (ii) the reaction duration and (iii) the availability of oxygen. An increase of any of these parameters leads to an increase in NO_x emissions. Hence, there is a trade-off between the HC and NO_x emissions, i.e. measures or running conditions that would decrease the HC emissions by increasing the combustion temperature contrariwise increase the NO_x emissions and vice versa. This trade-off is also depicted in figure 2-3 since air/fuel ratios above the stoichiometric one ($\lambda > 1$)—in other words lean air/fuel mixtures—lead to lower combustion temperatures with the afore said effects (Norbeck et al. 1996; Tennant 2003).

NO_x can be higher from an engine running on natural gas than the same one running on gasoline because of the higher in-cylinder temperature and longer duration of the combustion. The former can be explained by the higher isentropic coefficient κ of natural gas, which gives a higher final compression temperature T_e according to equation 2.4 for an ideal adiabatic compression. The latter can be amplified by advanced ignition timing in order to increase the engine performance. Again, the emissions are very dependent on the combustion system and drive concept (Duan 1996).

$$T_e = T_i \cdot \left(\frac{V_i}{V_e}\right)^{\kappa-1} \tag{2.4}$$

with indices i(nitial) and e(nd) as well as in-cylinder temperature T and cylinder volume V

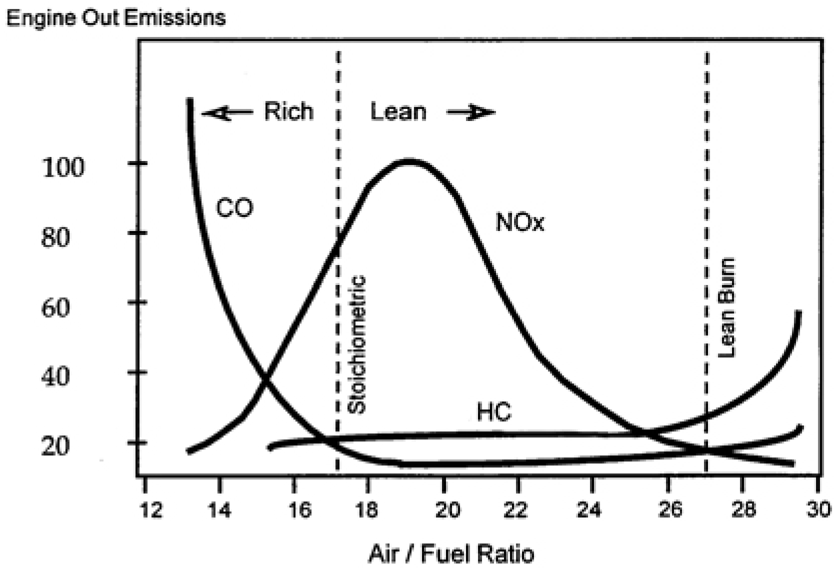

Figure 2-3: *Influence of air/fuel ratio on emissions from an SI natural gas engine (Nylund and Lawson 2000)*

Fuel and vehicle studies

Fleet studies with gasoline, bi-fuel and dedicated NGVs support the above conclusions by showing a power loss up to 15% and a reduced fuel storage by energy of some 50–60% between CNG and gasoline operation, whereas the fuel consumption decreased by some 10% (Whalen et al. 1999; Eudy 2000).

According to a literature review by Ristovski et al. (2004), dedicated NGVs generally show lower emissions of HC and NO_x than their gasoline counterparts, whereas bi-fuel NGVs tend to have higher emissions. In both cases, CO and CO_2 emissions are generally lower. These emission trends were also reflected in the aforementioned fleet studies (Whalen et al. 1999; Eudy 2000).

ADAC (2005) tested and compared the gasoline, diesel and bi-fuel natural gas model of a Volvo V70 passenger car. Again, the results show slightly higher HC and NO_x emissions from the bi-fuel NGV compared to the gasoline vehicle. In contrast, the HC and NO_x emissions from the bi-fuel model were considerably lower than the emissions from the diesel vehicle. The CO and CO_2 emissions were altogether lower in case of the bi-fuel NGV.

Summary

Range, performance and efficiency as well as emissions from an NGV mainly depend on the combustion system (e.g. engine design, compression ratio, supercharging) and drive concept (dedicated or bi-fuel). Compared to gasoline vehicles, the range of NGVs is normally restricted and the power output somewhat lower, whereas the efficiency tends to be slightly higher. HC and NO_x emissions from dedicated NGVs are generally lower, whereas bi-fuel NGVs tend to have higher emissions. Compared to diesel vehicles, both dedicated and bi-fuel NGVs normally show lower HC and NO_x emissions. In general, emissions of CO and CO_2 are lower for NGVs.

2.2 Hydrogen

2.2.1 General information

Hydrogen is the simplest and most abundant element in the universe. However, free hydrogen does not exist naturally on Earth in its gaseous form but is captured in more complex molecules. Therefore, hydrogen cannot be termed as an energy source (like petroleum). It is an energy carrier (like electricity), which has to be derived from other materials (Farrell et al. 2003; Johnston et al. 2005).

There are mainly two sources available for the production of hydrogen—fossil fuels and water—including a wide range of production methods that can be applied. The gasification of coal is the oldest method of obtaining hydrogen from fossil fuels. The most efficient and widely used process, however, is steam reforming of natural gas. At present, it is also the cheapest way of producing hydrogen. Another method is the partial oxidation of fossil fuels, which can be combined with steam reforming in a process called 'autothermal reforming'. Hydrogen can also be produced by the direct thermocatalytic decomposition (cracking) of methane or other hydrocarbons (Farrell et al. 2003; Rand and Dell 2005).

Electrolysis is the most common way to produce hydrogen from water but it is also a relatively energy-intensive way. Although electrolysis is a mature technology, only a few percent of world hydrogen is obtained by this method, and mostly as a by-product of the chlor-alkali process for the manufacture of chlorine and sodium hydroxide. Other methods to split up water into hydrogen are still far from practical realisation, including the decomposition of water in thermochemical cycles or directly via the harnessing of solar radiation (Rand and Dell 2005).

The worldwide production of hydrogen amounts to around 50 million tonnes per annum. Over 90% comes from fossil resources. Hydrogen is mainly used for the production of nitrogen fertilizers and for refining petroleum products. Lesser applications are found e.g. in chemical, food and plastics industries (Rand and Dell 2005).

2.2.2 Hydrogen projects in Sweden

In September 2003, Sweden's first hydrogen filling station was officially unveiled in Malmö, providing both pure hydrogen and fuel blends of natural gas and hydrogen. The on-site production of hydrogen is based on the electrolysis of water with electricity from wind power. The filling station is operated within the scope of the Malmö hydrogen bus project, which demonstrates fuel blends of natural gas and hydrogen in two standard natural gas buses (Stuart Energy 2004a; Ivarsson 2005).

Two months later, in November 2003, Sweden's second hydrogen filling station was inaugurated in Stockholm. It also comprises an electrolysis module for the production of hydrogen that is connected to the public power grid. The filling station is part of the Clean Urban Transport for Europe (CUTE) program, whereby nine European cities operate three fuel cell buses each in regular service (Stuart Energy 2004b).

Besides these two ongoing hydrogen projects, HyFuture—a regional collaboration between industries, universities and local governments in Western Sweden—works on establishing further hydrogen demonstration projects in order to introduce hydrogen infrastructure and applications. At the moment, pre-studies are being carried out for different demonstration projects like e.g. the replacement of diesel-driven auxiliary engines by fuel cell systems onboard ships in Gothenburg's harbour, or the implementation of a combined solar and fuel cell system as part of the energy supply of the Cultural Centre Vingen (Jönsson 2005).

Another pre-study is dealing with the extension of the Norwegian hydrogen infrastructure from Oslo along the west coast of Sweden over Gothenburg to Malmö.[6] In Norway, the project is called 'HyNor—The Hydrogen Road of Norway' and was established in 2003. The objective is a large-scale market demonstration of hydrogen in the transportation sector. Therefore, a hydrogen refuelling infrastructure will be implemented and operated during 2005 to 2008 along a route of 580 km from Oslo to Stavanger (HyNor 2005; Jönsson 2005).

[6] The project is called 'Hydrogen Highway along the Swedish West Coast'.

2.2.3 Vehicle application

In general, there are two possible ways of using hydrogen in a vehicle: either in fuel cells for the generation of electricity that powers an electric motor or in ICEs. At the moment, a widespread introduction of fuel cell vehicles is still far from realisation, last but not least due their prohibitive costs (up to 60 times higher per kW of produced power compared to ICEs), and numerous technical difficulties that still have to be resolved (Rand and Dell 2005). According to the purpose of this study, the following explanations are focused on hydrogen ICEs, which have the advantage of accessing the considerable operating experiences of natural gas engines.

ICEs that use hydrogen vary only slightly from commercial natural gas engines and, thus, present no considerable technological challenges. The self-ignition temperature of hydrogen is somewhat higher than that of natural gas (see appendix A) and, hence, ignition by compression alone is difficult and even failed in different tests with retrofitted diesel engines. Like natural gas, an externally supplied ignition is therefore needed (Das 2002; Farrell et al. 2003).

More than in case of natural gas, it is in storage that hydrogen suffers. Like natural gas, it can be transported and stored either in its gaseous state or liquefied. The major problems connected to gaseous hydrogen, however, are its small molecular size, which makes it easily diffusible, and a density much lower than that of natural gas, which consequently leads to a lower volumetric energy density (see appendix A). As a result, compressed hydrogen at 350 bar and ambient temperature has merely around 9% of the energy of gasoline, comparing the same volume. With regard to storage weight and volume, liquid hydrogen would be more attractive since its density is about 850 times greater than that of the gaseous form. However, the energy required to liquefy hydrogen is equal to approximately one-third of its energy content, while compression (to about 350 bar) takes only one-tenth. Furthermore, the distribution is both complex and costly, and the boil-off rate is such that the liquid can only be stored for a few days at most. New storage technologies (e.g. carbon nanotubes) may improve the performance of storage systems, but progress has been slow (Das 2002; Farrell et al. 2003; Karim 2003; Rand and Dell 2005).

Performance and efficiency

The use of hydrogen in fuel cell vehicles entails the electrification of the vehicle's power train, producing power at efficiencies much higher than ICEs—an important attraction to automakers also due to the high torque output of electric motors (Sperling and Cannon 2004; Johnston et al. 2005).[7] On the other hand, some experts assume that only a limited range of performance up to some 50 kW can be reasonably covered by the interconnection of fuel cell and electric motor, whereas ICEs are considered to be more suitable for higher power outputs (Das et al. 2000; Bargende and Greiner 2003).

Comparing the performance of ICEs, a further loss of power can be expected when switching from natural gas to hydrogen due to its lower volumetric heating value. The energy of the air/fuel mixture H_G, again, is somewhat lower for hydrogen than for natural gas considering stoichiometric mixtures ($\lambda = 1$) due to a lower density of the mixture ρ_G and a higher stoichiometric air/fuel ratio L_{st}. Unlike natural gas and gasoline, however, hydrogen possesses a flame speed that is nearly an order of magnitude higher (see appendix A). Hence, the combustion duration is much shorter, which allows retarded ignition timing and consequently leads to higher cycle efficiency η_i (Norbeck et al. 1996; Das 2002; Bargende and Greiner 2003; Karim 2003).

The latter also leads to a more stable combustion of lean mixtures—a favourable operating condition, particularly with regard to the flammability of hydrogen.[8] Hydrogen possesses wide flammability limits compared to gasoline and natural gas, i.e. a wide range of air/fuel ratios over which the engine can operate (see appendix A). This makes it possible to use even ultra-lean mixtures for engine operation, which leads to high engine efficiencies. These wide limits of flammability also enable the engine to adopt quality regulation like in diesel engines, i.e. the air/fuel ratio or 'quality' of the charge can easily be varied to meet different driving conditions or loads, and the intake air keeps unthrottled. Hence, there are no

[7] There is also the vision of the stationary use of FCVs as part of a distributed energy system, i.e. when electricity is not needed to run an FCV—most cars sit idle more than 90 percent of each day—its fuel cells could still be used to generate electricity for use in homes and businesses elsewhere (Sperling and Cannon 2004).

[8] A high combustion stability is characterised by low cycle-to-cycle variations of the combustion pressure, which results in a smooth engine operation.

throttling losses under part-load driving conditions (Norbeck et al. 1996; Das 2002; Berckmüller et al. 2003; Karim 2003).

Another fuel characteristic of hydrogen that gains in importance for lean operation is the minimum ignition energy, which is about an order of magnitude lower than that of natural gas and gasoline (see appendix A). This ensures prompt ignition of lean mixtures and, thus, good operating conditions. A drawback, however, is the higher risk of pre-ignition and backfire. Since almost any hydrogen/air mixture can be ignited due to the wide limits of flammability and only little energy is necessary to start up a combustion reaction, hot spots and even hot residuals in the cylinder can serve as sources of ignition, which particularly makes it difficult to operate a hydrogen engine under stoichiometric conditions (Norbeck et al. 1996; Berckmüller et al. 2003; Karim 2003).[9]

It must be noted, however, that besides a gain of efficiency, operation on lean air/fuel mixtures simultaneously leads to a lower power output of the engine due to the lower heating value H_G of lean air/fuel mixtures. According to Karim (2003), a lean-burn hydrogen engine needs to be some 40–60% larger in size than for stoichiometric gasoline operation, considering the same power output. Among other measures, the fast burning characteristics of hydrogen could be used for high-speed engine operation, which would allow an increase in power output (see equation 2.1) and, hence, reduce the penalty for lean mixture operation.

In contrast, Berckmüller et al. (2003) showed that with some engine modifications (supercharging, exhaust gas recirculation) in connection with an appropriate operation strategy, a hydrogen powered ICE allows power density (power per engine size) and power output on the same level as for gasoline engines and, at the same time, provides fuel efficiencies above diesel engines under part-load conditions. The key is the capability to burn stoichiometric mixtures (for power density and NO_x reduction in a catalyst at high load) and unthrottled operation on lean mixtures over nearly the complete operating range (for fuel efficiency).

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[9] *Backfire* into the inlet manifold occurs during the inlet valve open period, when fresh charge ignites early by mixing with hot residuals. *Pre-ignition* occurs during compression, resulting in steep pressure rise and high peak pressure.

Emissions

When hydrogen is burned in an ICE, the primary combustion product is water. In the absence of carbon and contaminants like sulphur and lead, the hydrogen-related exhaust emissions are free from oxides of carbon, unburned hydrocarbons and almost all other limited and unlimited pollutants. Only oxides of nitrogen are emitted that can directly be referred to the combustion of hydrogen. Measurable CO and HC emissions originate from lubricating oil and are far below the corresponding emissions from hydrocarbon-fuelled engines. Therefore, they can be reduced to almost zero with conventional catalysts (Berckmüller et al. 2003; Karim 2003)

As indicated above, NO_x levels of hydrocarbon-fuelled engines are higher around stoichiometric operating conditions due to the combined effects of higher combustion temperatures and available oxygen (see figure 2-3). The same trend is reflected in hydrogen engines. Especially the high burning rates of hydrogen may lead to higher pressures and temperatures that are reached during combustion. However, it is possible to limit this pollutant to very low levels by using lean mixtures (Norbeck et al. 1996; Das 2002).

Fuel and vehicle studies

In this study, operating data of a hydrogen vehicle is used that was tested on pure hydrogen (see appendix B.5). Among other things, the hydrogen ICE is equipped with a turbocharger and operated on very lean air/fuel mixtures with a relative air/fuel ratio λ above 3, i.e. hydrogen is burnt with three times more air than necessary for a stoichiometric combustion. With regard to the acceleration, the performance of the hydrogen vehicle is lower compared to its gasoline and CNG counterparts. On the other hand, the hydrogen vehicle shows an efficiency that is more than 10% higher. NO_x emissions could not be measured, but are supposed to be some 80% lower than for CNG operation (AVTA 2005; Mulligan 2005).

Summary

Hydrogen ICEs vary only slightly from commercial natural gas engines and, thus, present no considerable technological challenges. Variations between these two engine concepts mainly result from the fuel characteristics of hydrogen, which are significantly different from those of natural gas. First of all, hydrogen allows the adoption of quality control for high efficiencies under part-load driving conditions. Furthermore, hydrogen is particularly suitable for lean-burn engine operation, which also provides high efficiencies and, moreover, allows the regulation of NO_x—the only hydrogen-related emissions—to very low levels. Performance can be enhanced e.g. by applying higher engine speeds or stoichiometric engine operation. A major drawback that remains open is a further limitation of the vehicle range compared to NGVs.

2.3 Hydrogen-blended natural gas

2.3.1 General information

Hydrogen-blended compressed natural gas (HCNG) as a fuel for stationary and mobile applications has already been the subject of several research projects. These mixtures of natural gas and hydrogen are commonly known as Hythane®, which is a registered trademark of Brehon Energy PLC (Sierens and Rosseel 2000).

According to Teztlaff (2001) and Biogas Väst (2005), small fractions of hydrogen in natural gas (5–10% by volume) can be transported in natural gas pipelines without affecting their function. But also compression, storage and fuelling of HCNG is possible to some extent without adjustments of the equipment (Karlsson 2001).

2.3.2 HCNG projects in Sweden

In 2003, the inauguration of Sweden's first hydrogen filling station in Malmö also marked the kick-off for the first vehicle demonstration of HCNG in Europe. After the successful testing of two standard natural gas buses on a blend of natural gas and 8% hydrogen by volume, the operator recently increased the share of hydrogen in the fuel blend to 25%. The project will be finished in 2006 (Ny Teknik 2005).

2.3.3 Vehicle application

Due to the normally small proportions of hydrogen in the fuel mixture (up to some 5% hydrogen by mass and 30% by volume, respectively) the physical properties of the mixture are close to those of natural gas and do not have any significant impact on components designed for natural gas. Therefore, an NGV fuel system is generally compatible with HCNG, and only small modifications of a natural gas engine are needed to run on HCNG (Munshi et al. 2004).

Furthermore, a study carried out by Beckmann et al. (2005) revealed that a stable operation of a small uncharged four-stroke SI natural gas engine on blends of natural gas and up to 55% hydrogen by volume is possible without design-engineering modifications of the carburation and ignition system as well as of the combustion chamber.

Since hydrogen has a very low volumetric energy density, the volumetric energy density of an HCNG mixture decreases with an increasing proportion of hydrogen (Munshi et al. 2004). Hence, less fuel energy can be stored on board an NGV per unit storage volume, which consequently contributes to the storage problem as discussed in section 2.1.3 and 2.2.3.

From a technical point of view, HCNG is particularly interesting for the use in lean-burn natural gas engines, since the supplement of hydrogen to natural gas with its unique burning characteristics improves the lean-burn capability of the fuel. Therefore, many research projects are focused on this issue with regard to the heavy-duty vehicle sector (Sierens and Rosseel 2000). As indicated in section 2.2.3, lean-burn operation provides a measure for increasing the engine efficiency while regulating the NO_x emissions to very low levels. Under part-load conditions, however, the combustion stability of lean-burn natural gas engines becomes poor, which is often met by increasing the charge. As a result, the efficiency decreases while NO_x emissions increase. Adding hydrogen to natural gas can avoid this measure by improving the part-load properties of the fuel (Andersson 2002; Tunestål et al. 2002).

The studied demonstration project, however, aims at fuelling standard light-duty NGVs with HCNG, which are typically equipped with retrofitted gasoline engines. In other words, they are operated on stoichiometric air/fuel mixtures and with a three-way catalytic converter for exhaust gas aftertreatment. Therefore, the following explanations are focused on stoichiometric operating conditions.

Performance and efficiency

Without performing engine modifications, blending hydrogen with natural gas reduces the power output of the engine as a result of the lower volumetric energy density of hydrogen in relation to natural gas (Karner and Francfort 2003b).

Due to the significantly higher flame speed of hydrogen compared to natural gas and other hydrocarbon fuels (see appendix A), however, adding hydrogen to natural gas consequently increases the flame speed of the charge, which leads to an increased burn rate as well as an improved combustion stability. On the one hand, the increased burn rate and, hence, the reduced combustion duration allows retarded ignition timing, which decreases heat losses and results in a higher cycle efficiency η_i. Furthermore, the gain of stability can be used to extend the lean limit of a natural gas engine (Tunestål et al. 2004).

Emissions

Hydrogen addition in natural gas engines was found to decrease carbon-based emissions like CO_2, CO and HC, mainly due to the direct carbon replacement. Furthermore, the higher flame speed and burn rate of hydrogen, respectively, leads to a higher combustion pressure, temperature and, hence, higher oxidation rates, which also contribute to a reduction of HC emissions (Bauer and Forest 2001; Akansu et al. 2004).

On the other hand, the higher combustion temperature also results in increased NO_x emissions according to the trade-off discussed in section 2.1.3. However, Akansu et al. (2004) showed that noticeable reductions in NO_x can be obtained by leaner operation—as mentioned above—and by retarded ignition timing.

Fuel and vehicle studies

Akansu et al. (2004) carried out a survey of research papers on the utilisation of different HCNG blends in ICEs, and evaluated the results from an environmental, technical and economical point of view. The addition of hydrogen to natural gas reduces HC, CO and CO_2 emissions while having a tendency to increase NO_x emissions. Furthermore, the efficiency can be increased and the fuel consumption decreases with increasing hydrogen. The survey shows that 20–30% hydrogen enrichment of natural gas by volume gives the most favourable engine operation. Higher hydrogen contents undermine the knock resistance characteristics of natural gas, lower power output of the engine and increase the fuel cost. Lower hydrogen contents do not make enough use of the performance enhancement potential of hydrogen.

Munshi et al. (2004) carried out a literature review as well and analysed HCNG fuel properties with regard to the utilisation in a heavy-duty turbocharged lean-burn SI engines. The results of the study also indicate that 20–30% hydrogen by volume in an HCNG mixture provides the desired benefits in terms of emission reduction without unduly affecting engine performance and efficiency, whereas hydrogen contents beyond 30% by volume are associated with a penalty in terms of engine performance, hardware limitations as well as fuel storage and cost.

In this study, operating data of a dedicated NGV is used that was tested on CNG and HCNG with 15% hydrogen by volume and without any modifications of the engine (see appendix B.5). The testing of the HCNG fuel blend revealed lower HC, CO and CO_2 emissions, whereas NO_x emissions considerably increased by 91% compared to CNG operation. However, the NO_x emissions were still below the emissions of the gasoline counterpart. The efficiency was somewhat higher for the operation on HCNG (Karner and Francfort 2003a).

In contrast, operating data of a dedicated NGV is also consulted in this study that was operated on CNG and HCNG with 15 and 30% hydrogen by volume. This time, however, the vehicle was modified to run on the 30% HCNG fuel blend (see appendix B.5). The modifications include supercharging for higher power output as well as exhaust gas recirculation (EGR) for lower combustion temperatures in order to decrease NO_x emissions. As a result, NO_x emissions only slightly increased by maximum 15% when switching from CNG to HCNG while marginally increased HC emissions had to be accepted. CO and CO_2 emissions, again, decreased substantially, and the efficiency was slightly higher for the operation on HCNG, whereas the performance somewhat decreased (Karner and Francfort 2003b).

Summary

NGVs can normally be operated on common HCNG blends without any 'direct' modifications of the natural gas engine.[10] In general, HCNG fuel blends with a hydrogen proportion of 20–30% by volume are considered to give the most favourable engine operation in terms of emission reduction, performance maintenance and fuel costs. HC, CO and CO_2 emissions generally decrease with an increasing proportion of hydrogen in the fuel, while NO_x emissions tend to increase substantially without further modifications. Furthermore, efficiency increase, whereas the performance is somewhat lower for an NGV operated on HCNG.

[10] 'Indirect' engine modifications according to the fuel properties are handled to some extent by the engine management system, including air/fuel ratio or ignition timing.

2.4 Technological change

Technology provides humans with the capability of transforming their natural environment locally, regionally and, more recently, globally. Therefore, technology plays a significant role as both a source and a remedy of global environmental change like global warming. It relates to all major drivers of global environmental change such as population growth, economic development and resource use. Moreover, technology is also central in monitoring environmental impacts and implementing response strategies (Grübler 1998).

Technology consists of both hardware and software. While hardware stands for technology in terms of artefacts, software represents the disembodied nature of technology like knowledge and skills required to produce and use technological hardware. In this regard, knowledge is often distinguished between public knowledge that can be acquired by anyone, proprietary knowledge that is protected by patents and access is limited through licensing agreements as well as tacit knowledge that is unrecorded and passed on at first hand (Grübler 1998).

Institutions, including legislation, companies and capital markets as well as social norms and attitudes, are important determinants for the emergence and functionality of systems for producing and using technological hardware. They determine the development of particular combinations of hardware, their final success or rejection and, if successful, the pace of their integration in economy and society. Therefore, technology cannot be separated from the socio-economic context out of which it evolves and which is responsible for its production and its use. In turn, the socio-economic environment is shaped by technologies that are produced and used. Therefore, it turns out to be a difficult task to incorporate the numerous interrelationships among technology, economy, society, and environment (depicted in figure 2-4) in theory, models, and policy (Grübler 1998).

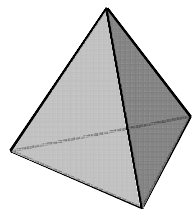

Figure 2-4: *Technological interrelationships*

The essential feature of technology is change. In the beginning, a new technology is immature, costly and limited in its applications. Niche market applications are the first touchstone for an emerging technology, where it has to prove its performance rather than its profitability. If it prevails, subsequent improvements and cost reductions can lead to wider applications (Grübler 1998).

Technologies change all the time individually and in their aggregate, typically by substituting older technologies. However, technological change is neither simple nor linear. In the beginning, uncertainty governs technological change. Moreover, it is dynamic (continuous introduction of new varieties, subsequent improvements and modifications) and cumulative (build-up on previous experience and knowledge). Last but not least, technological evolution is systemic. It is almost impossible to manage change through attention to just a few key technologies since technologies, in general, increasingly depend on one another for both production and use and, in particular, increasingly depend on infrastructures of transport, energy and communication (Grübler 1998).

All the above mentioned interdependences of technology cause enormous difficulties in implementing large-scale and radical changes. With regard to a radical change of energy and transport technology, considerable time will be needed since many stakeholders are involved and habits, institutions as well as technological networks are adapted to the use of fossil fuels. But these interdependences are also what causes technological changes to have such pervasive and extensive impacts once they are implemented—last but not least since they also set the prerequisites for new technologies. Thus, the challenge associated with the transition toward a sustainable energy and transport system is not only to start up diffusion of new technology immediately, but also to guide technology development with a long-term perspective in order to prevent the implementation of dead-end technology (Grübler 1998; Sandén 2004).

2.4.1 Technology life cycle

Technology obtain significance only through its application (innovation) and subsequent widespread adoption (diffusion). Understanding diffusion is crucial since it is the basis for technologies to exert any noticeable impact on economic growth, socio-economic transformations and on the environment. As indicated above, however, technological growth cannot be analysed by focusing on technology itself. The essence of technological diffusion is the interaction of technology with its environment, including other technologies (Grübler 1998).

Research into technological change has shown that the diffusion of technologies tends to follow an S-shaped curve as shown in figure 2-5. The thereof derived conceptual model of a technology life cycle can be divided into three phases: formation (introduction), growth (diffusion) and saturation (maturity).

The formative period is mainly governed by uncertainty since there are always various competing technologies that allow to perform a particular task. Due to the high costs of emerging technologies, their often inferior performance compared to that of existing technologies as well as possible infrastructure incompatibilities, market diffusion is slow (Grübler 1998; Sandén 2004). Moreover, principal supporters of new technologies are often unorganised and have little influence, which in turn slows down the diffusion process (Jacobsson and Johnson 2000). During this period, emphasis is placed on the demonstration of technical viability rather than on cost reduction with learning effects and technology improvements from experimentation and development (Grübler 1998).

In the growth phase, technical viability is established and further efforts lead to positive returns. Growth is stimulated by a number of positive feedback mechanisms such as economies of scale (in production and consumption), economies of scope (co-evolution of complementary technologies), learning by doing and learning by using (Grübler 1998). Unlike the large variety of technical options in the formative period, these mechanisms tend to reduce variety and create a dominant design, which further decrease uncertainty and increase the possibility to reduce costs through learning and scale economies (Sandén 2004).

Saturation sets in as diffusion slows down due to saturated markets and diminishing returns of further improvements. In this phase, competition is based almost entirely on cost reduction and externalities like environmental issues may become visible that also constrain a further diffusion (Grübler 1998; Sandén 2004).

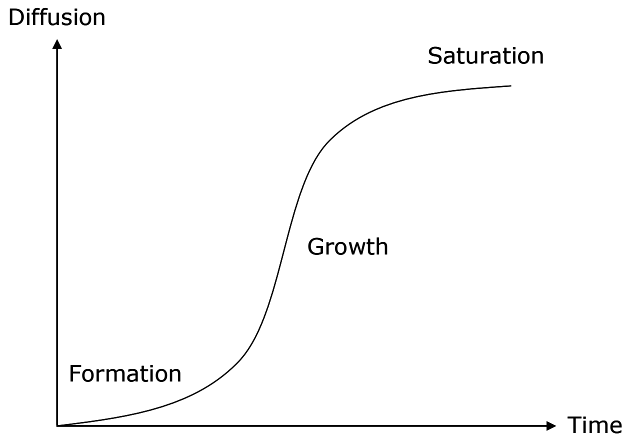

Figure 2-5: *Conceptual model of a technology life cycle (Grübler 1998)*

Besides economic issues, three important aspects determine the pace of technological diffusion: (i) compatibility, i.e. requirements for additional infrastructures or the existence of standards facilitating interchanges (network externalities), (ii) complexity with regard to learning and knowledge requirements for producing and using new technology and (iii) testability, i.e. the possibility to try out new technology, to easily obtain innovations and to gain experience and information from users (Grübler 1998).

However, as indicated in the beginning, it is difficult for radically new technologies to obtain significance in a market that is adapted to mature and prevailing technologies.

2.4.2 Demonstration projects

Demonstration projects are a standard instrument to foster new technologies in the pre-commercial or formative period of their technology life cycle. For this purpose, the formative period can be subdivided into two phases: (i) the experimental phase and (ii) the take-off phase (Karlström and Sandén 2004).

The primary objective of the experimental phase is technological development. Therefore, demonstration projects should be designed to maximise learning that can be fed back into the development process in order to reduce initial uncertainty. The performance of new technologies typically increase substantially as organisations and individuals gain experience with them. The keynote behind this organisational and individual learning is that learning depends on the actual accumulation of experience. In other words: without 'doing' there is no 'learning' (Grübler 1998; Karlström and Sandén 2004).

However, the assumption of a linear correlation between knowledge and technology generation would be grossly misleading. Innovations must be continuously experimented with, modified and improved. This implies a network of actors—including suppliers, users, research institutes and others—formed around a new technology to tailor innovations in the course of diffusion. Such a network of actors may evolve into an advocacy coalition with influence not only on the development of the demonstrated technology, but also on the development of related technologies and political framework processes. Through the exchange of ideas and information among its members, joint technological expectations may be created that influence the visions and expectations of other actors, and guide the further development into a particular direction (Grübler 1998; Karlström and Sandén 2004).

Forming an actors network, thus, is one important task for a demonstration project, particularly in the take-off phase. But the focus within this phase is also set to open up a market by increasing consumer awareness, and to highlight expected institutional barriers. Once the diffusion process is started up, positive feedback mechanisms further stimulate growth (Karlström and Sandén 2004).

One of the prerequisites for carrying out a demonstration project is to point out the potential of the demonstrated technology for solving socio-economic problems and meeting societal needs as well as to highlight the extent of this potential that should go far beyond the direct effects of the demonstration project. Therefore, the success of a demonstration project should not only be defined by the direct project results like technology performance and profitability. It is important to rather incorporate indirect project results that take the contribution of the project to the technological development process into account. Hence, even if a demonstration project failed with regard to the direct project results, it finally may have succeeded by paving the way for related technology (Karlström and Sandén 2004).

3 Method

In the ISO 14040 series, Life Cycle Assessment (LCA) is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 14040 1997). The life cycle approach means that a product is followed from its 'cradle' (raw material extraction), through the production of preliminary products and the product itself, further along its use phase to its 'grave' (disposal). Inputs (resource use) and outputs (emissions) of each process along this life cycle are quantified, and the potential impacts on the environment are assessed (Eyerer et al. 2003; Baumann and Tillman 2004).[11]

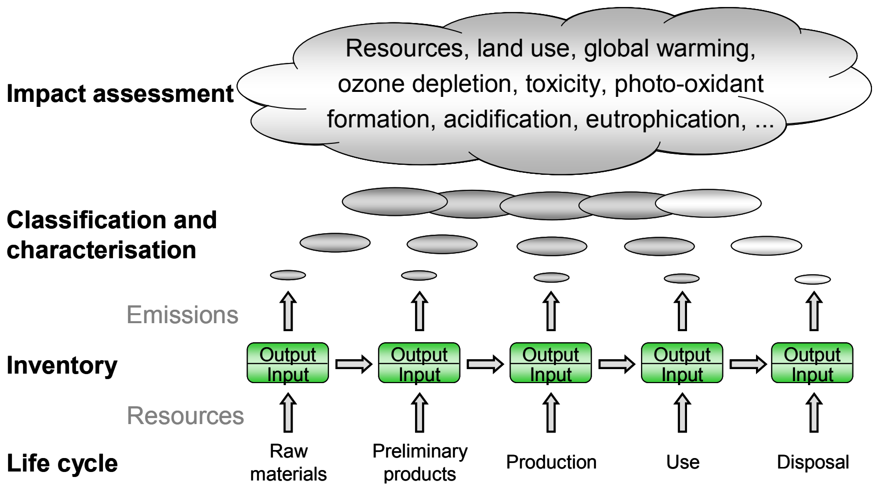

Figure 3-1: *Life cycle approach (Eyerer et al. 2003)*

LCA can be further described as a procedure for how such studies are carried out (figure 3-2). The first step is the goal and scope definition, in which the product to study and the purpose of the LCA are specified. Based on these specifications, a life cycle model is constructed, and the resources used as well as the emissions produced are calculated in the Life Cycle Inventory (LCI). The

[11] *Product* refers not only to material products, but also to services.

environmental consequences of the life cycle can be described in a subsequent step called Life Cycle Impact Assessment (LCIA). This is usually done by aggregating the inventory results in environmental impact categories through the act of classification and characterisation. Finally, the results are presented and interpreted either on the inventory or impact assessment level, or both, consistent with the defined goal and scope of the LCA (Eyerer et al. 2003; Baumann and Tillman 2004).

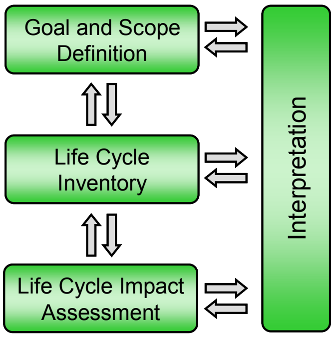

Figure 3-2: *LCA framework (ISO 14040 1997)*

LCA is a comprehensive method for the analysis of the potential environmental impact of product systems. It provides a clear life cycle logic with a methodology for describing, comparing and evaluating complex system chains with diverse environmental impacts. The holistic approach reveals 'hot spots' in the life cycle of a product and, thus, helps to avoid sub-optimisations that may be the result if only a few processes are focused on. However, the significance of an LCA highly depends on the stated purpose of the study as well as on the methodological choices that are made (Eyerer et al. 2003; Baumann and Tillman 2004).

3.1 Goal definition

According to the ISO standard (ISO 14041 1998), the goal definition "shall unambiguously state the intended application, the reason for carrying out the study and the intended audience". In other words, the context of the study must be clearly specified. Based on the goal, the requirements on the modelling to be done are determined in the scope definition. Hence, the goal definition is a crucial phase in an LCA study since different purposes require different methodological choices (Eyerer et al. 2003; Baumann and Tillman 2004).

3.1.1 Purpose

The purpose of this LCA study is to quantify and analyse the environmental aspects of using different blends of natural gas and hydrogen as vehicle fuels in ICEs within the scope of a hydrogen demonstration project.

3.1.2 Intended application and audience

The study is carried out within the scope of a proposed hydrogen demonstration project in Stenungsund, Sweden. Approximately one ton of pure hydrogen per hour is available from the petrochemical complex on site. This hydrogen surplus is mainly used together with fuel gas for the production of process heat (see also appendix B.2). With regard to these local conditions, it was discussed to upgrade a planned natural gas filling station in order to use part of this hydrogen surplus for the supply of different fuel blends of natural gas and hydrogen (see also appendix B.4).

In this context, the intended application of this LCA study is to gain knowledge about the technical and environmental properties of the proposed demonstration project in order to contribute to its further assessment. This implies that the LCA study is considered as one part of the project assessment that should contribute to the learning process associated with the demonstration of the different vehicle fuels.

According to the available data, the study was carried out for the following vehicles and fuels (see also appendix B.5):

- unmodified NGV operated on CNG and HCNG-15,
- modified NGV operated on CNG, HCNG-15 and HCNG-30 as well as a vehicle model operated on pure hydrogen.[12]

With this study, it is intended to address the different actors that are involved in the project as well as their possible questions concerning the use of the industrial by-product hydrogen.

[12] The attached numbers represent the volumetric share of hydrogen in the fuel blend.

3.2 Scope definition

3.2.1 Functional unit

LCA results are related to a specific function of the studied product, which is also a basis for comparisons of different alternatives. This implies a technical analysis of possible product functions as well as the specification of the function that is decisive in terms of the stated goal of the study. This function is described in a quantitative manner by the functional unit that corresponds to a reference flow in the life cycle model, and to which all other flows are related (Eyerer et al. 2003; Baumann and Tillman 2004).

The decisive function of the compared fuel blends is the powering of a vehicle by the conversion of the fuel energy in an internal combustion engine. The functional unit is defined as **1 vehicle km**. Thereof differing functional units are stated together with the corresponding figures.

The comparison of different fuel blends on basis of the functional unit implies the comparability of the studied vehicles in terms of size, power and other vehicle attributes. The unmodified and modified NGVs are of different vehicle types and, consequently, not directly comparable. The modified NGV and the hydrogen model are of the same type (see also appendix B.5).

3.2.2 System boundaries

According to the goal definition, the study compares the vehicle use of certain fuel blends at a future state. According to Sandén et al. (2005), this kind of study can be termed as prospective attributional product LCA, i.e. site-specific (as opposed to general) and average (as opposed to marginal) data is used to illustrate the life cycle impact of a specific product system at a future steady state.

In this 'stylised state', all electricity and heat is produced from natural gas.[13] In other words, a closed system is analysed—with natural gas as the only system input—in order to illustrate the

[13] Jonasson and Sandén (2004) use this term to refer to an extreme state that is unlikely to materialise. The stylised state presented here seems quite plausible, though.

differences between the investigated vehicle and fuel combinations in a clear way. This is also a plausible state as the petrochemical complex is being connected to the Swedish natural gas grid. The electricity production from natural gas, thus, could be a cheap and, in combination with the production of heat, also a very efficient alternative. However, the latter case of a combined heat and power production (CHP) is not considered in this LCA study.

The system boundaries are illustrated in figure 3-3. They comprise the following processes:

a) natural gas supply,
b) hydrogen supply,
c) electricity production,
d) filling station operation and
e) vehicle use.

This basically defined system is the same for the supply of the different fuel blends. Therefore, the system model in detail only includes those parts of the life cycle that are affected by changes of the fuel composition. The industrial process in figure 3-3, from which hydrogen is gained as a by-product, is shadowed since it is not affected by any system changes (see also section 3.2.2).

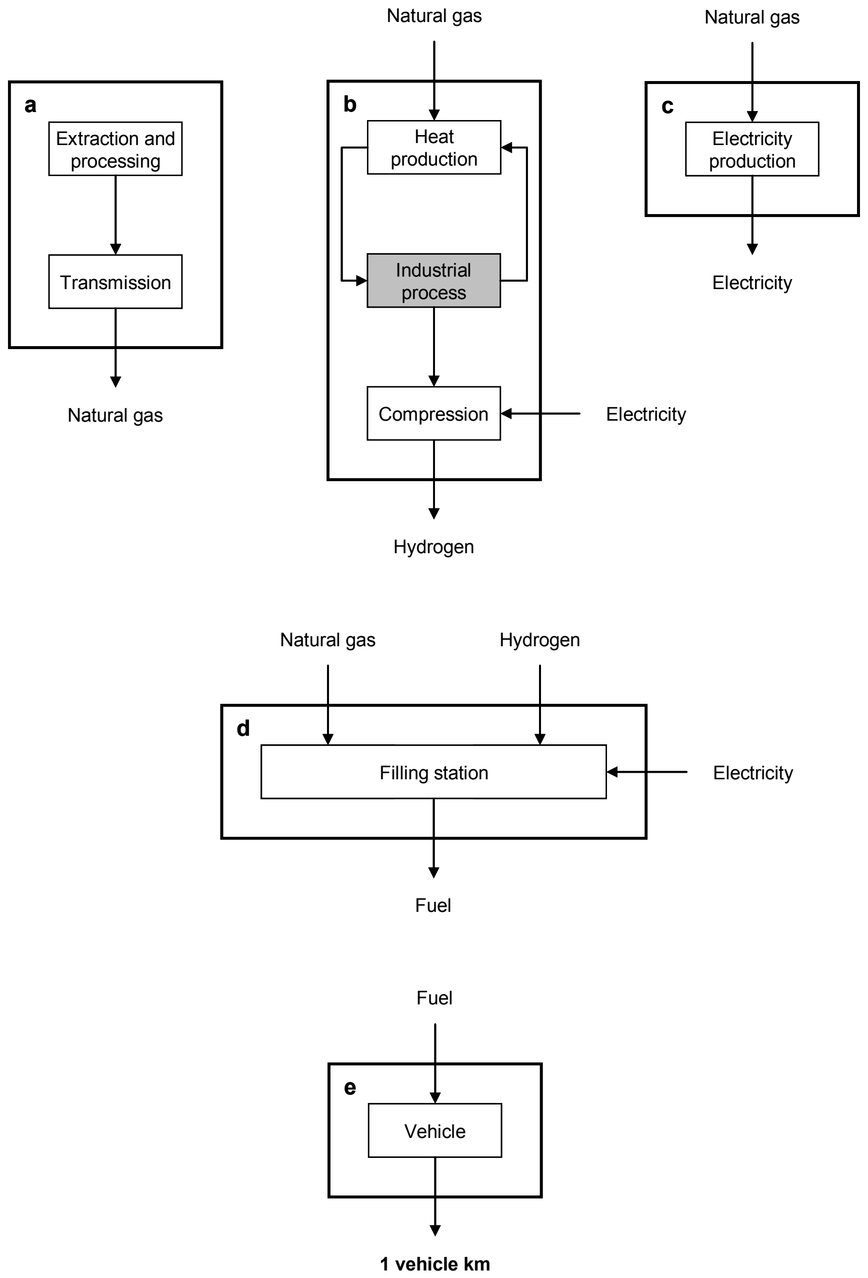

Figure 3-3: *System boundaries for (a) natural gas supply, (b) hydrogen supply, (c) electricity production, (d) filling station operation and (e) vehicle use*

Boundaries in relation to natural systems

In general, the boundary between the modelled technical system and the modelled surrounding natural system is determined by the processes that are under human control. This corresponds to the boundary between the inventory analysis and the impact assessment (Baumann and Tillman 2004).

This study considers emissions to air and, as far as data is available, energy use and waste production. Waste, however, is treated as an outflow not followed to the grave since it is not further included in the results. Furthermore, hydrogen is handled as a resource not traced back to its cradle.

Geographical boundaries

The extraction and processing of natural gas takes place in Denmark, whereas the further distribution is located in Sweden. Data for the studied vehicles is taken from a research program carried out in the state of Arizona, USA. In this study, however, the vehicle use is considered to be in Sweden and, thus, local differences (such as climate, topography, etc.) are assumed to be irrelevant. All other processes are located in Sweden.

Time-related boundaries

The key methodological problem of a prospective attributional LCA is to analyse a relevant state (Jonasson and Sandén 2004). With regard to the demonstration project, the system conditions are almost given for its implementation. The main task will be to build up a filling station at an appropriate location near the petrochemical complex in Stenungsund (see also appendix B.4). In case of a positive decision, this is assumed to take place in the near future and, hence, no significant system changes are expected. Therefore, data reflecting the current state of each system process is used in this study.

Boundaries within the technical system

Boundaries within the technical system can be mainly determined in two dimensions: related to capital goods, personnel etc. as well as related to life cycles of other products (Baumann and Tillman 2004).

Capital goods are buildings, machinery, vehicles and others that are used to produce the studied product. With the specification of the system boundaries, it has to be decided whether or not to include the environmental impact from production, maintenance and end use of capital goods. Personnel-related environmental impact is usually not included in an LCA (Baumann and Tillman 2004).

Since a steady future state is assumed, capital goods are not considered in this study. However, some collected data includes e.g. the construction of pipelines, which is stated together with the LCI data in the appendix. If capital goods would have to be considered, only those affected by changes of the system would be relevant. In detail, the switch from natural gas to blends of hydrogen and natural gas implies the investment in additional capital goods, such as the upgrading of the filling station, the construction of a hydrogen pipeline from the industrial area to the filling station and, as the case may be, the purchase of vehicles that are modified to run on a certain fuel.

Boundaries that are related to other products' life cycles usually refer to allocation problems, where the environmental load of one process has to be distributed on several products that share this process. In other words, the environmental load of one process has to be assigned to its different functions (Eyerer et al. 2003; Baumann and Tillman 2004).

In this study, an allocation problem is associated with the supply of hydrogen as a by-product of an industrial process. In this regard, it is not a function of the process to produce hydrogen, even though hydrogen is used for the demonstration project. The industrial process is consequently excluded from the study since it is not affected by system changes. However, the environmental relevance of this process and, thus, the allocation problem arises due to the fact that the by-product hydrogen is mainly used for the production of heat, which is fed back into the industrial process. Therefore, the amount of hydrogen that is used for the demonstration project has to be replaced by an alternative fuel that produces the same amount of heat. This way of dealing with an allocation problem is called system expansion and, in this case, includes the production of heat by using natural gas as alternative fuel.

3.2.3 Data quality

Assessing and reporting data quality is essential if the results of an LCA are to be properly interpreted and communicated. For this reason, a comprehensive documentation of the collected data can be found together with the LCI data for each process in part B of the appendix.

Data was mainly collected by literature research and interviews with project partners, operators of the facilities and their suppliers. Data gaps (missing data and data inconsistencies) were filled with estimates and assumptions based on the same sources. Swedish average data was collected for the natural gas supply, heat production and electricity production. Other data is site-specific.

Moreover, ISO 14041 (1998) requires a validity check of the collected data. This is done by a critical review of the collected data and comparisons with other available data sources.

3.2.4 Impact assessment method

As indicated above, the LCI results can be presented and interpreted either on the inventory or impact assessment level, or both. LCIA is a mandatory step in an LCA study, which aims at describing the potential environmental impact of the environmental loads quantified in the inventory analysis (Baumann and Tillman 2004).

In this study, the inventory results are presented and interpreted on both the inventory and impact assessment level according to the most important tailpipe emissions from vehicles operated on CNG and hydrogen. These are emissions to air of carbon dioxide (CO_2) and methane (CH_4), expressed on the impact assessment level as global warming potential (GWP), as well as nitrogen oxides (NO_x).

In addition, energy use is described in terms of the primary energy that is used for the supply of natural gas to the system. The impact assessment method applied in this study is illustrated in figure 3-4.

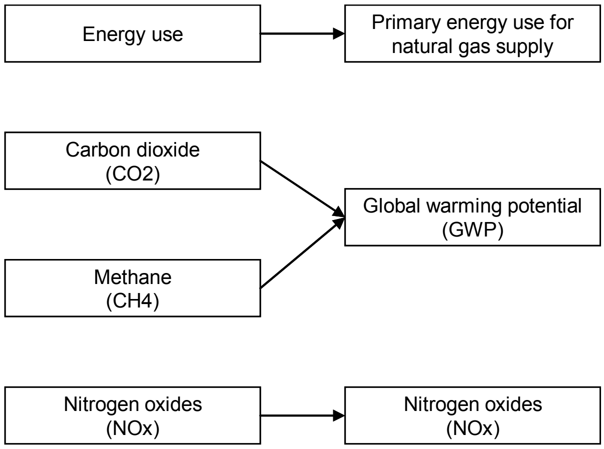

Figure 3-4: *Impact assessment method*

Energy use

In an LCI, energy use is always accounted for. It is an inventory parameter that is easy to communicate and often understood as an indicator for energy-related environmental impact, even though energy use as such does not cause environmental impact (Baumann and Tillman 2004).

Since the modelled system depends on natural gas as its only input (see figure 3-3), the total amount of natural gas that is consumed by the system is considered as an indicator for energy use. In the following, this indicator is represented by the primary energy use for the supply of natural gas to the system (also stated as ‘natural gas energy use’ or just ‘energy use’ if not further specified). Furthermore, the on-site electricity consumption for the compression of natural gas and hydrogen is given as additional information in section 4.1.

Global warming potential

During an LCIA, the inventory results are *classified* into certain impact categories according to their potential environmental impacts, and further *characterised* according to the extent of their environmental impact within a certain impact category (Eyerer et al. 2003; Baumann and Tillman 2004).

In this study, the LCIA considers the inventory results for CO_2 and CH_4. CO_2 is chosen since it is the most important greenhouse gas (GHG) regarding its worldwide emissions to air in connection with the energy conversion of carbon-based fuels. CH_4 is another important GHG and, moreover, it accounts for the bulk of the total emissions of unburned hydrocarbons to air when using natural gas as a vehicle fuel (see also section 2.1.3).

The potential contribution of CO_2 and CH_4 to global warming, i.e. their capacity to absorb infrared radiation and thereby heat the atmosphere, is expressed as their global warming potential (GWP). According to the UN Intergovernmental Panel on Climate Change (IPCC 1996), the capacity of CH_4 is 21 times higher than CO_2 per kg for a 100 year time frame.[14] GWP is normalised to CO_2 equivalents.

Nitrogen oxides

NO_x emissions to air can be considered as the main pollutant of concern when hydrogen is used solely or as a fuel additive in ICEs (see also sections 2.2.3 and 2.3.3). Furthermore, NO_x emissions contribute to a number of impact categories, such as acidification, eutrophication, photo-oxidant formation and human toxicity.

3.2.5 Assumptions and limitations

A major assumption and, hence, limitation of the study goes along with the heat production and system expansion, respectively. As indicated above, hydrogen that is used for the demonstration project has to be taken out of the heat production process and, consequently, replaced by natural gas as alternative fuel. It is supposed that the emissions might considerably vary with the share of hydrogen in the fuel. Especially the NO_x emissions are assumed to be lower with a decreasing share of hydrogen, whereas the emissions of unburned hydrocarbons could be higher (compare with section 2.3.3).

With the available data, however, it is not possible to properly estimate the hydrogen-related emissions since the effects of different hydrogen supplements on the combustion characteristics are

[14] IPCC (2001a) actually recommends a GWP for CH_4 of 23 kg CO_2 eqv./kg for a 100 years time frame. However, in this study the outdated value is used since the other references used also refer to this value, and differences in the results between the recommended and the outdated value are negligible (see section 4.2).

unknown. The same applies for the adjustment of operating parameters to the fuel composition. Furthermore, a linear approximation might not be applicable (Hoelzner and Szyszka 1994). Instead, the calculations are based on constant emission factors for the heat production from natural gas, which are not further adjusted to the share of hydrogen in the fuel. However, this is assumed to be a valid approximation since maximum 5 kg/hr out of 380 kg/hr hydrogen will be used for the demonstration project, which equals about 0.17 MW that have to be replaced by natural gas in a 57 MW steam boiler.

A sensitivity analysis was performed in order to assess the possible effects on the results and the conclusions of the study, if hydrogen-related emissions would be considered. The same was done for estimated data in connection with minor assumptions, regarding the supply of natural gas, the compression of natural gas and hydrogen as well as the operation of the hydrogen vehicle (see section 5.1).

4 Results

In the following, the results are presented in two groups for each category. The first group (including two bars) represents the unmodified vehicle operated on CNG and HCNG-15. The second group (including four bars) represents the modified vehicle operated on CNG, HCNG-15, HCNG-30 and hydrogen. It should be noted, however, that it is about a differently modified vehicle in the case of hydrogen, but based on the same vehicle type (see also appendix B.5).

For a proper interpretation of the results, the fuel properties are given in table 4-1.

Table 4-1: *Fuel properties of CNG, HCNG and hydrogen*

	CNG	HCNG-15	HCNG-30	Hydrogen
Share of hydrogen				
by volume	0.00%	15.00%	30.00%	100.00%
by mass	0.00%	1.85%	4.38%	100.00%
by energy	0.00%	4.54%	10.36%	100.00%
Density [kg/Nm³]	0.84	0.73	0.61	0.09
Heating value [MJ/Nm³]	40.00	35.62	31.23	10.78

Furthermore, the volumetric as well as the energy-related fuel consumption is listed in table 4-2 for each vehicle and fuel.

Table 4-2: *Fuel economy of unmodified and modified vehicle*

	Nm³/100 km	MJ/km
Unmodified vehicle		
CNG	16.81	6.72
HCNG-15	18.20	6.48
Modified vehicle		
CNG	13.69	5.48
HCNG-15	15.83	5.64
HCNG-30	17.37	5.43
Hydrogen	40.63	4.38

From the figures in table 4-2 we can see that the efficiency tends to increase when switching from CNG to hydrogen-blended fuels and hydrogen, respectively (compare with section 2.3.3). However, we can also see that the efficiency of the modified vehicle first decrease when switching from CNG to HCNG-15, and that the gain of efficiency for HCNG-30 is only marginal. This is connected with the modifications of the vehicle. On the one hand, the modifications aim at lowering the combustion temperature in order to decrease the NO_x emissions (compare with section 2.1.3). On the other hand, the vehicle is modified to run on HCNG-30, which might explain the lower efficiency for the vehicle operation on HCNG-15 (see also appendix B.5).

The different magnitudes of fuel consumption between the unmodified and the modified vehicle can be explained by the different vehicle types. The same characteristics are also reflected in the fuel economy of their gasoline counterparts with a consumption of roughly 20 l/100 km and 16 l/100 km, respectively (EPA 2005). In general, the studied vehicles are characterised by a high fuel consumption, which is not representative for common European light-duty vehicles (see also appendix B.5). For comparison, the European well-to-wheel (WTW) analyses carried out by GM (2002) and Edwards et al. (2003) both calculate with a fuel consumption in the dimension of 2.3 MJ/km for dedicated NGVs.

4.1 Energy use

With regard to 1 MJ of supplied fuel at the filling station, the total natural gas consumption and, hence, the primary energy use for the supply of natural gas to the system (in the following stated as 'natural gas energy use' or just 'energy use' if not further specified) increases towards higher shares of hydrogen in the fuel as shown in table 4-3. This is due to the additional demand for natural gas in order to produce heat and electricity within the scope of the hydrogen supply (see also appendix C).

Table 4-3: *Natural gas energy use for fuel supply*

	Energy use [MJ/MJ fuel]
Vehicle fuel	
CNG	1.10
HCNG-15	1.13
HCNG-30	1.16
Hydrogen	1.68

Figure 4-1 shows the results for the natural gas energy use and, as additional information, figure 4-2 shows the on-site electricity consumption for the compression of natural gas and hydrogen. Both figures are related to the functional unit of 1 vehicle km.

From figure 4-1 we can see that the energy use decreases for the unmodified vehicle, which can be explained by the considerable increase of the vehicle efficiency compared to a slight increase only of the energy use per MJ fuel. In contrast, the energy use increases for the modified vehicle when switching from CNG to HCNG-15 since both, the energy-related fuel consumption and the energy use per MJ fuel, increase. For HCNG-30 and hydrogen, the energy use is higher than for CNG since both times the increase of the energy use per MJ fuel is substantially higher than the increase of the vehicle efficiency.

As shown figure 4-2, the on-site electricity consumption rises with an increasing share of hydrogen in the fuel for both the modified and unmodified vehicle since additional electricity is needed for the compression of hydrogen.

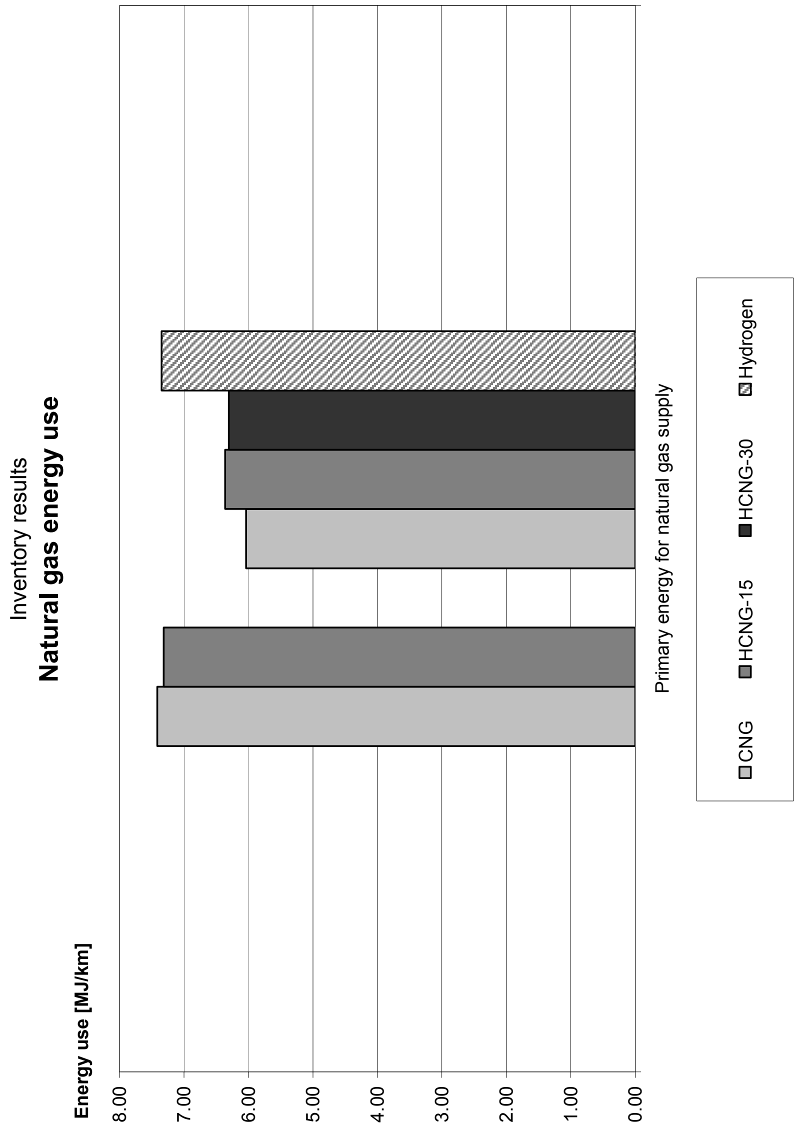

Figure 4-1: *LCA results for natural gas energy use*

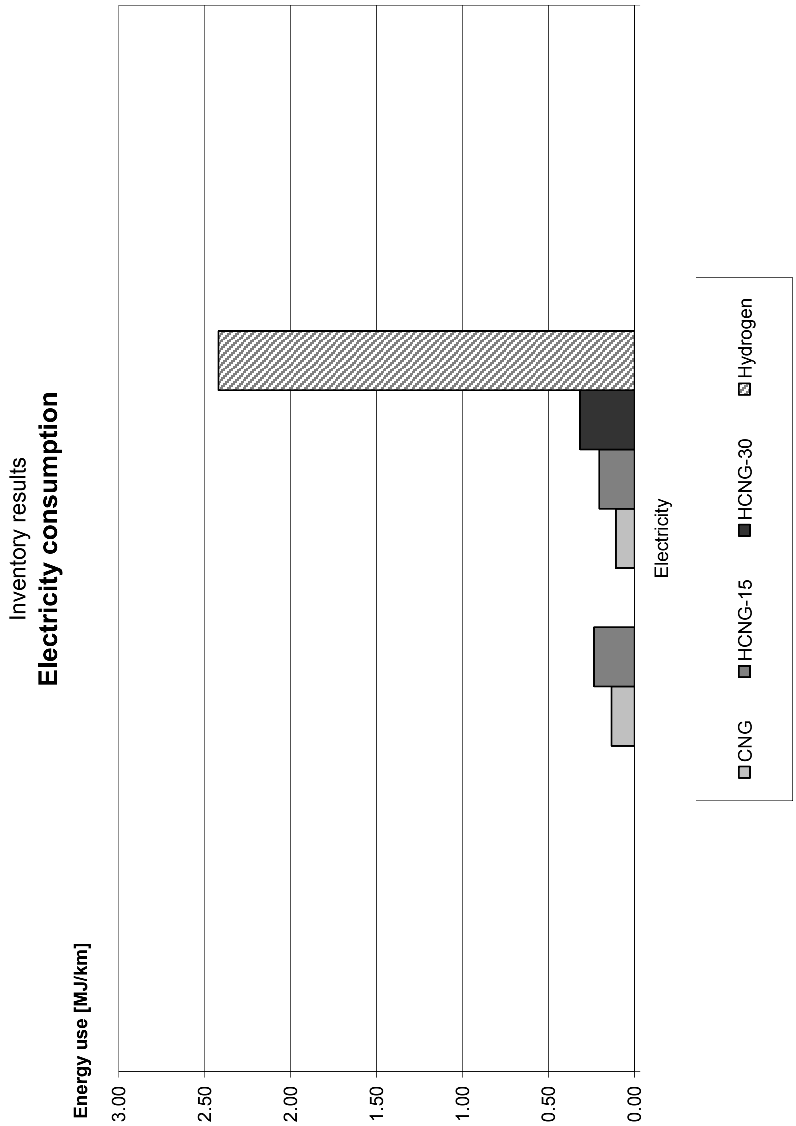

Figure 4-2: *LCA results for electricity consumption*

4.2 Global warming potential

From table 4-4, which shows the global warming potential with regard to 1 MJ of supplied fuel at the filling station, we can see a progressive increase of GWP towards higher shares of hydrogen in the fuel. This is mainly due to the increasing heat and electricity production in order to supply hydrogen to the filling station. The associated natural gas supply has only a marginal influence on this GWP increase (see appendix C).

Table 4-4: *Global warming potential (100 years) of fuel supply*

	GWP [g CO_2 eqv./MJ fuel]
Vehicle fuel	
CNG	6.50
HCNG-15	10.52
HCNG-30	15.67
Hydrogen	95.05

In figure 4-3 we can see the results for the global warming potential of the different system processes as well as the total GWP of the entire system, all related to the functional unit of 1 vehicle km.

The CO_2 emissions are about 400 up to some 4,000 times higher than the CH_4 emissions and, thus, CO_2 is actually the only relevant GHG in this study with regard to GWP.[15] More precisely, the CH_4 emissions account for about 5% of the total GWP of the natural gas supply and decrease to roughly 0.5% for the supply of hydrogen. Furthermore, the natural gas supply and the vehicle use almost solely contribute to the total emissions of CH_4 in almost equal shares, except for the hydrogen vehicle. With regard to CO_2, the emissions from the vehicle use-phase are up to almost an order of magnitude higher than those from the corresponding fuel supply chains, again except for the hydrogen vehicle. Of course, we also see the same emission trend for the natural gas supply as for the natural gas energy use discussed in section 4.1.

[15] According to IPCC (2001a), the global warming potential of CH_4 ranges from 62 kg CO_2 eqv./kg for a 20 years time frame down to 7 kg CO_2 eqv./kg for a 500 years time frame.

Both, the heat and the electricity production are characterised by a progressive emission increase towards a hydrogen share of 100% as a result of the increasing amounts of natural gas that are supplied to the corresponding combustion processes.

In case of the vehicle use, we see, on the one hand, a general decrease of the GWP along increasing shares of hydrogen in the fuel, mainly due to the direct carbon replacement. On the other hand, the decrease for the unmodified vehicle is much stronger than for the modified vehicle, which again can be referred to the reduced combustion temperature in the modified vehicle. There are naturally no GHG emissions from the vehicle that is operated on pure hydrogen.

Altogether, we see that for CNG and HCNG the main impacts come from the vehicle use-phase, whereas the GWP of the hydrogen vehicle originates almost completely from the emissions associated with the heat and electricity production. However, we can also see that the emissions from the heat and electricity production have a noticeable effect on the total results for the HCNG-operated vehicles relative to the CNG case, i.e. for the unmodified vehicle there is still a benefit left from the vehicle use-phase, whereas the smaller benefit from the operation of the modified vehicle is foiled by the emissions from the heat and electricity production processes.

It should be noted that the CH_4 emissions from the vehicle use illustrate the trade-off described in the theory chapter (see section 2.1.3). For the unmodified vehicle, an emission reduction of nearly 34% can be achieved when using HCNG-15 instead of CNG, which results in a total CH_4 reduction of about 22% for the whole system. In contrast, the emissions from the modified vehicle slightly increase by some 3% and 8% when switching from CNG to HCNG-15 and HCNG-30, respectively. The latter can be explained by the lowered combustion temperatures due to the modifications that aim at reducing the NO_x emissions (compare with section 2.1.3).

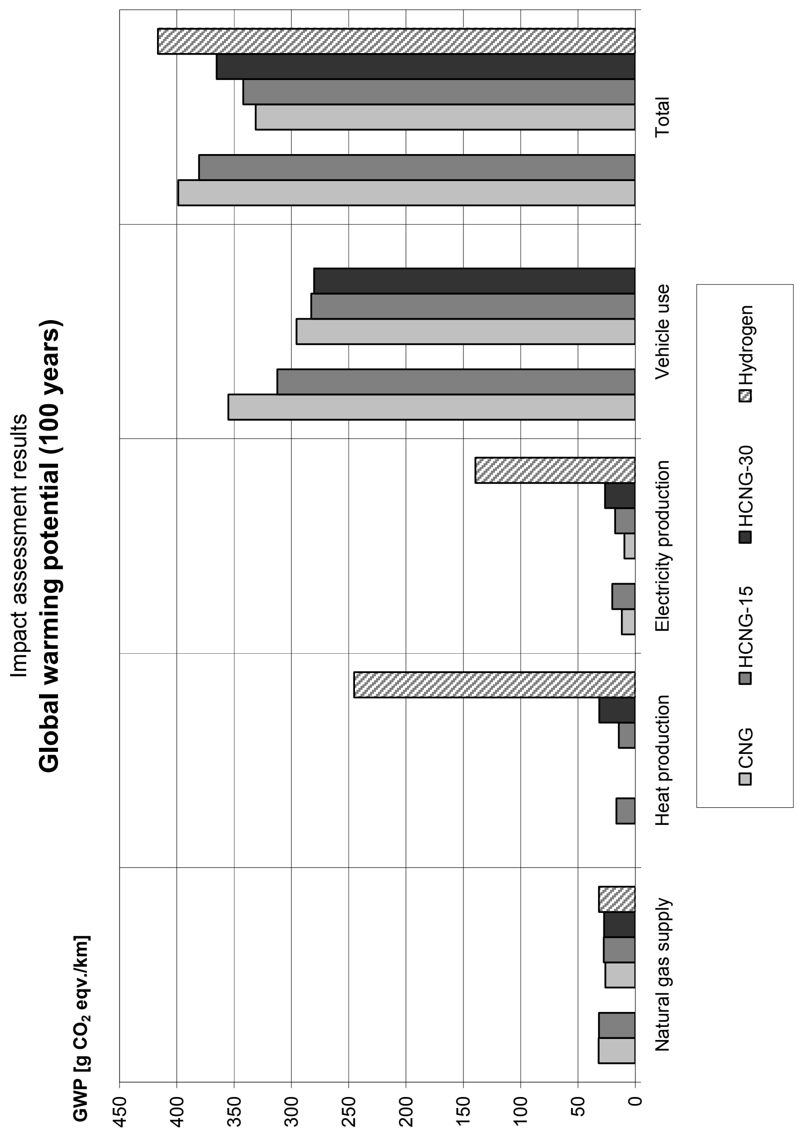

Figure 4-3: *LCA results for global warming potential (100 years)*

4.3 Nitrogen oxides

From table 4-5, which shows the emissions of nitrogen oxides to air with regard to 1 MJ of supplied fuel at the filling station, we can see a progressive increase of NO_x emissions towards higher shares of hydrogen in the fuel. This again is mainly due to the increasing heat and electricity production in order to supply hydrogen to the filling station. The associated natural gas supply has a minor influence on this emission increase (see appendix C).

Table 4-5: *Emissions of nitrogen oxides to air from fuel supply*

	NO_x [10^{-2} g/MJ fuel]
Vehicle fuel	
CNG	2.25
HCNG-15	2.65
HCNG-30	3.16
Hydrogen	11.04

Figure 4-4 shows the emissions of nitrogen oxides to air from the different system processes as well as the total NO_x emissions from the entire system, all related to the functional unit of 1 vehicle km.

Again, we can see the already discussed emission trend for the natural gas supply (see figure 4-1), but compared to the GWP with a much higher contribution to the total results.

Like in case of the GWP results, the emissions from the heat and electricity production show a progressive increase towards higher shares of hydrogen in the fuel.

The NO_x emissions from the vehicle use point out an inverse trend compared to the GWP progression, i.e. we can see a considerable increase of NO_x emissions from the unmodified vehicle compared to a slight increase only for the modified vehicle with higher shares of hydrogen in the fuel. Here we can clearly see the effects of the vehicle modifications and the combustion temperature, respectively, on the NO_x formation (compare with section 2.1.3). Furthermore, there are very low NO_x emissions from the operation of the hydrogen vehicle, which are, as already mentioned, the only fuel-related tailpipe emissions when using hydrogen in an ICE except for water vapour (see also section 2.2.3).

As a result, we can see a considerable increase of the total NO_x emissions for the unmodified vehicle and a lower but still noticeable increase for the modified vehicle. An interesting point is that the vehicle use is not the dominating source of the total NO_x emissions. For CNG and HCNG, the impact from the natural gas supply is even higher. Furthermore, the heat and electricity production together with the natural gas supply almost completely contribute to the total NO_x emissions from the hydrogen use. Like in the case of the GWP results, the heat and electricity production have a noticeable influence on the relative NO_x results.

As discussed in section 3.2.5, it is assumed that NO_x emissions from the heat production might be lower the more hydrogen is taken out of this process and replaced by natural gas as alternative fuel. However, it is also stated that only a small amount of the hydrogen surplus is used. Furthermore, it is shown in a sensitivity analysis (see section 5.1) that there are no reasonable figures for a NO_x credit that would lead to a qualitative change of the total results.

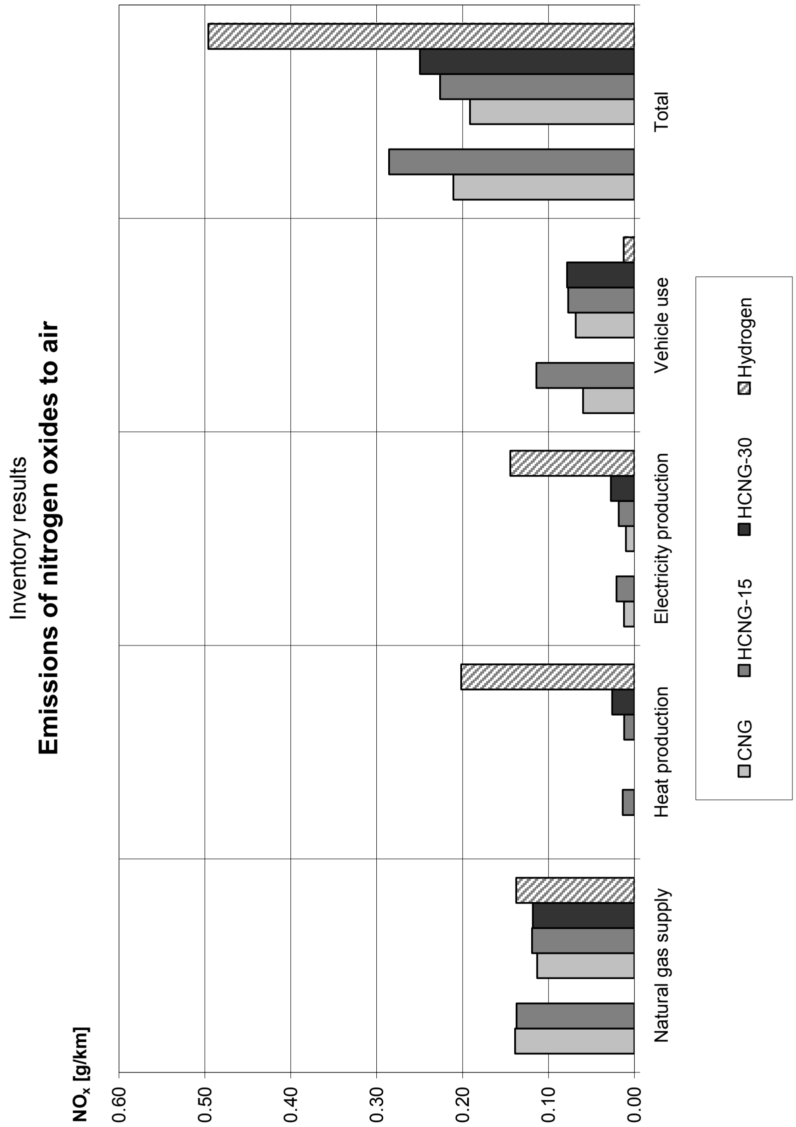

Figure 4-4: *LCA results for emissions of nitrogen oxides to air*

5 Discussion

In this chapter, the results of a sensitivity analysis are given that address the data uncertainties of the LCI. Furthermore, a sensitivity analysis was conducted in order to deal with the major assumption stated in section 3.2.5 concerning hydrogen-related NO_x emissions.

According to the goal definition, the intention of this study is to contribute to the assessment of the demonstration project. Against this background, the discussion is oriented towards questions that might be posed by different actors of the demonstration project. The questions that are dealt with can be expressed as follows:

- "Where should the hydrogen come from?"
- "What fuel should be used in the vehicle?"
- "Is it reasonable to carry out the demonstration project?"

In the following, some required background information with these questions are provided in order to draw the conclusions consistent to the goal definition of the study.

5.1 Sensitivity analysis

A sensitivity analysis was performed to examine the effects of varying the base case assumptions for the following processes:

- *Natural gas supply*
  The results of this study refer to natural gas that is solely imported from Denmark. However, natural gas from Norway and Russia might be introduced to the Swedish gas market in the near future (see appendix B.1). Hence, the results were recalculated for each of these potential natural gas sources according to LCA data from Gunnarsson and Skarphagen (1999) recommended by IVL (Uppenberg et al. 2001, see appendix D).

- *Natural gas and hydrogen compression*
  The electricity consumption of the natural gas filling station and compression, respectively, is assumed to be 0.2 kWh/Nm^3 by the end of 2005 (see also appendix B.4). Therefore, a sensitivity case was performed, using the actual consumption that amounts to 0.3 kWh/Nm^3.

  Furthermore, the data used in this study considers an hydrogen inlet pressure of 10 bar according to the reference filling station in Malmö, whereas the inlet pressure at the project site will be 25 bar (see appendix B.4). In the sensitivity case, the electricity consumption of the hydrogen compressors was therefore set to a lower average value according to data from two other studies that ranges from 0.18 kWh/Nm^3 (GM 2002) to 0.24 kWh/Nm^3 (Edwards et al. 2003).

- *Use-phase of hydrogen vehicle*
  According to Mulligan (2005), the modified vehicle operated on hydrogen might meet the emission standard for a Super Ultra Low Emission Vehicle (SULEV) of 0.02 grams NO_x per mile. Emission tests, however, are still owing (see also appendix B.5). Therefore, a sensitivity analysis was conducted using the Ultra Low Emission Vehicle (ULEV) standard of 0.07 grams NO_x per mile.

With the variation of the base case assumptions for the above mentioned processes, a best case and a worst case scenario were analysed in order to quantify the maximum uncertainty. Hence, the best case scenario comprises data for Norwegian natural gas and a lower electricity consumption for the compression of hydrogen. In contrast, the worst case scenario deals with Russian natural gas, a higher electricity consumption for the compression of natural gas as well as higher NO_x emissions from the hydrogen vehicle. The relative results compared to the base case are shown in table 5-1 and table 5-2.

Table 5-1: *Best case scenario analysis*

	Energy use	**GWP**	**NO_x**
Unmodified vehicle			
CNG	-3.1%	-3.3%	-51.8%
HCNG-15	-4.5%	-4.9%	-39.8%
Modified vehicle			
CNG	-3.1%	-3.3%	-46.4%
HCNG-15	-4.5%	-4.8%	-43.7%
HCNG-30	-6.1%	-6.0%	-41.7%
Hydrogen	-23.3%	-23.3%	-39.8%

In the best case scenario, as shown in table 5-1, we can see considerable changes of the NO_x emissions as well as of the energy use and the GWP in the hydrogen case.

Table 5-2: *Worst case scenario analysis*

	Energy use	**GWP**	**NO_x**
Unmodified vehicle			
CNG	+9.7%	+13.9%	+3.9%
HCNG-15	+9.5%	+14.2%	+2.6%
Modified vehicle			
CNG	+9.7%	+13.6%	+3.5%
HCNG-15	+9.5%	+13.8%	+2.9%
HCNG-30	+9.4%	+12.6%	+2.4%
Hydrogen	+8.0%	+11.5%	+6.3%

From table 5-2 we can see that in the worst case scenario the results for all impact indicators differ by maximally 14.2%.

Comparing the total results from the base case with those from the best and worst case scenarios (see appendix D), there are no qualitative changes in the NO_x results noticeable, i.e. the progression along the different vehicle and fuel cases remains the same. The same applies for energy use and GWP with regard to the unmodified vehicle. Regarding the modified vehicle, however, we see that the energy use and GWP for hydrogen in the best case is lower than for CNG and HCNG, which is contrary to the base and the worst case. This can be explained by the lower electricity consumption for the compression of hydrogen in the best case scenario, which totally amounts to 0.420 kWh/Nm³ hydrogen compared to 0.987 kWh/Nm³ hydrogen in the base case.

The latter issue raises the question, how low the total electricity consumption for the compression of hydrogen must be in order to result in a lower environmental impact from the hydrogen case compared to the other fuel cases. Therefore, a break-even analysis was performed to investigate the trade-offs of energy use and GWP that are related to the corresponding total electricity consumption of the hydrogen compression (see appendix D). The results are given in table 5-3 for energy use, and in table 5-4 for GWP.

Table 5-3: *Break-even results for energy use*

	CNG	HCNG-15	HCNG-30
Hydrogen compression			
Electricity [kWh/Nm³ hydrogen]	0.501	0.599	0.543

From table 5-3 we can see that the electricity consumption for the trade-off in case of CNG is the lowest, followed by HCNG-30 and HCNG-15, which consequentially goes along with the progression of the energy use discussed in section 4.1.

Table 5-4: *Break-even results for GWP*

	CNG	HCNG-15	HCNG-30
Hydrogen compression			
Electricity [kWh/Nm³ hydrogen]	0.429	0.470	0.603

From table 5-4 we can see again that the electricity consumption for the trade-off in case of CNG is the lowest, and increases along higher shares of hydrogen in the fuel according to the GWP trend discussed in section 4.2.

As discussed in section 3.2.5, a major assumption goes along with the heat production and system expansion, respectively. Emissions from the production of process heat might considerably vary with the share of hydrogen in the fuel. In particular, it is assumed that the NO_x emissions from this process might be lower the more hydrogen is taken out of it and replaced by natural gas (compare with section 2.3.3), which is not accounted for in the calculations. In order to take these considerations into account, the NO_x emissions from the heat production process have to be credited with the NO_x emissions associated with the hydrogen that is put out of the process.

$$NO_{x\ (\text{non-accounted})} - NO_x\ \text{credit} = NO_{x\ (\text{accounted})} \qquad (5.1)$$

The consideration of such a NO_x credit might have a noticeable influence on the total results for the modified vehicle operated on hydrogen since the total NO_x emissions mostly result from the heat production process in this case. Therefore, an additional sensitivity analysis was performed in order to show if it is a possible scenario that the total NO_x emissions from the modified vehicle operated on hydrogen can be lower than from the same vehicle operated on CNG and HCNG. In other words, it was analysed if there are reasonable figures for a NO_x credit that would lead to this scenario. Therefore, another break-even analysis was performed to investigate the trade-offs of NO_x emissions that are related to the corresponding NO_x credits for the heat production (see appendix D). The results are shown in table 5-5.

Table 5-5: *Break-even results for NO_x emissions*

	CNG	HCNG-15	HCNG-30
Heat production			
NO_x credit [g/MJ hydrogen]	0.0695	0.0654	0.0645

The figures in table 5-5 reveal that the discussed scenario is not possible with regard to reasonable figures for a NO_x credit because the NO_x emissions from the heat production maximally amount to

0.046 g NO_x/MJ fuel. In other words, the NO_x emissions from the vehicle operation on hydrogen are always higher compared to the vehicle operation on the other fuels.

The same conclusion can be drawn by directly comparing the total results (see figure 4-4), since the differences in total NO_x emissions between the vehicle use of the natural gas containing fuels and hydrogen are generally higher than the corresponding NO_x emissions from the heat production process. Hence, not even zero emissions from the heat production would offset these differences.

5.2 Steam reforming versus hydrogen surplus

As indicated in section 3.2.2, the availability of natural gas on site the industrial area in Stenungsund makes it plausible to use natural gas for the production of heat and electricity. With regard to a hydrogen demonstration project, it is relevant to consider the production of hydrogen via natural gas steam reforming as well.

Data for the hydrogen production via natural gas steam reforming is taken from an LCA study carried out by the U.S. Department of National Renewable Energy Laboratory (NREL) (Spath and Mann 2001). The results are shown in table 5-6 together with the results for the hydrogen supply in Stenungsund (labelled as hydrogen surplus). The filling station process is excluded from the results, i.e. only the hydrogen supply to the filling station is considered. The functional unit (fu) is 1 MJ hydrogen.

Table 5-6: *Steam reforming (Spath and Mann 2001) vs. hydrogen surplus*

	Steam reforming	Hydrogen surplus
Impact indicators		
Energy use [MJ/fu]	1.58	1.25
GWP [g CO_2 eqv./fu]	99.03	70.63
NO_x [g/fu]	0.10	0.08

The results show both a lower energy use and a lower GWP in case of the supply of surplus hydrogen. The same applies for emissions of NO_x, but these numbers should be regarded as a matter of aftertreatment. As already mentioned, CH_4 accounts for roughly 0.5% of the total GWP for the supply of surplus hydrogen, whereas the share is almost 11% in case of natural gas steam reforming (Spath and Mann 2001).

It should be noted, that the capacity of the considered hydrogen plant in the NREL LCA study (1.5 million Nm^3/day) lies beyond the capacities that are dealt with in this demonstration project (see appendix B.2). According to Spath and Mann (2001), care should be taken in scaling the results to other hydrogen production systems since the impact indicators are functions of the size of the plant and the technology. For example, reducing the efficiency from 89.3% to 80% would increase the impact indicators by 15.6%.

For comparison, the GM Well-to-Wheel Analysis (GM 2002) was consulted as another data source. According to this study, the GWP of natural gas steam reforming on site the filling station (considering an average EU natural gas mix) amounts to 92.9 g CO_2 eqv./MJ hydrogen, which is still higher than for the supply of surplus hydrogen. In the case of Swedish natural gas, the total primary energy use for the supply of natural gas to this steam reforming process on site the filling station would amount to 1.54 MJ/MJ hydrogen.

5.3 Fleet results for vehicle demonstration

If hydrogen should be used for a vehicle demonstration, the question remains what kind of hydrogen fuel should be used. An answer might be given by looking at LCA results for certain vehicle fleets. The idea is that with the availability of a certain amount of hydrogen a corresponding number of vehicles can be refuelled. Hence, scale effects have to be considered when assessing the demonstration.

The scaling factors for the modified vehicles are calculated on basis of their hydrogen consumption related to the amount of hydrogen that is needed to run a hydrogen vehicle. The numbers are given in table 5-7.

Table 5-7: *Hydrogen consumptions and scaling factors*

	H_2 consumption [MJ/km]	**Scaling factor** [-]
Modified vehicle		
HCNG-15	0.29	25.43
HCNG-30	0.65	11.25
Hydrogen	7.35	1.00

For the further assessment, the CNG-related fleet results are calculated by applying the above scaling factors on the differences between the LCA results for the CNG case and the other fuel cases. This time, however, the functional unit is 1 km of the corresponding vehicle fleet. The results are shown in table 5-8.

Table 5-8: *Fleet results for modified vehicle*

	Energy use [MJ/km]	**GWP** [g/km]	**NO_x** [g/km]
Modified vehicle			
HCNG-15	+10.68	+274.10	+0.89
HCNG-30	+5.34	+382.78	+0.65
Hydrogen	+3.62	+85.23	+0.30

From table 5-8 we can see that all results are higher compared to the CNG case. Furthermore, the results show that the hydrogen fleet would have the best environmental performance.

The results in table 5-8 refer to the modified vehicle only due to the availability and comparability of data for all three fuel cases. Assuming similar scaling factors for the unmodified vehicle, it can be expected that the corresponding fleet results for NO_x will be considerably higher compared to an imaginary hydrogen case (compare with figure 4-4), whereas the energy use will be even lower than in the CNG case (compare with figure 4-1). The fleet results for GWP will also be lower than in the CNG case (compare with figure 4-3) but it is not possible to further estimate the results compared to a potential hydrogen case without concrete figures for the considered hydrogen vehicle.

5.4 Assessment of demonstration project

Potential environmental impacts are often used as arguments for or against a demonstration project. However, to properly assess the effective environmental consequences of using a new technology in a demonstration project instead of a baseline technology is not trivial. Therefore, direct environmental results, like the ones from an attributional LCA, are not seldom misinterpreted since the dynamics of technological change are disregarded. A major methodological problem thus arises from how to compare potential consequences and the direct environmental impact of a demonstration project. In general, the direct environmental consequences of a demonstration project are only limited. However, the project could serve as a stepping stone for further developments and, from an environmental point of view, these are as important as the ones of the demonstration project itself (Karlström and Sandén 2004).

According to the theoretical background discussed in section 2.4, the considered demonstration project can be assigned to the early formative period of the applied hydrogen technology. In this experimental phase, a demonstration project should be designed to maximise learning. Therefore, the discussion of the LCA results should also include the question to what extent the LCA study could contribute to the different dimensions of technological change associated with the demonstration project. At this point, it should be noted that a detailed and thorough answer to this question lies beyond the scope of this study. However, additional findings are given in the following that emanated from the LCA study and might contribute to a further assessment of the demonstration project in the broader context of technological change.

First of all, it should be referred to the pre-study carried out by Engstrand (2004). It provides background information and points out possible actors as well as legal and economic considerations. Karlsson (2001) carried out another pre-study in the run-up to the Malmö Bus Project that deals with the applicability of hydrogen-blended natural gas as a fuel for natural gas buses. Besides technical considerations, this study also highlights legal and economic issues as well as safety aspects.

In general, an assessment should take compatibility, complexity and testability issues into account, as discussed in section 2.4, which imply analyses of institutional barriers and technological constraints, the availability of knowledge and experience, involved actors and potential consumers as well as the accessibility of new technology and other issues concerning technological change and diffusion.

6 Conclusions

The results show that the environmental benefits of performing the demonstration project are limited, which was somewhat expected in the run-up to this study. Considering a certain amount of hydrogen that is available for vehicle demonstration, the corresponding fleet of hydrogen vehicles would have the best environmental performance compared to fleets of the modified vehicles running on HCNG-15 and HCNG-30. However, there are no overall benefits connected to the use of any of these fuels compared to the use of CNG. The latter also applies to fleet considerations for the unmodified vehicle.

However, it has been shown that the supply of surplus hydrogen is environmentally preferable compared to the supply of hydrogen via natural gas steam reforming. Furthermore, it has been shown that differences in energy use and GWP between the hydrogen case and the other fuel cases can be offset by a lower electricity consumption for the compression of hydrogen.

In general, the results reveal that the potential environmental impact from the fuel supply chain considerably increases towards a hydrogen share of 100% in the fuel (see also appendix C). Hence, characteristic trends of the total results for different fuel cases mainly depend on the efficiency and emission characteristics of the considered vehicles.

We can also see from the results that the fuel supply processes—the natural gas supply and, in particular, the heat and electricity production—are decisive for the total environmental impact associated with the use of pure hydrogen. In contrast, the vehicle use-phase dominates the total results when using CNG and HCNG, except for NO_x, which is also influenced by the natural gas supply. However, the heat and electricity production considerably affect the results and, therefore, can be considered as decisive system processes with regard to the differences between the potential environmental impacts from the different fuel cases. In this respect, producing heat and power in an CHP plant might have a considerable effect on the total results with lower emissions from the life cycle of HCNG and hydrogen.

Besides these environmental considerations, however, it has to be taken into account that potential environmental impacts as direct project results cannot be consulted alone when assessing the demonstration project and deciding whether it should be performed or not. In the experimental phase of using hydrogen as a vehicle fuel, a demonstration project should be designed to maximise learning that can be fed back into the development process. Hence, the question arises in which case learning effects are greatest. On the one hand, technological change is more radical when using pure hydrogen. On the other hand, more vehicles and possibly more actors are involved when using HCNG.

The demonstration of HCNG might have a greater potential since it offers the opportunity for a broader public to get in touch with hydrogen and, in particular, to gain experience with its application as an alternative fuel. Hence, it might be easier to open up a market for HCNG than for more complex and radical hydrogen technology due to a better accessibility and an increased customer awareness. Furthermore, the introduction of HCNG might pave the way for related technologies and, in the long-run, for hydrogen technology. However, the assessment of the demonstration project has to be extended by focussing on the dynamics of technological change in order to prove these assumptions.

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Appendix

The appendix is subdivided into four parts. Part A compares the fuel properties of gasoline, natural gas and hydrogen that are dealt with in the theory chapter. Part B provides an extensive documentation of the collected LCI data together with the corresponding data tables. Part C comprises the LCI results for the considered fuel cases in this study and, finally, part D provides data for the sensitivity analysis and the presentation of the results as well as the presentation of the break-even analyses discussed in section 5.1.

A Fuel properties

Table A-1 provides an overview of all relevant fuel properties of gasoline, natural gas and hydrogen that are mentioned in the theory chapter.

Table A-1: *Fuel properties of gasoline, natural gas and hydrogen*

		Gasoline [a]	**Natural gas**	**Hydrogen**
Fuel property				
Density ρ	[kg/m³]	760	172.73 [b]	23.73(39.64) [c]
Calorific value H_u	[MJ/kg]	42.00	47.62	120.00
Vol. energy density	[MJ/l]	31.70	8.23 [b]	2.85(4.76) [c]
Mixture density ρ_G [d]	[kg/m³]	1.38	1.24 [e]	0.94
Air/fuel ratio L_{st} [d]	[kg/kg]	14.5	17.2 [e]	34.0
Heating value H_G [d]	[MJ/m³]	3.67	3.40 [e]	3.21
Max. flame speed [f]	[cm/s]	47	43	346
Octane number RON [g]	[-]	95	120+	130+
Self-ignition temp. [g]	[°C]	257.2	540.0	582.2
Flammability limits [g]	[vol%]	1.4 … 7.6	5.3 … 15	4.1 … 74
Min. ignition energy [h]	[mJ]	0.25	0.28	0.02

[a] for Euro Super (Bargende and Greiner 2003)
[b] for compressed natural gas at 200 bar (Opel 2005)
[c] for compressed hydrogen at 350(700) bar (Cederberg et al. 2002)
[d] for stoichiometric air/fuel mixtures (Nylund and Lawson 2000)
[e] for methane (Nylund and Lawson 2000)
[f] according to HyWeb (2005)
[g] according to AFDC (2005c)
[h] according to Karim (2003)

B LCI data and documentation

B.1 Natural gas supply

Extraction and processing

Data for the production and distribution of natural gas is taken from the “Environmental factbook for fuels” (Uppenberg et al. 2001) published by the Swedish Environmental Research Institute (IVL). Their calculations are based on Sydkraft’s LCA report “Environmental impact from Sydkraft’s electricity production 1999” (Hansson et al. 2000), which is recommended by the IVL due to its high quality.

The natural gas supply chain described in Sydkraft’s LCA report (Hansson et al. 2000) includes the extraction of natural gas from Danish oil and gas fields in the North Sea, the pipeline transport to the gas processing facilities in Nybro, Denmark, the processing of natural gas as well as the pipeline transport of the processed natural gas to Sydkraft’s combined heat and power (CHP) plant in Malmö, Sweden. The data also includes the construction of pipelines and the operation of facilities.

The literature data taken from Bakkane (1994) and used for the extraction of natural gas can be considered as a main limitation of most of the LCA studies about natural gas in Sweden so far. On the one hand, Norwegian data is taken and used for Danish facilities in the North Sea. On the other hand, the data based on Bakkane (1994) comes from 1991 and it is stated in Vattenfall’s LCA report (Brännström-Norberg et al. 1996) that the calculated emissions from the Norwegian gas production are not representative for today since it has been estimated that by 2000 it would be possible to reduce the emissions of CO_2 and NO_x by 35% and 25%, respectively.

Today, all natural gas sold and used in Sweden is imported from Denmark. However, with regard to a further extension of the natural gas grid in Sweden it is expected that most of the natural gas will be imported from Russia and Norway. Several studies have been carried out, which assessed the environmental impacts of Russian and Norwegian natural gas for the Swedish gas market (Pastore 1998; Gunnarsson and Skarphagen 1999; Uppenberg et al. 2001). However, the environmental impacts from these potential sources are not considered in the results of this study, even though their introduction could take place within the time boundaries determined in the goal and scope definition of the LCA. Therefore, a sensitivity analysis was performed to examine the changes in the LCA results for the cases, where natural gas is imported from Norway or Russia (see section 5.1).

Transmission

The Swedish high-pressure transmission network and basic grid, respectively, runs from Dragør in Denmark to Stenungsund (see figure 2-2). The main pipeline is about 300 km long and designed for a maximum pressure of 80 bar. The pipeline from Gothenburg to Stenungsund has a length of 58 km and an operating pressure of 16 bar. By the end of 2005, the pressure will be raised to 28.6 bar due to new customers in Gothenburg and Stenungsund that will be connected to the natural gas grid. Along this transmission network there are 40 measuring and regulating (MR) stations, which represent the connection to the distribution network with an operating pressure of maximum 4 bar. There are no compressor stations in the Swedish transmission network (Nilsson 1997; Engstrand 2005; Karlsson 2005).

Leakages of natural gas along the transmission network are mainly based on the diffusion from valves, but also station blowdowns during maintenance works account for differences in the gas balance. The operator aims at keeping these differences within the gas balance under 0.2% of the transported amount of natural gas (Carlsrud 2003).

In a confidential EUROGAS study, reference values have been determined for the emission of CH_4 in connection with the production, transmission and distribution of natural gas. For the transmission of natural gas in Sweden, the Swedish Gas Centre (SGC 2000) calculated 0.11 g CH_4 per Nm^3 transported natural gas, which equals roughly 19% of the total CH_4 emissions from the entire natural gas supply chain. The CH_4 emissions connected to station blowdowns are negligible since the blowed off amount of natural gas amounts to roughly 1,000 Nm^3 a year compared to around 900 millions Nm^3 natural gas that are transported annually (Carlsrud 2003).

Extraction and processing

Functional unit (fu)	1 Nm³ processed natural gas
Reference/contact person	Uppenberg et al. (2001) Miljöfaktabok för bränslen IVL Svenska Miljöinstitutet AB Stockholm
Reference year/period	1999
Location	Southern Sweden

	Amount/fu	Unit
Energy use	2.69E+00	MJ
Renewable energy use	6.77E-03	MJ
Biomass	0.00E+00	MJ
Hydropower	6.77E-03	MJ
Non-renewable energy use	2.68E+00	MJ
Coal	4.61E-02	MJ
Crude oil	3.31E-01	MJ
Natural gas	2.30E+00	MJ
Emissions to air		
Ammonia (NH3)	0.00E+00	g
Benzene (C6H6)	6.80E-02	g
Carbon dioxide (CO2)	1.72E+02	g
Carbon monoxide (CO)		g
Halogenated HC (CFC/HCFC)	0.00E+00	g
Halogenated HC (HCFC-22)	2.00E-06	g
Hydrochloric acid (HCl)	2.52E-04	g
Hydrofluoric acid (HF)	4.00E-05	g
Methane (CH4)	4.80E-01	g
Nitrogen oxides (NOx)	8.00E-01	g
Nitrous oxide (N2O)	3.92E-03	g
Non-methane HC (NMVOC)	1.04E-01	g
Particles	1.32E-02	g
Sulphur oxides (SOx)	1.32E-01	g
Waste generation	1.73E+01	g
Hazardous waste	1.72E+00	g
Other waste	1.56E+01	g

Transmission

Functional unit (fu)	1 Nm³ supplied natural gas
Reference/contact person	Svenskt Gastekniskt Center AB (2000) Små metanläckage från de svenska naturgasnäten Sammanfattning av SGC rapport 089
Reference year/period	2000
Location	Southern Sweden

	Amount/fu	Unit
Input		
Processed natural gas	1.00E+00	Nm³
Emissions to air		
Methane (CH4)	1.10E-01	g

B.2 Hydrogen supply

Stenungsund, located about 50 km north of Gothenburg, is the centre of the petrochemical industry in Sweden. Figure B-1 shows that inside this fully integrated petrochemical complex there are three companies, which are connected to a hydrogen (vätgas) pipeline. They, both, produce and use hydrogen (as described in the following). Hydrogen is transported at 28–30 bar pressure.

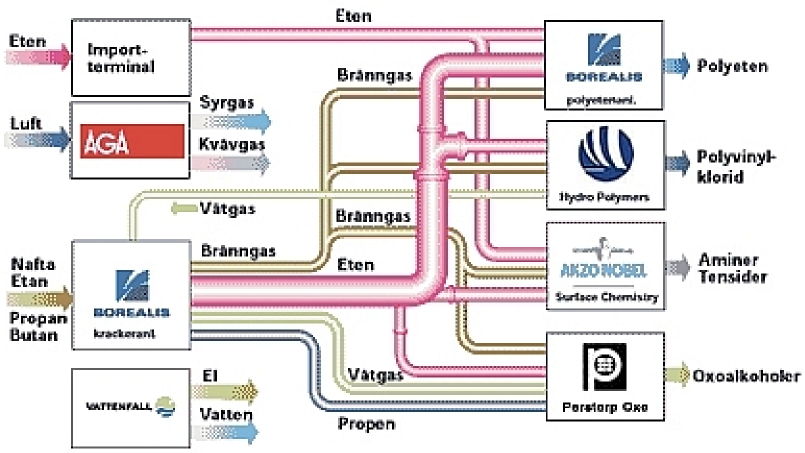


Figure B-1: *Petrochemical industry in Stenungsund (Kastö 2002)*

Petrochemical industry

Borealis

The company operates two plants in Stenungsund, a cracker and a polyethylene facility. Besides the feedstock for the polymer processing industry, the cracker facility produces fuel gas and hydrogen-rich gas (about 80% hydrogen and 20% methane by volume). Depending on the demand for pure hydrogen, part of the hydrogen-rich gas is processed in a Pressure Swing Adsorption (PSA) unit, which can produce up to 1 ton of pure hydrogen per hour. The rest of the hydrogen-rich gas is added to the fuel gas, which is used inside Borealis and also sold to other companies. The internal demand for hydrogen averages 20 kg/hr for the reactors in the polyethylene facility and up to 200 kg/hr for the cracker unit. Another 150–400 kg/hr are sold to other companies (Ryding 2005).

Hydro Polymers

The company operates a polyvinyl chloride (PVC) resin/paste plant in Stenungsund. The first production step is the manufacturing of chlorine and caustic soda in an electrolysis process. As a by-product of this process, around 380 kg of pure hydrogen per hour are produced. Normally, all of this hydrogen is used together with fuel gas from Borealis in a steam boiler. A small amount of hydrogen is sometimes sold to other companies (Jorlöv 2005).

Perstorp Oxo

The company manufactures aldehydes, alcohols, organic acids and plasticizers for vinyl plastic in Stenungsund. In May 2004, Perstorp Oxo switched from oil to natural gas as the raw material for the base process. Hence, the company could also start to manufacture its own hydrogen. In a partial oxidation process, natural gas is converted to hydrogen-rich syngas, which is further processed in a PSA unit. Approximately 700–800 kg of pure hydrogen per hour are produced and used inside the company. In case of a production shortage, a small amount of hydrogen is purchased from Borealis or Hydro Polymers (Lind 2005).

Hydrogen supplier for demonstration project

Hydro Polymers is the only company of the petrochemical complex in Stenungsund, which directly gains hydrogen of high purity as a by-product from one of its production processes. Thus, Hydro Polymers would be the most appropriate supplier of hydrogen for the demonstration project since the other companies need a further processing step to derive pure hydrogen from hydrogen-rich gas. However, it has to be taken into account that hydrogen at Hydro Polymers is internally used at 2.5 bar (Jorlöv 2005). Therefore, it has to be compressed to 28 bar when fed into the hydrogen pipeline.

According to the pre-study of the demonstration project, a hydrogen capacity of 2 kg/hr was estimated to be sufficient, but probably up to 5 kg/hr will have to be purchased from the industry.

Hydrogen compression

The electricity consumption for the compression of hydrogen is estimated according to the hydrogen compressor specifications listed in table B-1.

Table B-1: *Hydrogen compressor specifications (Connelly 2005)*

	Type 1	Type 2
Operating parameters		
Capacity	34 Nm³/hr	68 Nm³/hr
Inlet pressure	20–40 bar	20–40 bar
Discharge pressure	250 bar	250 bar
Motor	15 kW	30 kW

The average electricity consumption accounts for 65% of the kW rating per unit (Connelly 2005), which results in 0.287 kWh/Nm³ for both compressor types.

According to HyWeb (2005), the work $w_{t,ith}$ for an ideal isothermal compression can be calculated according to equation B.1.

$$w_{t,ith} \sim Z \cdot \ln\left(\frac{p_2}{p_1}\right) \tag{B.1}$$

with inlet pressure p_1 and discharge pressure p_2

In equation B.1, Z stands for a correction factor for the hydrogen gas according to equation B.2.

$$Z = \frac{K(p_1) + K(p_2)}{2\,K(p_1)} \tag{B.2}$$

with $K(p) = 1 + \frac{p}{150\ \text{MPa}}$

Due to this relationship between the work $w_{t,ith}$ and the discharge pressure p_2 as well as the inlet pressure p_1, about the same energy is required for equal compression ratios. Since the ratio for the compression from 2.5 to 28 bar lies within the range of the above compressor specifications, the calculated electricity consumption of 0.287 kWh/Nm³ is used in this study. A sensitivity analysis was performed to determine how changing this number would affect the results (see section 5.1).

The pressure after the PSA process already meets the requirement for the supply to the hydrogen pipeline. However, adapted from Izumi et al. (2002), the electricity consumption is estimated to be considerably higher than for the hydrogen compression.

Heat production

Since hydrogen is used for the production of process heat inside the company, the branched off amount of hydrogen would have to be replaced by increasing the purchased amount of fuel gas from Borealis. Today, Borealis again would meet this growing demand by increasing the delivered amount of propane. However, at present the company is being connected to the natural gas grid and, thus, the near-term replacement for hydrogen would be natural gas (Ryding 2005).

Data for the heat production is taken from Uppenberg et al. (2001). They refer to Swedish average emission factors for district heating plants with capacities between 50 and 300 MW. The NO_x emissions of 0.049 g/MJ fuel were adjusted to 0.046 g/MJ fuel according to the specifications of the considered steam boiler process at Hydro Polymers with an efficiency of 93.4% (Jorlöv 2005).

The amount of natural gas that has to replace the branched off hydrogen for the production of the same amount of heat is calculated on basis of the net calorific values for hydrogen and natural gas. This implies equal efficiencies for the energy conversion in the heat production process, independent of the applied fuel composition. The efficiency of a steam boiler process is defined by the ratio of the heat liberation from the fuel gas and the heat received by the steam, whereas the latter mainly depends on the boiler geometry. According to Battistella (2005), the heat liberation should be the same for different blends of natural gas and hydrogen and, thus, a constant efficiency can be assumed.

Hydrogen compression

Functional unit (fu)	1 Nm^3 supplied hydrogen
Reference/contact person	Berndt-Olof Jorlöv, Production Manager Hydro Polymers AB, Stenungsund E-mail: berndt-olof.jorlov@hydro.com Phone: +46 (0)303 876 79 Tom Connelly, Tech. Sales Engineer Hydro-Pac Inc. E-mail: tomc@hydropac.com Phone: +1 814 474 1511
Reference year/period	2005
Location	Stenungsund, Sweden

	Amount/fu	Unit
Input		
Hydrogen	1.00E+00	Nm^3
Energy use		
Electricity	1.03E+00	MJ

District heating plant

Functional unit (fu)	1 Nm^3 supplied natural gas
Reference/contact person	Uppenberg et al. (2001) Miljöfaktabok för bränslen IVL Svenska Miljöinstitutet AB Stockholm Berndt-Olof Jorlöv, Production Manager Hydro Polymers AB, Stenungsund E-mail: berndt-olof.jorlov@hydro.com Phone: +46 (0)303 876 79
Reference year/period	1998
Location	Sweden

	Amount/fu	Unit
Input		
Supplied natural gas	1.00E+00	Nm^3
Emissions to air		
Ammonia (NH3)	0.00E+00	g
Carbon dioxide (CO2)	2.24E+03	g
Carbon monoxide (CO)	4.00E-01	g
Methane (CH4)	4.00E-03	g
Nitrogen oxides (NOx)	1.84E+00	g
Nitrous oxide (N2O)	2.00E-02	g
Non-methane HC (NMVOC)	4.00E-02	g
Sulphur oxides (SOx)	0.00E+00	g

B.3 Electricity production

According to the goal and scope definition, all electricity consumed by the studied system is produced from natural gas. Data for the corresponding power plant is taken from Uppenberg et al. (2001). The data represents Swedish average emission factors for the use of natural gas in a gas turbine process with an overall efficiency of 58%.

Power plant

Functional unit (fu)	1 MJ electricity
Reference/contact person	Uppenberg et al. (2001) Miljöfaktabok för bränslen IVL Svenska Miljöinstitutet AB Stockholm
Reference year/period	1999
Location	Sweden

	Amount/fu	Unit
Input		
Supplied natural gas	4.31E-02	Nm^3
Emissions to air		
Ammonia (NH3)	0.00E+00	g
Carbon dioxide (CO2)	9.66E+01	g
Carbon monoxide (CO)	1.72E-02	g
Methane (CH4)	1.72E-04	g
Nitrogen oxides (NOx)	1.00E-01	g
Nitrous oxide (N2O)	8.62E-04	g
Non-methane HC (NMVOC)	1.72E-03	g
Sulphur oxides (SOx)	0.00E+00	g

B.4 Filling station operation

In a pre-study of the demonstration project, two locations for the filling station near the petrochemical industry in Stenungsund (maximum 1 km away) were discussed. However, the natural gas filling station that was planned to be upgraded to a combined hydrogen/natural gas filling station was finished about 6.5 km outside the industrial area at Stora Höga (figure B-2). This location is not appropriate for the discussed demonstration project since the costs for the construction of the hydrogen pipeline would be out of scale (Engstrand 2005). Nevertheless, data for the filling station in Stora Höga is used in this study since it is expected that a realisation of the proposed demonstration project depends on the provision of a similar filling station near the petrochemical complex.

Figure B-2: *Map of Stenungsund (Map24 2005)*

The filling station in Stora Höga is designed for both light-duty and heavy duty vehicles, except buses. The capacity amounts to approximately 60,000 Nm^3 natural gas per month. The single units of the filling station are: inlet pipe, compressor building with hydraulic compressor (discharge pressure of 250 bar), high pressure storage (water volume of 4,000 litres), high pressure outgoing pipe, dispenser as well as different regulating devices (Ramberg 2005).

The energy consumption of the natural gas filling station currently amounts to 0.3–0.35 kWh/Nm^3, but it will be lowered to roughly 0.2 kWh/Nm^3 by the end of 2005 since the pressure in the natural gas grid will be raised from 16 to 28.6 bar. Furthermore, 250 litres of hydraulic oil are exchanged every 5,000 hours as well as gas filters are exchanged in different time schedules (Ramberg 2005). However, the latter is not considered in the study since the amount of exchanged hydraulic oil and gas filters are negligible compared to the amount of natural gas that is refuelled within the same period. The same applies for the hydrogen part of the filling station.

For the supply of HCNG and pure hydrogen, the natural gas filling station has mainly to be upgraded with hydrogen compressor, storage and dispenser. Data is taken from the hydrogen filling station in Malmö that was finished in 2003. The production capacity amounts to 36 Nm^3 hydrogen per hour (75 kg per day) with a maximum storage of 95 kg hydrogen at a pressure of 393 bar (water volume of 3,690 litres). A dual fuel dispenser was installed that delivers HCNG at 250 bar and pure hydrogen at 350 bar. Furthermore, the filling station is equipped with two hydrogen compressors (for regular and back-up operation). The total energy consumption of the filling station, including electrolyser, amounts to 5.5 kWh/Nm^3 hydrogen. The hydrogen production alone (electrolyser including rectifier and auxiliaries) has an energy consumption of 4.8 kWh/Nm^3. Hence, 0.7 kWh/Nm^3 are assigned to the operation of the filling station (Ivarsson 2005; Machens 2005).

For both the natural gas and the hydrogen part of the filling station, data for the energy consumption is only available for the entire filling station. However, the compression of natural gas and hydrogen, respectively, accounts for almost all the energy that is needed for the operation of the filling station. Therefore, the compressors are credited with the whole energy consumption of the corresponding part of the filling station and further distinctions between single units are not considered in this study.

A sensitivity analysis was performed, using an average value for the hydrogen compression according to other fuel and vehicle studies (see section 5.1).

Filling station (natural gas)

Functional unit (fu)	1 Nm^3 dispensed natural gas
Reference/contact person	Bo Ramberg, Managing Director FordonsGas Sverige AB, Göteborg E-mail: bo.ramberg@fordonsgas.se Phone: +46 (0)31 63 45 31
Reference year/period	2005
Location	Stora Höga, Sweden

	Amount/fu	Unit
Input		
Supplied natural gas	1.00E+00	Nm^3
Energy use		
Electricity	7.20E-01	MJ

Filling station (hydrogen)

Functional unit (fu)	1 Nm^3 dispensed hydrogen
Reference/contact person	Staffan Ivarsson, Director of Gas Development Sydkraft Gas AB, Malmö E-mail: staffan.ivarsson@sydkraft.se Phone: +46 (0)40 24 47 13
Reference year/period	2005
Location	Malmö, Sweden

	Amount/fu	Unit
Input		
Supplied hydrogen	1.00E+00	Nm^3
Energy use		
Electricity	2.52E+00	MJ

B.5 Vehicle use

Since 2001, the Arizona Public Service (APS), in cooperation with Electric Transportation Applications (ETA) and the U.S. Department of Energy's Advanced Vehicle Testing Activity (ATVA), has tested different vehicles operated on CNG, HCNG and hydrogen. Although the tested vehicles are not commonly found on Swedish roads, the test results were used since it is assumed that comparable results of other vehicle types would mainly differ by quantity.

Unmodified NGV

In 2002, APS tested a Dodge Ram Wagon Van (figure B-3) on HCNG with 15% hydrogen by volume, after it had been operated on CNG only. The test conditions and results are given in Karner and Francfort (2003a).

Figure B-3: *Dodge Ram Wagon Van (Karner and Francfort 2003a)*

The Dodge Ram Wagon Van is equipped from the factory for operation on CNG, and it is not further modified. The emission measurements were performed according to the Federal Test Procedure (FTP-75). This test consists of three phases (cold start, transient and hot start), which cover 1,874 seconds and 17.77 kilometres at an average speed of 33.96 km/h.

Modified NGV

In 2003, APS tested the acceleration, range, and exhaust emissions of a Ford F-150 pickup truck (figure B-4). The test vehicle was operated on 100% CNG and blends of 15 and 30% HCNG. The test conditions and results are given in Karner and Francfort (2003b).

Figure B-4: *Ford F-150 (Karner and Francfort 2003b)*

Unlike the Dodge Ram Wagon Van, the Ford F-150 test vehicle is equipped with a factory CNG engine that is modified to run on blends of CNG and up to 30% hydrogen by volume. The modifications include supercharging, ignition modifications, and exhaust gas recirculation. The emission measurements were also performed according to the Federal Test Procedure (FTP-75).

Hydrogen vehicle

In 2004, the follow-up model of the Ford F-150 was also tested by APS but this time equipped with a hydrogen ICE and, consequently, operated on pure hydrogen (AVTA 2005). However, the emissions test failed since the vehicle's emissions were too clean for the sensor equipment to measure anything, but new tests were planned for January 2005 (Francfort 2005). According to Mulligan (2005), the vehicle manufacturer supposes that the California emission standard of 0.02 grams NO_x per mile for a Super Ultra Low Emission vehicle (SULEV) could be achieved. Due to this uncertainty, a sensitivity analysis was performed by applying the emission standard for an Ultra Low Emission vehicle (ULEV) that amounts to 0.07 grams NO_x per mile (see section 5.1).

Fuel consumption

The fuel consumption of the hydrogen vehicle was measured during an SAE J1634 driving cycle based on the FTP-75 driving cycle (AVTA 2005). In contrast, the fuel consumption of the unmodified vehicle is based on regular operation, and for the modified vehicle it was determined by a test drive at a constant speed of 72.42 km/h over a distance of 96.56 km (Karner and Francfort 2003). Therefore, the fuel consumptions of the unmodified and modified vehicle had to be recalculated in order to go along with the measured FTP-75 emissions.

Concerning this matter, a linear approximation was applied on data from two vehicle studies (Whalen et al. 1999; Eudy 2000), regarding two dedicated NGVs with similar emission characteristics to those of the considered CNG-operated unmodified and modified vehicle. For the evaluation, the CO_2 emissions were consulted since it is assumed that the CO_2 emissions per MJ natural gas differ only marginal as shown in figure B-5.

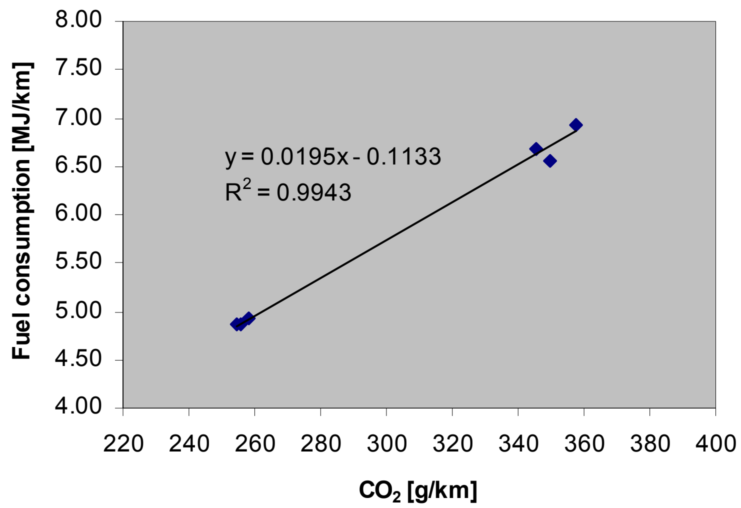


***Figure B-5:** Linear approximation of fuel consumption*

Unmodified NGV

Functional unit (fu)	1 vehicle km
Reference/contact person	Karner, D. and Francfort, J. (2003a) Dodge Ram Wagon Van - Hydrogen/CNG Operations Summary Idaho National Engineering and Environmental Laboratory
Reference year/period	2001/2002
Location	Arizona, USA

	Amount/fu	Unit
Input		
CNG	6.72E+00	MJ
Emissions to air		
Carbon dioxide (CO2)	3.51E+02	g
Carbon monoxide (CO)	1.36E+00	g
Methane (CH4)	1.79E-01	g
Nitrogen oxides (NOx)	5.97E-02	g
Non-methane HC (NMHC)	3.23E-02	g
Total hydrocarbons (HC)	2.43E-01	g

	Amount/fu	Unit
Input		
HCNG-15	6.48E+00	MJ
Emissions to air		
Carbon dioxide (CO2)	3.12E+02	g
Carbon monoxide (CO)	6.08E-01	g
Methane (CH4)	1.19E-01	g
Nitrogen oxides (NOx)	1.14E-01	g
Non-methane HC (NMHC)	1.90E-02	g
Total hydrocarbons (HC)	1.58E-01	g

Modified NGV (1)

Functional unit (fu)	1 vehicle km
Reference/contact person	Karner, D. and Francfort, J. (2003b) Hydrogen/CNG Blended Fuels: Performance Testing in a Ford F-150 Idaho National Engineering and Environmental Laboratory
Reference year/period	2003
Location	Arizona, USA

	Amount/fu	Unit
Input		
CNG	5.48E+00	MJ
Emissions to air		
Carbon dioxide (CO2)	2.94E+02	g
Carbon monoxide (CO)	3.52E-01	g
Methane (CH4)	7.95E-02	g
Nitrogen oxides (NOx)	6.84E-02	g
Non-methane HC (NMHC)	1.43E-02	g
Total hydrocarbons (HC)	1.07E-01	g

	Amount/fu	Unit
Input		
HCNG-15	5.64E+00	MJ
Emissions to air		
Carbon dioxide (CO2)	2.81E+02	g
Carbon monoxide (CO)	2.90E-01	g
Methane (CH4)	8.20E-02	g
Nitrogen oxides (NOx)	7.71E-02	g
Non-methane HC (NMHC)	1.55E-02	g
Total hydrocarbons (HC)	1.11E-01	g

Modified NGV (2)

Functional unit (fu)	1 vehicle km
Reference/contact person	Karner, D. and Francfort, J. (2003b) Hydrogen/CNG Blended Fuels: Performance Testing in a Ford F-150 Idaho National Engineering and Environmental Laboratory
Reference year/period	2003
Location	Arizona, USA

	Amount/fu	Unit
Input		
HCNG-30	5.43E+00	MJ
Emissions to air		
Carbon dioxide (CO2)	2.78E+02	g
Carbon monoxide (CO)	2.63E-01	g
Methane (CH4)	8.57E-02	g
Nitrogen oxides (NOx)	7.83E-02	g
Non-methane HC (NMHC)	8.08E-03	g
Total hydrocarbons (HC)	1.09E-01	g

Hydrogen vehicle

Functional unit (fu) 1 vehicle km

Reference/contact person 2003 Hydrogen ICE Truck (ETA 2005)

Collier Technologies, Inc. (CT 2005)

Reference year/period 2004

Location Arizona, USA

	Amount/fu	Unit
Input		
Hydrogen	4.38E+00	MJ
Emissions to air		
Carbon dioxide (CO2)		g
Carbon monoxide (CO)		g
Methane (CH4)		g
Nitrogen oxides (NOx)	1.24E-02	g
Non-methane HC (NMHC)		g
Total hydrocarbons (HC)		g

C LCI results

The inventory results for the different fuel cases were obtained by the calculation procedure following Baumann and Tillman (2004): for each process of the system model, the collected data was normalised, i.e. the inputs and outputs of each process were related to the function of the process (see appendix B). Thereafter, the flows linking the processes as well as the flows passing the system boundaries were calculated, referring to the flow representing the functional unit. Finally, the energy use, emissions to air and waste generation were summed up for the whole system.

In the following, the results for the supply of CNG, HCNG-15, HCNG-30 and hydrogen are given that are related to the functional unit (fu) of 1 MJ dispensed fuel. In order to get the total LCI results, including the vehicle use-phase, these results have to be multiplied with the fuel input of the corresponding vehicles as well as added to the corresponding vehicle emissions (see appendix B.5).

The energy use figures in the following data tables refer to the use of additional energy resources for the supply of natural gas, and do not include the feedstock energy of the supplied natural gas.

Inventory results CNG (1)

Functional unit (fu) 1 MJ dispensed CNG

	Natural gas supply		Heat production	
	Amount/fu	Unit	Amount/fu	Unit
Energy use	6.94E-02	MJ		MJ
Renewable energy use	1.75E-04	MJ		MJ
Biomass	0.00E+00	MJ		MJ
Hydropower	1.75E-04	MJ		MJ
Non-renewable energy use	6.93E-02	MJ		MJ
Coal	1.19E-03	MJ		MJ
Crude oil	8.55E-03	MJ		MJ
Natural gas	5.95E-02	MJ		MJ
Emissions to air				
Ammonia (NH3)	0.00E+00	g	0.00E+00	g
Benzene (C6H6)	1.76E-03	g		g
Carbon dioxide (CO2)	4.44E+00	g	0.00E+00	g
Carbon monoxide (CO)		g	0.00E+00	g
Halogenated HC (CFC/HCFC)	0.00E+00	g		g
Halogenated HC (HCFC-22)	5.17E-08	g		g
Hydrochloric acid (HCl)	6.51E-06	g		g
Hydrofluoric acid (HF)	1.03E-06	g		g
Methane (CH4)	1.52E-02	g	0.00E+00	g
Nitrogen oxides (NOx)	2.07E-02	g	0.00E+00	g
Nitrous oxide (N2O)	1.01E-04	g	0.00E+00	g
Non-methane HC (NMVOC)	2.69E-03	g	0.00E+00	g
Particles	3.41E-04	g		g
Sulphur oxides (SOx)	3.41E-03	g	0.00E+00	g
Waste generation	4.47E-01	g		g
Hazardous waste	4.44E-02	g		g
Other waste	4.03E-01	g		g

Inventory results CNG (2)

Functional unit (fu) 1 MJ dispensed CNG

	Electricity production		Total	
	Amount/fu	Unit	Amount/fu	Unit
Energy use		MJ	6.94E-02	MJ
Renewable energy use		MJ	1.75E-04	MJ
Biomass		MJ	0.00E+00	MJ
Hydropower		MJ	1.75E-04	MJ
Non-renewable energy use		MJ	6.93E-02	MJ
Coal		MJ	1.19E-03	MJ
Crude oil		MJ	8.55E-03	MJ
Natural gas		MJ	5.95E-02	MJ
Emissions to air				
Ammonia (NH3)	0.00E+00	g	0.00E+00	g
Benzene (C6H6)		g	1.76E-03	g
Carbon dioxide (CO2)	1.74E+00	g	6.18E+00	g
Carbon monoxide (CO)	3.10E-04	g	3.10E-04	g
Halogenated HC (CFC/HCFC)		g	0.00E+00	g
Halogenated HC (HCFC-22)		g	5.17E-08	g
Hydrochloric acid (HCl)		g	6.51E-06	g
Hydrofluoric acid (HF)		g	1.03E-06	g
Methane (CH4)	3.10E-06	g	1.52E-02	g
Nitrogen oxides (NOx)	1.80E-03	g	2.25E-02	g
Nitrous oxide (N2O)	1.55E-05	g	1.17E-04	g
Non-methane HC (NMVOC)	3.10E-05	g	2.72E-03	g
Particles		g	3.41E-04	g
Sulphur oxides (SOx)	0.00E+00	g	3.41E-03	g
Waste generation		g	4.47E-01	g
Hazardous waste		g	4.44E-02	g
Other waste		g	4.03E-01	g

Inventory results HCNG-15 (1)

Functional unit (fu) 1 MJ dispensed HCNG-15

	Natural gas supply		Heat production	
	Amount/fu	Unit	Amount/fu	Unit
Energy use	7.11E-02	MJ		MJ
Renewable energy use	1.79E-04	MJ		MJ
Biomass	0.00E+00	MJ		MJ
Hydropower	1.79E-04	MJ		MJ
Non-renewable energy use	7.09E-02	MJ		MJ
Coal	1.22E-03	MJ		MJ
Crude oil	8.76E-03	MJ		MJ
Natural gas	6.09E-02	MJ		MJ
Emissions to air				
Ammonia (NH3)	0.00E+00	g	0.00E+00	g
Benzene (C6H6)	1.80E-03	g		g
Carbon dioxide (CO2)	4.55E+00	g	2.54E+00	g
Carbon monoxide (CO)		g	4.54E-04	g
Halogenated HC (CFC/HCFC)	0.00E+00	g		g
Halogenated HC (HCFC-22)	5.29E-08	g		g
Hydrochloric acid (HCl)	6.66E-06	g		g
Hydrofluoric acid (HF)	1.06E-06	g		g
Methane (CH4)	1.56E-02	g	4.54E-06	g
Nitrogen oxides (NOx)	2.12E-02	g	2.09E-03	g
Nitrous oxide (N2O)	1.04E-04	g	2.27E-05	g
Non-methane HC (NMVOC)	2.75E-03	g	4.54E-05	g
Particles	3.49E-04	g		g
Sulphur oxides (SOx)	3.49E-03	g	0.00E+00	g
Waste generation	4.58E-01	g		g
Hazardous waste	4.55E-02	g		g
Other waste	4.12E-01	g		g

Inventory results HCNG-15 (2)

Functional unit (fu) 1 MJ dispensed HCNG-15

	Electricity production		Total	
	Amount/fu	Unit	Amount/fu	Unit
Energy use		MJ	7.11E-02	MJ
Renewable energy use		MJ	1.79E-04	MJ
Biomass		MJ	0.00E+00	MJ
Hydropower		MJ	1.79E-04	MJ
Non-renewable energy use		MJ	7.09E-02	MJ
Coal		MJ	1.22E-03	MJ
Crude oil		MJ	8.76E-03	MJ
Natural gas		MJ	6.09E-02	MJ
Emissions to air				
Ammonia (NH3)	0.00E+00	g	0.00E+00	g
Benzene (C6H6)		g	1.80E-03	g
Carbon dioxide (CO2)	3.10E+00	g	1.02E+01	g
Carbon monoxide (CO)	5.54E-04	g	1.01E-03	g
Halogenated HC (CFC/HCFC)		g	0.00E+00	g
Halogenated HC (HCFC-22)		g	5.29E-08	g
Hydrochloric acid (HCl)		g	6.66E-06	g
Hydrofluoric acid (HF)		g	1.06E-06	g
Methane (CH4)	5.54E-06	g	1.56E-02	g
Nitrogen oxides (NOx)	3.21E-03	g	2.65E-02	g
Nitrous oxide (N2O)	2.77E-05	g	1.54E-04	g
Non-methane HC (NMVOC)	5.54E-05	g	2.85E-03	g
Particles		g	3.49E-04	g
Sulphur oxides (SOx)	0.00E+00	g	3.49E-03	g
Waste generation		g	4.58E-01	g
Hazardous waste		g	4.55E-02	g
Other waste		g	4.12E-01	g

Inventory results HCNG-30 (1)

Functional unit (fu) 1 MJ dispensed HCNG-30

	Natural gas supply		Heat production	
	Amount/fu	Unit	Amount/fu	Unit
Energy use	7.32E-02	MJ		MJ
Renewable energy use	1.84E-04	MJ		MJ
Biomass	0.00E+00	MJ		MJ
Hydropower	1.84E-04	MJ		MJ
Non-renewable energy use	7.30E-02	MJ		MJ
Coal	1.25E-03	MJ		MJ
Crude oil	9.02E-03	MJ		MJ
Natural gas	6.27E-02	MJ		MJ
Emissions to air				
Ammonia (NH3)	0.00E+00	g	0.00E+00	g
Benzene (C6H6)	1.85E-03	g		g
Carbon dioxide (CO2)	4.68E+00	g	5.80E+00	g
Carbon monoxide (CO)		g	1.04E-03	g
Halogenated HC (CFC/HCFC)	0.00E+00	g		g
Halogenated HC (HCFC-22)	5.44E-08	g		g
Hydrochloric acid (HCl)	6.86E-06	g		g
Hydrofluoric acid (HF)	1.09E-06	g		g
Methane (CH4)	1.61E-02	g	1.04E-05	g
Nitrogen oxides (NOx)	2.18E-02	g	4.76E-03	g
Nitrous oxide (N2O)	1.07E-04	g	5.18E-05	g
Non-methane HC (NMVOC)	2.83E-03	g	1.04E-04	g
Particles	3.59E-04	g		g
Sulphur oxides (SOx)	3.59E-03	g	0.00E+00	g
Waste generation	4.71E-01	g		g
Hazardous waste	4.68E-02	g		g
Other waste	4.25E-01	g		g

Inventory results HCNG-30 (2)

Functional unit (fu) 1 MJ dispensed HCNG-30

	Electricity production		**Total**	
	Amount/fu	Unit	Amount/fu	Unit
Energy use		MJ	7.32E-02	MJ
Renewable energy use		MJ	1.84E-04	MJ
Biomass		MJ	0.00E+00	MJ
Hydropower		MJ	1.84E-04	MJ
Non-renewable energy use		MJ	7.30E-02	MJ
Coal		MJ	1.25E-03	MJ
Crude oil		MJ	9.02E-03	MJ
Natural gas		MJ	6.27E-02	MJ
Emissions to air				
Ammonia (NH3)	0.00E+00	g	0.00E+00	g
Benzene (C6H6)		g	1.85E-03	g
Carbon dioxide (CO2)	4.85E+00	g	1.53E+01	g
Carbon monoxide (CO)	8.66E-04	g	1.90E-03	g
Halogenated HC (CFC/HCFC)		g	0.00E+00	g
Halogenated HC (HCFC-22)		g	5.44E-08	g
Hydrochloric acid (HCl)		g	6.86E-06	g
Hydrofluoric acid (HF)		g	1.09E-06	g
Methane (CH4)	8.66E-06	g	1.61E-02	g
Nitrogen oxides (NOx)	5.03E-03	g	3.16E-02	g
Nitrous oxide (N2O)	4.33E-05	g	2.02E-04	g
Non-methane HC (NMVOC)	8.66E-05	g	3.02E-03	g
Particles		g	3.59E-04	g
Sulphur oxides (SOx)	0.00E+00	g	3.59E-03	g
Waste generation		g	4.71E-01	g
Hazardous waste		g	4.68E-02	g
Other waste		g	4.25E-01	g

Inventory results hydrogen (1)

Functional unit (fu) 1 MJ dispensed hydrogen

	Natural gas supply		Heat production	
	Amount/fu	Unit	Amount/fu	Unit
Energy use	1.06E-01	MJ		MJ
Renewable energy use	2.66E-04	MJ		MJ
Biomass	0.00E+00	MJ		MJ
Hydropower	2.66E-04	MJ		MJ
Non-renewable energy use	1.05E-01	MJ		MJ
Coal	1.81E-03	MJ		MJ
Crude oil	1.30E-02	MJ		MJ
Natural gas	9.05E-02	MJ		MJ
Emissions to air				
Ammonia (NH3)	0.00E+00	g	0.00E+00	g
Benzene (C6H6)	2.67E-03	g		g
Carbon dioxide (CO2)	6.76E+00	g	5.60E+01	g
Carbon monoxide (CO)		g	1.00E-02	g
Halogenated HC (CFC/HCFC)	0.00E+00	g		g
Halogenated HC (HCFC-22)	7.86E-08	g		g
Hydrochloric acid (HCl)	9.90E-06	g		g
Hydrofluoric acid (HF)	1.57E-06	g		g
Methane (CH4)	2.32E-02	g	1.00E-04	g
Nitrogen oxides (NOx)	3.14E-02	g	4.60E-02	g
Nitrous oxide (N2O)	1.54E-04	g	5.00E-04	g
Non-methane HC (NMVOC)	4.08E-03	g	1.00E-03	g
Particles	5.18E-04	g		g
Sulphur oxides (SOx)	5.18E-03	g	0.00E+00	g
Waste generation	6.80E-01	g		g
Hazardous waste	6.76E-02	g		g
Other waste	6.13E-01	g		g

Inventory results hydrogen (2)

Functional unit (fu) 1 MJ dispensed hydrogen

	Electricity production		Total	
	Amount/fu	Unit	Amount/fu	Unit
Energy use		MJ	1.06E-01	MJ
Renewable energy use		MJ	2.66E-04	MJ
Biomass		MJ	0.00E+00	MJ
Hydropower		MJ	2.66E-04	MJ
Non-renewable energy use		MJ	1.05E-01	MJ
Coal		MJ	1.81E-03	MJ
Crude oil		MJ	1.30E-02	MJ
Natural gas		MJ	9.05E-02	MJ
Emissions to air				
Ammonia (NH3)	0.00E+00	g	0.00E+00	g
Benzene (C6H6)		g	2.67E-03	g
Carbon dioxide (CO2)	3.18E+01	g	9.46E+01	g
Carbon monoxide (CO)	5.68E-03	g	1.57E-02	g
Halogenated HC (CFC/HCFC)		g	0.00E+00	g
Halogenated HC (HCFC-22)		g	7.86E-08	g
Hydrochloric acid (HCl)		g	9.90E-06	g
Hydrofluoric acid (HF)		g	1.57E-06	g
Methane (CH4)	5.68E-05	g	2.33E-02	g
Nitrogen oxides (NOx)	3.29E-02	g	1.10E-01	g
Nitrous oxide (N2O)	2.84E-04	g	9.38E-04	g
Non-methane HC (NMVOC)	5.68E-04	g	5.65E-03	g
Particles		g	5.18E-04	g
Sulphur oxides (SOx)	0.00E+00	g	5.18E-03	g
Waste generation		g	6.80E-01	g
Hazardous waste		g	6.76E-02	g
Other waste		g	6.13E-01	g

D Sensitivity analysis data

This part of the appendix provides data for the sensitivity analysis as well as the presentation of the results discussed in section 5.1. In this context, LCI data for Norwegian and Russian natural gas is taken from Gunnarsson and Skarphagen (1999) recommended by IVL (Uppenberg et al. 2001). Their LCA study deals with future scenarios for an extended Scandinavian natural gas network called the 'Nordic Gas Grid' (NGG). In these scenarios, natural gas either comes from Norwegian oil and gas fields in the North Sea or from gas fields in Western Siberia (Russia). Furthermore, the break-even analyses for the different impact indicators are presented according to section 5.1.

The energy use figures in the following data tables refer to the use of additional energy resources for the supply of natural gas, and do not include the feedstock energy of the supplied natural gas.

Natural gas Norway

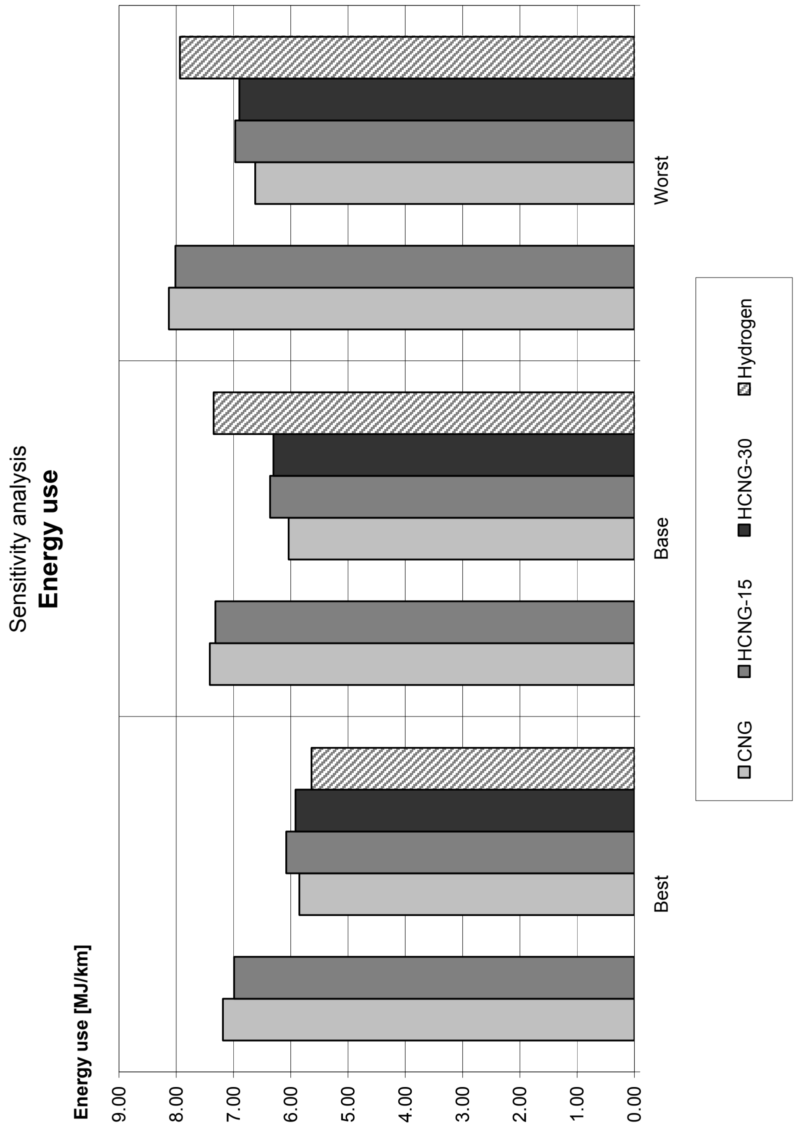
Functional unit (fu)	1 Nm³ processed natural gas
Reference/contact person	Uppenberg et al. (2001) Miljöfaktabok för bränslen IVL Svenska Miljöinstitutet AB Stockholm
Reference year/period	2005
Location	Southern Sweden

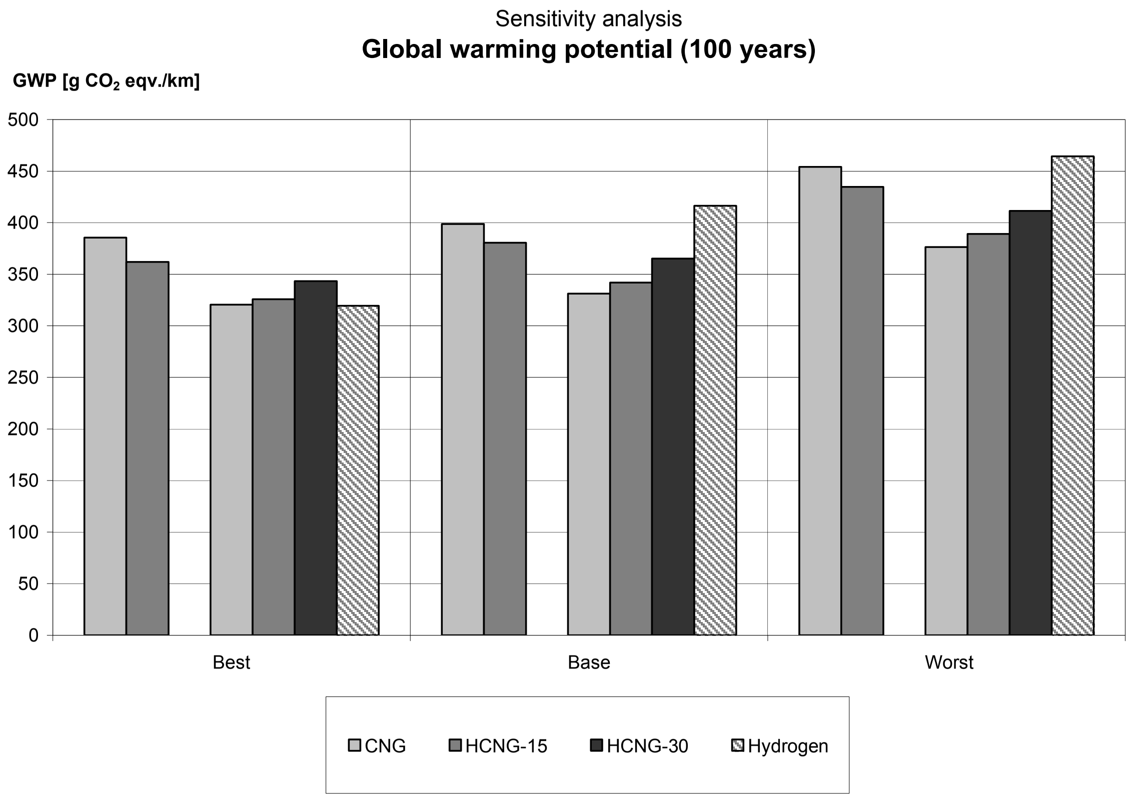
	Amount/fu	Unit
Energy use	1.37E+00	MJ
Renewable energy use	4.28E-02	MJ
Biomass	1.07E-03	MJ
Hydropower	4.18E-02	MJ
Non-renewable energy use	1.32E+00	MJ
Coal	1.14E-02	MJ
Crude oil	8.78E-02	MJ
Natural gas	1.22E+00	MJ
Emissions to air		
Ammonia (NH3)		g
Benzene (C6H6)		g
Carbon dioxide (CO2)	1.04E+02	g
Carbon monoxide (CO)	2.52E-02	g
Halogenated HC (CFC/HCFC)		g
Halogenated HC (HCFC-22)		g
Hydrochloric acid (HCl)	1.68E-04	g
Hydrofluoric acid (HF)		g
Methane (CH4)	8.40E-02	g
Nitrogen oxides (NOx)	1.72E-01	g
Nitrous oxide (N2O)	3.32E-04	g
Non-methane HC (NMVOC)	4.40E-03	g
Particles	6.00E-03	g
Sulphur oxides (SOx)	2.36E-02	g
Waste generation		g
Hazardous waste		g
Other waste		g

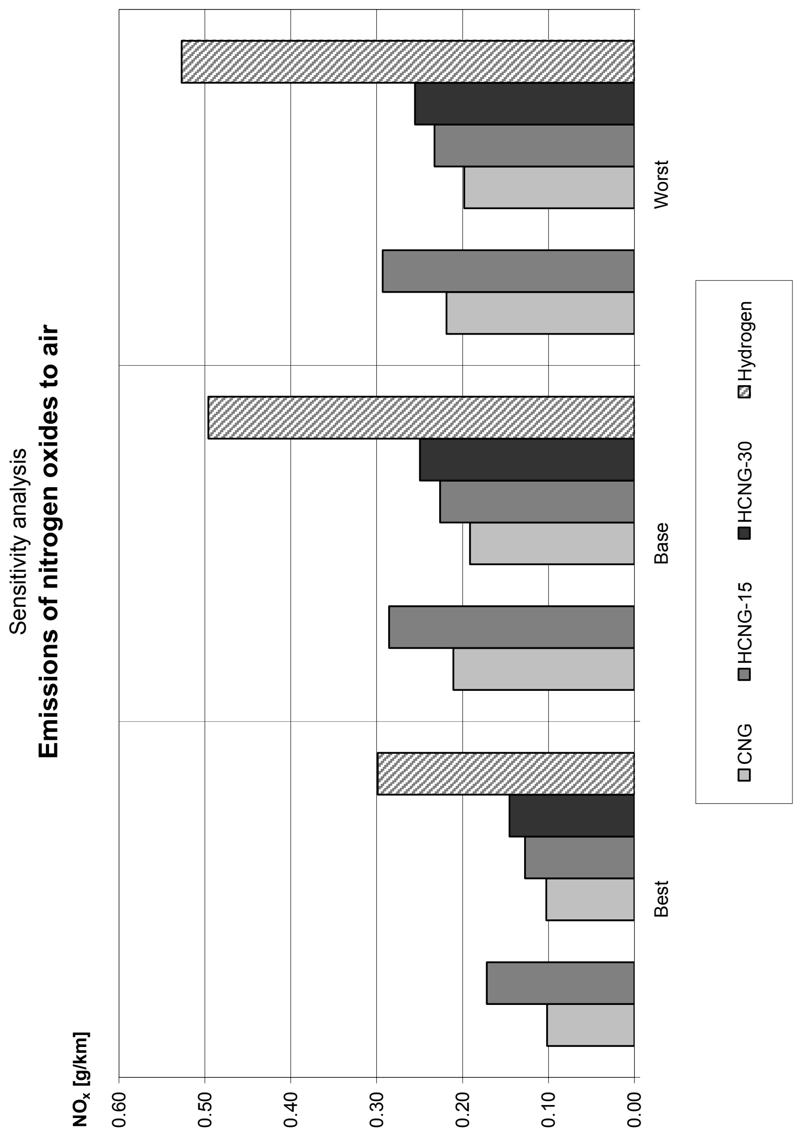
Natural gas Russia

Functional unit (fu)	1 Nm³ processed natural gas
Reference/contact person	Uppenberg et al. (2001) Miljöfaktabok för bränslen IVL Svenska Miljöinstitutet AB Stockholm
Reference year/period	2005
Location	Southern Sweden

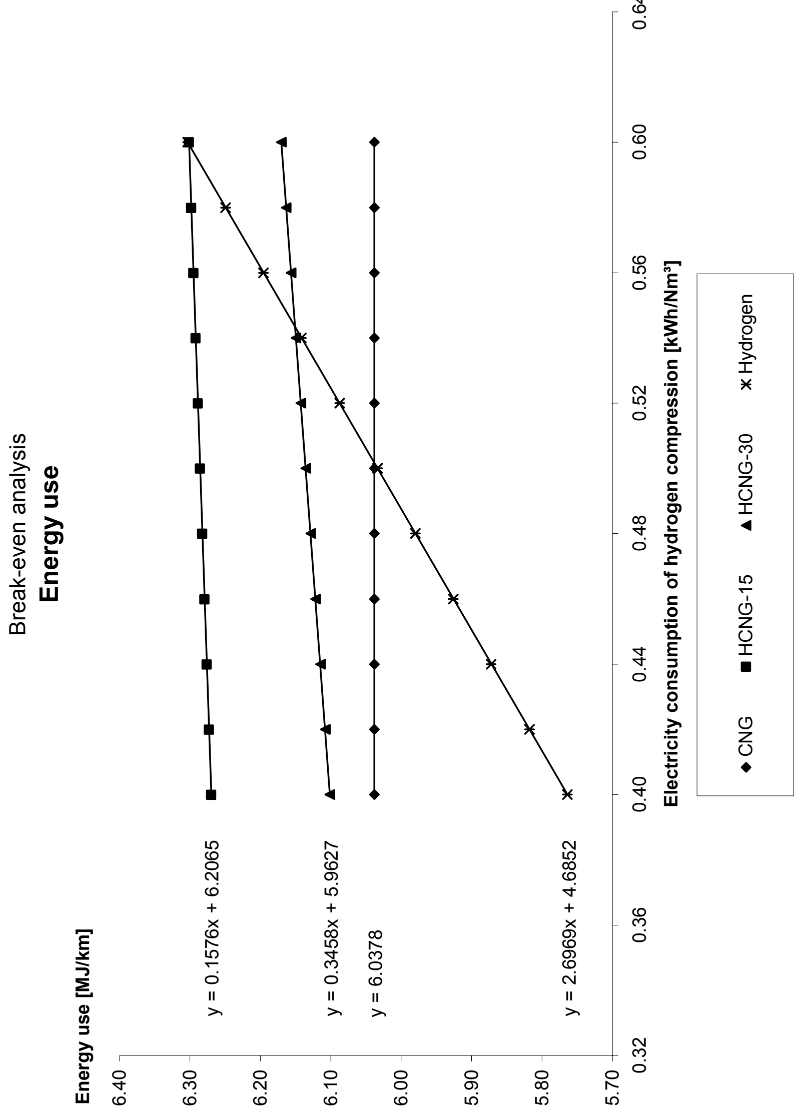
	Amount/fu	Unit
Energy use	6.11E+00	MJ
Renewable energy use	4.78E-03	MJ
Biomass	7.49E-04	MJ
Hydropower	4.03E-03	MJ
Non-renewable energy use	6.11E+00	MJ
Coal	3.74E-03	MJ
Crude oil	2.02E-01	MJ
Natural gas	5.90E+00	MJ
Emissions to air		
Ammonia (NH3)		g
Benzene (C6H6)		g
Carbon dioxide (CO2)	4.08E+02	g
Carbon monoxide (CO)	4.40E-05	g
Halogenated HC (CFC/HCFC)		g
Halogenated HC (HCFC-22)		g
Hydrochloric acid (HCl)	2.08E+00	g
Hydrofluoric acid (HF)		g
Methane (CH4)	2.48E+00	g
Nitrogen oxides (NOx)	3.28E-01	g
Nitrous oxide (N2O)	4.40E-05	g
Non-methane HC (NMVOC)	4.40E-03	g
Particles	6.80E-03	g
Sulphur oxides (SOx)	1.52E-02	g
Waste generation		g
Hazardous waste		g
Other waste		g

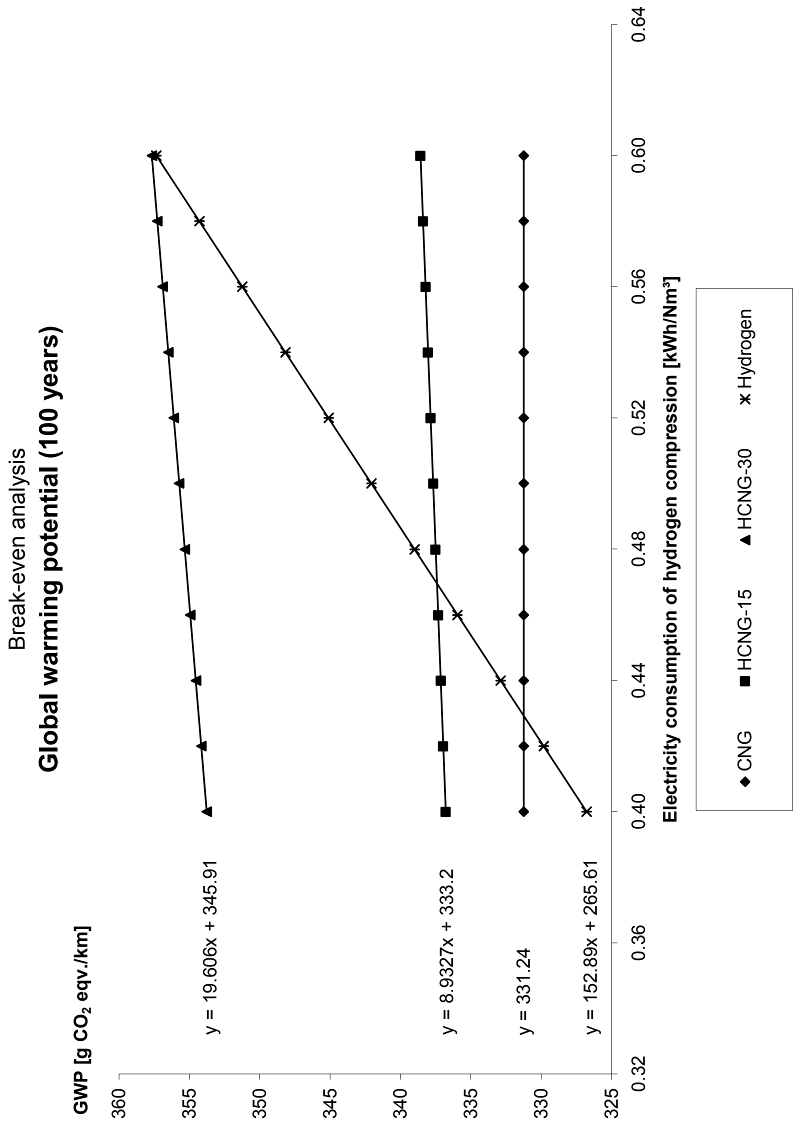

Sensitivity analysis
Energy use
Energy use [MJ/km]
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Best
Base
Worst
CNG
HCNG-15
HCNG-30
Hydrogen

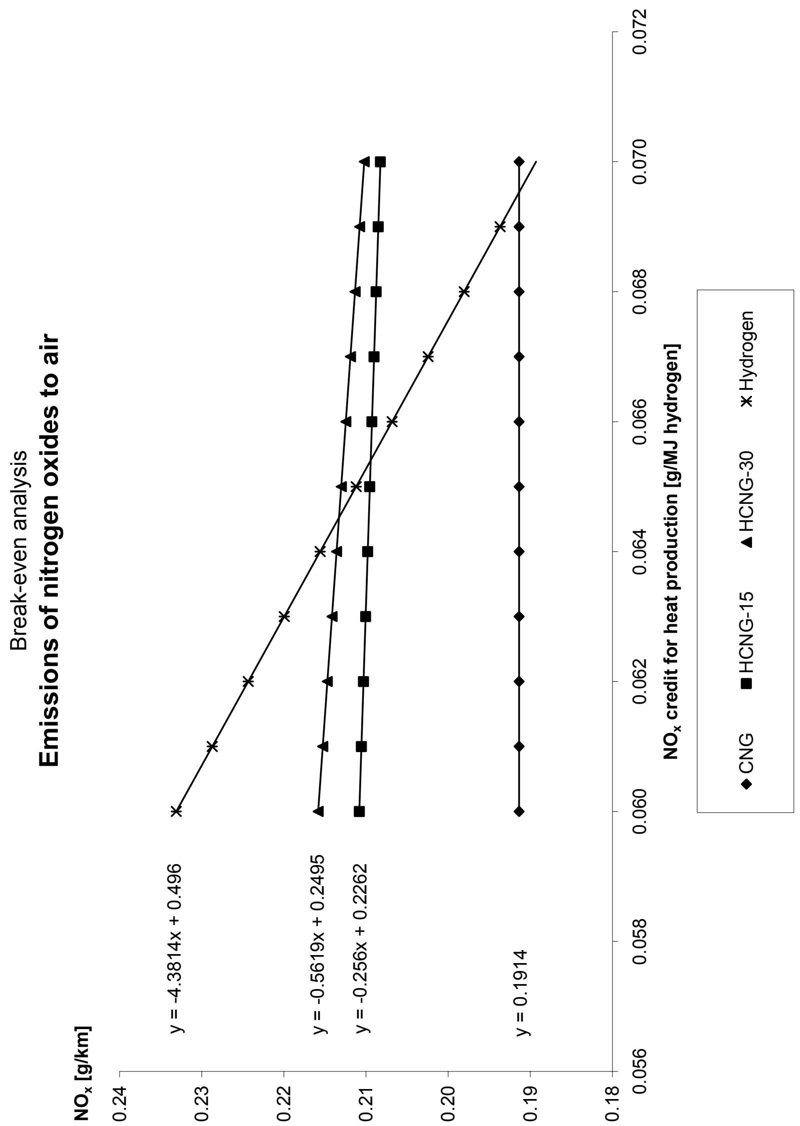

Sensitivity analysis
Global warming potential (100 years)
GWP [g CO2 eqv./km]
500
450
400
350
300
250
200
150
100
50
0
Best
Base
Worst
CNG
HCNG-15
HCNG-30
Hydrogen



Sensitivity analysis
Emissions of nitrogen oxides to air
NOx [g/km]
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Best
Base
Worst
CNG
HCNG-15
HCNG-30
Hydrogen


Break-even analysis
Energy use
Energy use [MJ/km]
6.40
6.30
6.20
6.10
6.00
5.90
5.80
5.70
0.32
0.36
0.40
0.44
0.48
0.52
0.56
0.60
0.64
Electricity consumption of hydrogen compression [kWh/Nm³]
y = 0.1576x + 6.2065
y = 0.3458x + 5.9627
y = 6.0378
y = 2.6969x + 4.6852
CNG
HCNG-15
HCNG-30
Hydrogen


Break-even analysis
Global warming potential (100 years)
GWP [g CO2 eqv./km]
360
355
350
345
340
335
330
325
0.32
0.36
0.40
0.44
0.48
0.52
0.56
0.60
0.64
y = 19.606x + 345.91
y = 8.9327x + 333.2
y = 331.24
y = 152.89x + 265.61
Electricity consumption of hydrogen compression [kWh/Nm³]
CNG
HCNG-15
HCNG-30
Hydrogen


Break-even analysis
Emissions of nitrogen oxides to air
NO_x [g/km]
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0.056
0.058
0.060
0.062
0.064
0.066
0.068
0.070
0.072
NO_x credit for heat production [g/MJ hydrogen]
y = -4.3814x + 0.496
y = -0.5619x + 0.2495
y = -0.256x + 0.2262
y = 0.1914
CNG
HCNG-15
HCNG-30
Hydrogen