PATHWAYS FOR NATURAL GAS INTO ADVANCED VEHICLES

Part A: Technology and Fuels for New Generation Vehicles

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PART B: EXAMPLES OF NEW GENERATION VEHICLES

ABSTRACT

We are entering an era when vehicle technology is going to be diversified. We are facing developments that include improved internal combustion engines, hybrid power trains and fuel cell vehicles, and the fuel spectrum is predicted to grow broader. Energy security, diversification of sources and sustainability are issues discussed as they relate to various fuel alternatives.

With today's knowledge, the first fuel cell vehicles will be equipped with PEM fuel cell stacks that operate on hydrogen. Hydrogen can be generated either outside the vehicle or on-board the vehicle. There are several fuel options competing to be the preferred fuel for fuel cell vehicles: sulphur-free gasoline type hydrocarbons, methanol and hydrogen - either gaseous or liquid.

It will take years for FC vehicles to really penetrate the market. Meanwhile, we will still be running vehicles equipped with internal combustion engines. Emissions have to be controlled, and therefore practically sulphur-free fuels will be needed. Here the use of natural gas will make a strong point, both regarding possibilities for emission reductions and energy diversification. Thus natural gas has found its way, for example, into the transportation energy scenarios of the European Commission for the year 2020.

Natural gas will also play a significant role in supplying energy to fuel cell vehicles. Today, the greater part of hydrogen for industrial purposes is produced from natural gas by steam reforming. For energy purposes, hydrogen could be produced from natural gas in both centralised and decentralised systems. Centralised production would even make it possible to remove CO_2 by sequestration. It is doubtful with today's technology if it is possible to combine natural gas storage on-board the vehicle with on-board reforming for fuel cell vehicles due to weight and space constraints. If it were possible, it would be a tremendous opportunity to utilise the existing CNG or LNG refuelling network.

This report or "Position Paper", which has been prepared within the IANGV Technical Committee, is a status report on vehicle propulsion and fuel technologies. It strives to answer the question as to how natural gas can make a contribution to fuelling the vehicles of the future.

The report, which was completed in April 2002, covers, among other things, advances in engine, propulsion and fuel technologies, fuel options, fuel cell technology, hydrogen production and handling and system level efficiencies and emissions. The newest data in the report dates from February 2002. Development in the fuel cell sector is so fast that some information becomes outdated very rapidly. The report does not deal with economic aspects of different fuel and propulsion options.

PREFACE

The IANGV Technical Committee was reorganised at the NGV2000 Conference, held in Yokohama, Japan in October 2000. The Committee is now chaired by Dr. Nils-Olof Nylund of VTT, Finland. Vice Chairman is Alex Lawson of Alex Lawson Associates Inc., Canada. The Committee has decided to focus upon just a few topical items. These items are:

Engines and emissions;
Pathways to hydrogen;
Cylinder handling; and
Fuel composition/quality.

The need for a study on pathways to hydrogen was much emphasised. The content of the study was discussed at an ad-hoc Technical Committee meeting conjunction with the ENGVA Annual European NGV Conference in Malmö, May 2001, and at the regular IANGV TC meeting in San Francisco, October 2001.

The report at hand, “Pathways for natural gas into advanced vehicles”, has a slightly broader scope than just fuel cell vehicles and their fuels. It is seen that natural gas can make a significant contribution to transportation energy, both in vehicles equipped with internal combustion engines and in future fuel cell vehicles.

The report was compiled by a team at VTT Processes (formerly VTT Energy) consisting of Dr. Nils-Olof Nylund, Dr. Juhani Laurikko and Mr. Markku Ikonen. It is a snapshot of a very dynamic situation regarding development in engines, fuels, propulsion systems and fuel cells. Dr. Alex Lawson contributed significantly with ideas to the report. Dr. Jeffrey Seisler and Dr. Garth Harris served as principal reviewers of the report. Mr. John Stephenson reviewed the report for language.

The IANGV wishes to extend its gratitude to all people who have contributed to this IANGV report.

Jeffrey Seisler
President, IANGV

SUMMARY

The aim of the report is to look to increasing the availability of energy for transport and to improving the efficiency with which it can be supplied and used.

It has been prepared within the IANGV Technical Committee, and is a status report on developments in engine, propulsion and fuel technologies. It emphasises advanced vehicles and fuel options for advanced vehicles, including fuel cell (FC) vehicles. It also touches upon hydrogen production and handling and system level efficiencies and emissions of different fuel alternatives.

The world vehicle population and transportation demand is steadily increasing. Today's surface transportation is heavily dependent on oil. This situation can be alleviated by technologies to increase vehicle efficiency and also by the introduction of alternative fuels.

During the energy crises of the 70's alternative fuels were discussed from an energy security point of view. Then came the reduction of harmful emissions and greenhouse gas emissions. For the future, new vehicle technologies like FC vehicles will bring new fuels to the market. Regulated emissions will be controlled by advanced engine and after-treatment technologies, while the issues of energy security and greenhouse gas emissions will remain.

At this writing, the European Commission is discussing a new biofuels directive, which would mandate a certain share of biofuels in the transportation sector. Included in the proposal is also a target that natural gas and hydrogen should account for certain shares of transportation energy. The figures proposed for 2020 are biofuels 8 %, natural gas 10 % and hydrogen 5 %. Both the introduction of alternative fuels and improvements in propulsion technologies are estimated to have a potential for changes in the order of 20 % in transportation fuel use by 2020. It is generally believed that hybridisation and introduction of fuel cell technology will improve vehicle efficiency.

Emission regulations are becoming increasingly stringent. This requires the engine and vehicle manufacturers to introduce new and more efficient exhaust after-treatment systems. The new catalyst technologies again require practically sulphur free fuels. To promote the introduction of sulphur free fuels, Germany will introduce a tax incentive for 10 ppm (parts per million) sulphur fuels in 2003. Within the European Union, full market penetration of 10 ppm sulphur fuels is expected by 2011.

Natural gas typically contains 1-2 ppm sulphur. However, the sulphur based odorants commonly used in natural gas bring sulphur content close to 10 ppm. Therefore, attention must be given to the development of sulphur free odorants. In addition, the general specifications for natural gas quality in vehicles should be checked to ensure correspondence with the development of the sulphur content of liquid transportation fuels.

Vehicles powered by internal combustion engines have not yet reached the end of the line. There is still potential for both emission reductions and improvements in engine efficiency. New engine features are, among others, variable valve timing, direct injection, variable compression ratio, new catalysts, increased electrical voltage and sophisticated OBD (on-board diagnostics) systems. In the case of spark-ignition (SI) engines, the emphasis of future activities will be on improvements in efficiency.

As for diesel, most of the work will focus on emission reduction (particulates, nitrogen oxides). The great improvements in engine performance, especially the reductions in exhaust emissions, have been possible by replacing simple mechanical control systems with electronics. This applies both for gasoline and diesel engines. For natural gas engines, especially for heavy-duty services, development of direct injection fuel systems and improved engine efficiency should be emphasised.

One of the basic problems with SI engines is that engine efficiency depends very much on engine load. Light-duty vehicle engines are in general operated on very low average loads, which result in low efficiency.

A hybrid vehicle combines two power sources, in most cases an internal combustion engine (ICE) and an electric motor. A hybrid system allows the ICE to operate on favourable loads for improved fuel economy. The electric system will boost performance when needed, and also in some case regenerate braking energy. There are several different levels of hybridisation, from minimal hybrids with an integrated starter-generator for boosting accelerations to full serial hybrid vehicles with electric propulsion motors.

Lack of space and the heavy weight of a "full" hybrid vehicle make the use of natural gas in these vehicles somewhat problematic, since the natural gas containers are larger and heavier than liquid fuel tanks. In this respect, the most likely use for natural gas among hybrid vehicles would be in those vehicles that are bigger than passenger cars. In the case of a minimal hybrid vehicle with an ISG (Integrated Starter/Generator) system, natural gas would work well, since there is no need for very large additional technical devices on-board the vehicle. Because minimal hybrids seem to be an option for the near future, natural gas would have potential for hybrid vehicles, at least in the short term.

A fuel cell (FC) is an electrochemical device in which hydrogen combines with oxygen to produce electrical energy without any moving parts. Direct methane and methanol FCs are under development. Fuel cells are promoted for automotive applications for several reasons. One of the main advantages of a fuel cell is that the efficiency of the fuel cell itself is rather independent of load. The efficiency of the total fuel cell system including auxiliaries varies somewhat with power, nevertheless the FC system gives a clear advantage over SI ICEs at low loads. This means that FC technology has an inherent hybridisation effect, which can be amplified using a combination of FC and batteries. Basically a FC vehicle is an electric vehicle with electric motors for propulsion with the FC acting as a range extender.

Automotive fuel cells operate at low temperature, and are practically emission free. PEM (proton exchange membrane) -type fuel stacks operate on hydrogen. FC vehicles fuelled with pure hydrogen provide the possibility of creating a transportation system that does not generate CO_2 emissions. The ultimate goal is the use of hydrogen from renewable energy sources.

The question of fuel is one of the most important ones in bringing FC vehicles with PEM stacks on the market. A commercial infrastructure for hydrogen production and distribution does not yet exist. Apart from the associated cost of building a new infrastructure, widespread public distribution of hydrogen also presents some technical difficulties. Gaseous hydrogen has very low energy density in storage, liquefied hydrogen in turn requires very low temperatures.

However, some of the automotive manufacturers have stated that they will launch FC vehicles in 2003 or 2004. This means that these vehicles will have to rely on other fuels than hydrogen, or as one option, hydrogen produced locally. If any other fuel than hydrogen is used, then the fuel will have to be processed into hydrogen, either on-site at the refuelling station or on-board in the vehicle. Many of the automotive companies involved have built FC demonstration vehicles that include on-board fuel processors.

The most important processes for hydrogen production from hydrocarbons, using the chemical route, are steam reforming (STM) and partial oxidation (POX) in combination with water gas shift (WGS). These processes can also be used in on-board automotive applications. Top-of-the-line fuels at this moment for on-board reforming are methanol and gasoline, although commercial gasoline grades of today might not be suitable due to too high a sulphur content. Other fuels discussed in this context are ethanol, DME (di-methyl-ether) and for obvious reasons also natural gas. Looking just at the ease of on-board reforming, methanol seems to be the preferred fuel.

Today approximately 500 billion Nm^3 of hydrogen is traded world wide. The vast majority of this volume originates from fossil fuel sources, mainly natural gas, or as a by-product in the chemical industry or from crude oil refining processes. The production of hydrogen as by-product accounts for 190 billion Nm^3 world-wide (38 %), of which about 2 % or 10 billion Nm^3 stems from chlorine-alkaline electrolysis.

Natural gas will play a significant role in fuelling FC vehicles. This could be accomplished mainly through on-site or centralised production of hydrogen from natural gas. Centralised systems would make it possible to remove CO_2 by sequestration, thus creating a carbon-free fuel cycle. Some areas in the world have an extensive natural gas pipeline network both for household and industrial purposes. The number of NG refuelling stations is also increasing steadily. Relatively small on-site reformers could conveniently be placed at NG refuelling stations or other locations alongside the natural gas pipeline network. The equipment to refuel gaseous hydrogen is in principle similar to equipment used for compressed natural gas.

In theory, it could be possible to use methane also for on-board reformer equipped FC vehicles. The great advantage of this would be that the existing CNG (or LNG) refuelling network could be used to fuel FC vehicles. The sulphur level of most natural gas qualities is so low that they would be suitable for on-board reforming. However, at this stage of reformer and FC technology, a combination of natural gas storage, reformer and fuel cell stack, seems to be a troublesome combination regarding both weight and space requirements for light-duty vehicles, which in this respect are more critical than for example buses. On-board reforming of natural gas is perhaps something that the natural gas industry should try to promote.

Methane (natural gas) is a highly versatile light hydrocarbon that can be utilised as such or as feedstock to different processes to make other products that can be used as fuels and energy sources in the transport sector. Natural gas can also provide energy (both heat and electricity) to be used in fuel processing. Thus there are many pathways for natural gas into transportation energy.

When evaluating different fuels and fuel pathways one has to take into account many aspects:

- adequacy of fuel supply
- location of fuel source
- process efficiency
- ease of transport and storage
- modifications needed in the distribution/refuelling network
- modifications needed in the vehicles
- fuel effects on vehicle performance (power, emissions, ease of use)
- life cycle energy consumption and emissions, including greenhouse gas emissions.

No single fuel can meet all requirements in an optimal way. That is why we probably will have in the future a variety of different fuel options.

Hydrogen produced from natural gas is commonly used for upgrading conventional fuel qualities, mainly diesel fuel. Hydrogenation of a fuel just to increase the heat content is an energy consuming and CO_2 adding process, even if the hydrogen is generated from natural gas. Therefore such a process should always result in an improvement in the fuel quality for better end-use efficiency in the engine, or for reduced emissions.

Methane can, using the synthesis gas route, be converted into an array of different products. Methanol from natural gas is a commodity chemical used widely in the chemical industry. The interest in methanol as a fuel for ICE engines has somewhat faded, but as mentioned earlier, methanol is a viable fuel for on-board reforming. Synthetic Fischer-Tropsch diesel is highly interesting. This fuel, which fits into existing refuelling systems and vehicles, has superior performance compared to conventional diesel fuel.

Processing natural gas into fuels like methanol and FT diesel requires energy. The synfuel pathways require more energy than gasoline, diesel, CNG and even LNG. The synfuel routes however, like LNG, make it possible to utilise isolated NG resources and to transport NG based fuels in liquid form.

It is interesting to study well-to-wheel efficiencies for different fuel pathways. Such an assessment is typically divided into two parts: well-to-tank (WTT) and tank-to-wheel (TTW). The first part, WTT, bringing the fuel into the fuel tank is fuel specific. The latter, TTW, depends mainly on the propulsion system used. When energy use over the whole fuel chain is known, it is relatively easy to estimate CO_2 emissions using fuel specific emission factors. This applies for fossil fuel pathways. If the fuel chain contains renewable energy or CO_2 sequestration, this will of course affect the total balance.

Most of the well-to-wheel (WTW) energy figures used in the study at hand were taken from a recent Swedish study by Ecotraffic ERD[3]. These figures, however, were compared to other studies and are commented upon. The following statements are based on the Ecotraffic ERD[3] study.

WTT efficiency for conventional liquid fuels range from 83-88 %, diesel being better than gasoline. CNG and LNG both fall within that same range, CNG being closest to diesel. All other options have a lower efficiency. Of the synfuel alternatives, methanol and DME have the highest efficiency, some 67 %. FT diesel, which in terms of distribution and end-use would be an easy alternative, has an efficiency of some 55 %. Efficiency of natural gas to gaseous hydrogen is 61 %.

If hydrogen were produced by electrolysis from electricity generated from natural gas, efficiency would be only 37 %. Using on-site electrolysis would also unduly transfer electrical load to the outer edges of the grid rather than putting it closer to the electricity production sites.

There are also great variations in powerplant efficiencies. Powerplant efficiency for SI ICEs is estimated at 12 %, compression ignition (CI) ICEs at 18 % and FC at 23 %. If a reformer is needed, reformer efficiency has to be taken into consideration. This is estimated at 78 % for hydrocarbons and 86 % for methanol.

The efficiency benefits that can be gained by hybridisation vary with propulsion technology (and in reality, also with actual duty cycles). The hybridisation benefit is biggest for spark-ignition ICEs, +23 %, and somewhat smaller, 20 % for CI ICEs and only 4 % for FC vehicles. The most recent FC vehicles are designed with fast-reacting stacks so they can manage without batteries as an energy buffer.

The outcome is that without hybridisation, CI ICE on conventional diesel fuel is the most energy efficient alternative (15.5 %), closely followed by natural gas (CNG or LNG) used on a FC vehicle with on-board reformer. Conventional gasoline is ranked 8th (12.4 %) preceded by FC on gasoline, FC on gaseous hydrogen, FC on methanol and direct use of CNG in SI ICEs.

Hybridisation changes the situation somewhat. CI ICE is still first (18.6 %), followed closely by natural gas in SI ICE or FC applications. All "direct" natural gas pathways (CNG or LNG either in SI ICE or on-board reformer FC) have efficiencies in the range of 15.5-16 %. Gasoline in ICE will move up two positions to 6th, whereas gasoline for FC will fall back from 4th to 7th. With hybridisation, methanol FC will fall also back. All these figures are based on WTW efficiencies.

A further alternative, direct injection of natural gas for ICEs was evaluated. If diesel-like engine efficiency could be achieved, this alternative would be as efficient as diesel.

The outcome is that natural gas pathways, involving either direct use in ICEs or hydrogen from natural gas (on-board or on-site) are quite efficient. Using an intermediate liquid phase will reduce overall efficiency. However, one has to keep in mind that overall efficiency is not the only criterion when choosing between fuel alternatives. There are numerous other parameters that have to be taken into consideration.

When looking at the route natural gas to electricity to hydrogen, the total WTW efficiency of this path is, however, quite poor. Natural gas fired powerplants reach production efficiencies between 35 % to 60 %, and combined with other upstream losses the throughput of energy as electrical energy to a site is in the order of 30 % to 50 %. When the literature quotes for the electrolysis processes efficiencies ranging from 60 % (small, local) to 76 % (large, central) the total fuel production efficiency would be between 20 % and 40 %; this is considerably less than in the case of hydrogen reformed from natural gas. All total WTW efficiencies for this case are below 10 %, being the lowest in all the optional pathways considered.

Greenhouse gas (GHG) emissions from all these optional fuel/engine combinations discussed can be obtained, if the total energy consumption of the given pathway is first calculated. The carbon content of the feedstock (crude, natural gas) is then used to evaluate the total CO_2 emissions. This will further enhance the attractiveness of natural gas, as the specific CO_2 emission per unit of energy for methane is some 25 % lower than for oil.

However, if natural gas is used in ICEs, some emissions of methane will occur, even if catalytic converters are used, as methane is the most difficult of all hydrocarbons to oxidise. Furthermore, if an ICE is used, exhaust gases usually contain nitrous oxide, which also is a powerful GHG.

When a fuel cell powerplant is used, apart from CO_2 no other GHG emissions are generated if the hydrogen is produced in central, large-scale plants. Centralised production of hydrogen would also enable the capture of CO_2, if necessary. Furthermore, if an on-board fuel reformer is used, some local emissions are generated, but usually only at trace level.

However, if electrolysis is used to produce hydrogen, some new elements must be considered. Should the electricity be produced using hydro or nuclear power, it can yield to a totally carbon-free fuel chain. The same effect can in principle be achieved, if renewable biomass is used as feedstock or fuel.

Taking into account the tremendous progress in exhaust after-treatment, no alternative - with the exception of conventional diesel without after-treatment - can be ruled out on the basis of toxic exhaust emissions. Both gasoline and natural gas using proper technology qualify for super ultra low emissions (SULEV). It can be debated if zero emissions from a hydrogen fuelled FC vehicle is much better than close to zero emissions from a ICE vehicle with advanced catalyst systems.

Both for advanced and less advanced SI ICEs natural gas is a high quality, practically sulphur free fuel. In less advanced engines, switching from poor quality gasoline to natural gas will improve emission performance both in quantitative and qualitative ways.

The industry leader in PEM FC stack development is Ballard Power Systems (BPS, Vancouver, B.C.). It began the R&D to build FC systems targeted mainly for transportation applications as eraly as the 1980's. The development of fuel cell power plant for automotive use is quite active, and many major automotive OEM's have already announced their plans to produce such vehicles in the near future. DaimlerChrysler stated that FC vehicles could be series produced and put on road in 2004. As Ford is strongly allied with DC and BPS, their plans are closely aligned. Furthermore, Toyota has recently announced that it has plans to produce 30 to 50 hydrogen-fuelled vehicles, based on their FCHV-4 prototype, as early as 2003. A similar schedule, but without any information as to vehicle numbers, has also been released by Honda.

However, these are only starting points, where cars placed in the hands of some "qualified customers" will take part in demonstrations and field tests. It is expected that higher production volumes of such vehicles will allow them to enter normal circulation from 2010 onwards. Some experts see that it would be close to year 2025 before FC could seriously challenge ICE as the prime mover in automobiles, although in other vehicles and applications this could happen much sooner.

One could try to draw some parallels to the market penetration of natural gas vehicles. Even though natural gas vehicles and refuelling technology is mature compared to FC vehicles, the number of refuelling stations and vehicles is increasing relatively slowly. FC vehicles will most probably have to rely on yet another refuelling network to be built, and this will no doubt make the process slow. Progress could be hastened if on-board reforming of natural gas were applicable, as the natural gas refuelling network then could be used to serve both ICE and FC vehicles.

GLOSSARY OF ABBREVIATIONS

AFC	alkaline fuel cell
AFR	air to fuel ratio
APU	auxiliary power unit
ATR	autothermal reformer
CARB	California Air Resources Board
CI(-ICE)	compression ignition (-internal combustion engine)
CIDI	compression ignition, direct injection
CNG	compressed natural gas
CPO	catalytic partial oxidation
DISI	direct injection, spark ignition
DME	di-methyl-ether
DMFC	direct methanol fuel cell
DOHC	double overhead cam
EA	extended autonomy
ECD	energy conversion device
EGR	exhaust gas recirculation
EIHP	European Integrated Hydrogen Project
EM	electric motor
EOBD	European on-board diagnostics
ETM	electric traction motor
FC	fuel cell (fuel consumption)
FCV	fuel cell vehicle
FFV	fuel flexible vehicle
FT	Fischer-Tropsch
GHG	greenhouse gas
GRPE	Working Party on Pollution and Energy
GTR	global technical regulations
HCCI	homogeneous charge compression ignition
ICE	inernal combustion engine
ILEV	inherently low emissions vehicle
IMA	integrated motor assist
ISG	integrated starter generator
LEV	low emisisons vehicle
LNG	liquefied natural gas
MCFC	molten carbonate fuel cell
MIL	malfunction indicator light
MPI	multi-point (fuel) injection
MTG	methanol to gasoline
NG	natural gas
NGV	natural gas vehicle
NiMH	nickel metal hydride
NMHC	non-methane hydrocarbons
OBD	on-board diagnostics
OEM	original equipment manufacturer
PAFC	phosphoric acid fuel cell
PEM	polymer electrolyte membrane
PM	particulate matter
PNGV	Partnership for New Generation Vehicles
POX	partial oxidation
PrOX	preferential oxidation

P-ZEV	partial-credit zero emissions vehicle
RFD	reformulated (low sulphur) diesel
RME	rape seed methyl ester
RVP	Reid vapour pressure
SI(-ICE)	spark ignition (internal combustion engine)
SOFC	solid oxide fuel cell
STM	steam reforming
SULEV	super ultra low emissions vehicle
TC	Technical Committee
THT	tetrahydrothiofen
TTW	tank to wheel
ULEV	ultra-low emissions vehicle
WGS	water gas shift
WTT	well to tank
WTW	well to wheel
WWFC	World-Wide Fuel Charter
ZEV	zero emissions vehicle

1. Introduction

The world vehicle population is steadily increasing. This also means an increase in the need for transport fuels and, especially in less developed markets, an increase in toxic vehicle emissions. Increasing CO_2 emissions is a global problem.

Petroleum based fuels are a limited resource. There is a wide variation in the estimates as to how large the oil reserves are and when oil production will reach its peak. Figure 1.1 shows a typical prediction on future world energy consumption /1.1/. In this case oil production is estimated to peak around 2020-2030. In the foreseeable future an increase in the price of oil products can be expected. This is partly due to the fact that the quality requirements on transport fuels are constantly increasing /1.2,1.3/.

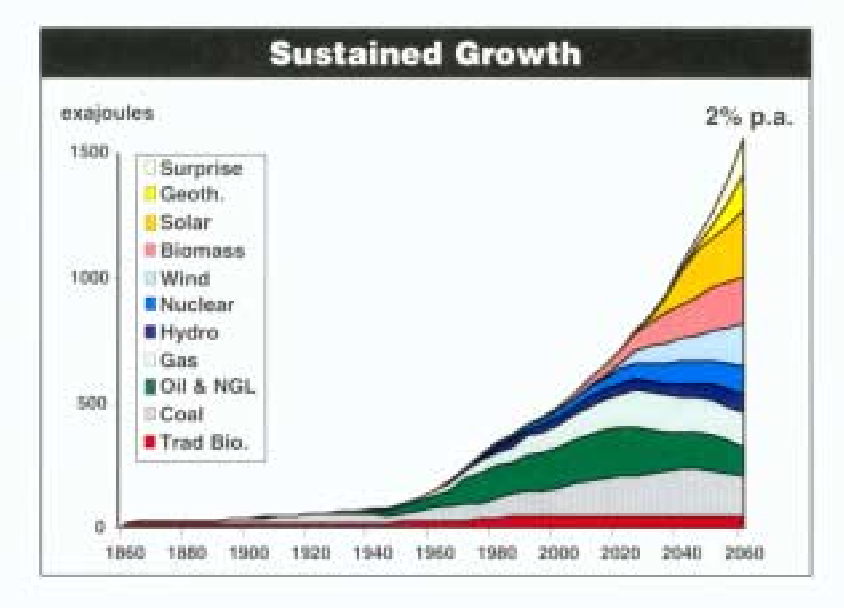

Figure 1.1. Energy scenario by Shell International /1.1/.

Dependence on petroleum based transport fuels can be alleviated by technologies to increase vehicle energy efficiency and also by the introduction of alternative fuels. Alternative propulsion and fuel technologies may also be promoted as a way to reduce emissions, both harmful poisonous emissions and/or greenhouse gas emissions. Figure 1.2 shows an estimate of the development of world CO_2 emissions based on International Energy Agency figures /1.4,1.5/. The international process to limit CO_2 emissions has been rather slow. However, limitations on CO_2 emissions are going to be introduced, based both on compulsory and voluntary agreements. The transport sector has to carry its share of the burden. One example of a voluntary agreement to reduce CO_2 emissions is the agreement between the European automotive manufacturers ACEA and the European Commission to limit the average new passenger car CO_2 emissions to 140 g/km by the year 2008 /1.6/.

Traditionally the vehicle market has been more or less totally dominated by conventional gasoline and diesel fuelled vehicles. Modern electronics and catalyst technology have brought down the emission levels of new gasoline vehicles close to zero, at least in a historic perspective /1.7/. The diesel engine, on the other hand, is still unbeatable regarding energy conversion efficiency. Furthermore, its exhaust after-treatment is rapidly advancing, and will soon bring it close to gasoline vehicle levels in terms of toxic exhaust emissions.

Different kinds of hybrid vehicles and also fuel cell vehicles running on hydrogen have been brought forward as options for the future /1.8,1.9/. We are most certainly going to see a strong evolution in both vehicle and propulsion technology in the near future and an increase in technology options /1.4/.

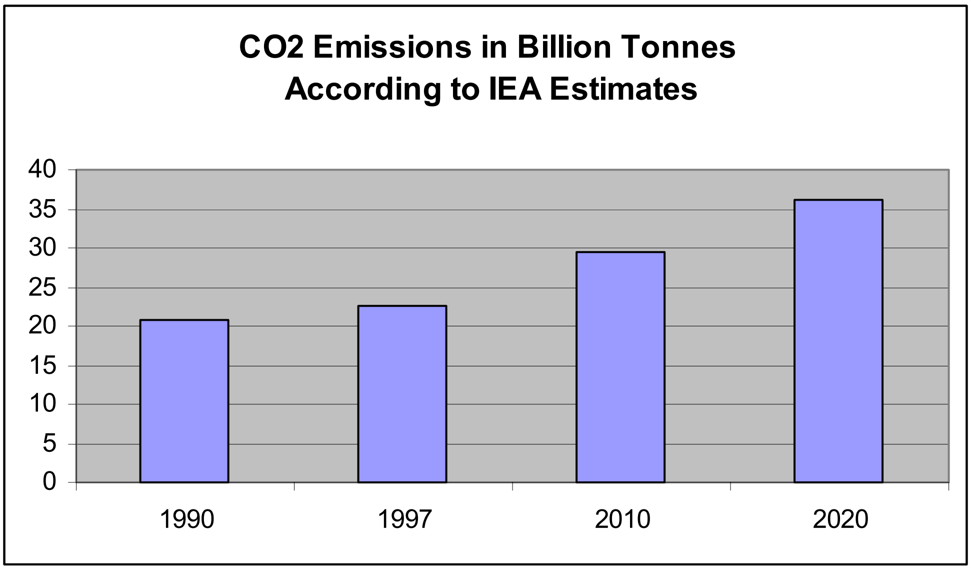

Figure 1.2. Estimate of the development of world CO_2 emissions based on International Energy Agency figures /1.4,1.5/.

The question raised from the natural gas industry is how natural gas can position itself as a transport fuel or energy source in the future.

Natural gas has many advantages as a transport fuel /1.10/. Therefore, it is estimated that natural gas will make a significant contribution to the energy mix for decades to come (Figure 1). Of all fossil fuels natural gas (methane) has the highest hydrogen to carbon ratio. This means that substituting gasoline for natural gas reduces overall CO_2 emissions by some 25 %. A high hydrogen/carbon ratio is also advantageous when producing hydrogen through reforming. Methane can also be produced from renewable sources, i.e. by cleaning up biogas from digesters and waste-water treatment plants.

New technologies such as direct injection of natural gas are emerging for heavy-duty engines, and this will result in CO_2 emission benefits when replacing diesel with natural gas in heavy-duty vehicles /1.11/.

All sophisticated vehicles equipped with spark-ignition engines rely on exhaust gas after-treatment for low emissions. Exhaust catalysts require lead-free fuel. New catalyst technologies like NO_x storage catalysts for lean-burn engines also require practically sulphur free fuel /1.12/. Methane being both unleaded and sulphur free with high octane rating is in many aspects an ideal fuel for spark-ignition engines.

Clean burning natural gas gives the highest relative reductions in regulated emissions in engines with no or less sophisticated exhaust after-treatment. This aspect is very important in developing markets with a high demand on transport fuel. Independent of vehicle technology, natural gas gives the lowest exhaust toxicity and exhaust reactivity.

Hydrogen has often been mentioned as the fuel for the future /1.13,1.14/. In principle, hydrogen can contribute to energy systems totally free of carbon and CO_2 emissions. Burning hydrogen results in formation of water only. However, hydrogen cannot be found as such in nature, and is therefore to be considered more as an energy carrier than an energy source. Hydrogen can be produced by electrolysis from water or by chemical processing of hydrocarbons, alcohols and biomass. The future primary energy source of the hydrogen will determine the total CO_2 effects. If hydrogen is produced using renewable sources (hydropower, wind, solar, biomass) or nuclear power, then the hydrogen cycle will be CO_2 neutral.

Much attention has been given to fuel cell (FC) vehicles fuelled with hydrogen. Fuel cell vehicles are claimed to have negligible emissions, high efficiency and low CO_2 emissions. Even internal combustion engines, if modified properly, can be operated on hydrogen.

The fuel cell stack itself operates on pure hydrogen. The efficiency of hydrogen conversion into electric energy is high, in the order of 60-70 % /1.15/. When operating on fuels other than hydrogen, i.e. hydrocarbons or alcohols, a fuel processor (reformer) is needed to extract the hydrogen. Basically the energy bound to the carbon part of the fuel is used as process heat or wasted, resulting in CO_2 emissions. The reforming can take place either on-site or on-board.

Starting from a fossil fuel (oil, natural gas), the overall efficiency of a FC vehicle is reduced considerably compared to the figures for the fuel cell stack alone. Total CO_2 emissions will be in same order of magnitude as for conventional diesel vehicles and higher compared to a diesel-hybrid vehicle /1.16/. If FC vehicles are going to make a major impact on the reduction of CO_2 emissions in the future, then the primary energy for hydrogen production must be a renewable source or nuclear energy.

The fuel question for FC vehicles is at the moment a contentious issue. Handling and storing hydrogen presents considerable technical difficulties. Hydrogen can be stored in compressed or liquefied form or bound into metal hydrides or carbon fibers. It is predicted that the use of compressed hydrogen will be limited to fleet operations. Transportation of gaseous hydrogen over long distances is not practical. At least for public operations, using hydrocarbons or alcohols as fuel would be an easier way to handle refuelling. This route, however, requires on-board reforming to hydrogen, which in turn lowers the total system efficiency.

Natural gas can play a significant role in fuelling future FC vehicles. Methanol, which is one of the preferred fuels for FC vehicles, is today produced from natural gas. Due to fuel chemistry, reforming of natural gas is more efficient than reforming other hydrocarbons such as gasoline type components /1.17/. This leaves open the option to use natural gas as the fuel for on-board reformer equipped FC vehicles. Some areas in the world have a widely distributed natural gas network. This would make it possible to arrange a distributed network for hydrogen filling stations based on on-site reformed natural gas.

For the future, processing natural gas at remote location into liquefied hydrogen in combination with CO_2 recovery is considered to be one option. In sequestering, CO_2 is removed and then stored in the same wellheads from which the gas is drawn. CO_2 removal and storage could of course be used also for other fossil fuels.

This report is intended to highlight new vehicle technology and to discuss fuel options for new types of vehicles. The use of natural gas as a fuel for conventional vehicles was basically covered in the IANGV year 2000 emissions report /1.10/. However, the information in that report is currently being updated in a task undertaken by the IANGV Technical Committee.

The report at hand is divided into two parts:

Part A: Technology and fuels for new generation vehicles

Part B: Examples of new generation vehicles

The report focuses mainly on technology and fuel options for light-duty vehicles, but it also contains examples on advanced heavy-duty vehicles. One of the key issues in this report is how natural gas position itself as a fuel option for fuel cell vehicles, i.e. which contribution can natural gas make on the pathway to hydrogen. Figure 1.3 shows some pathways for natural gas into transport energy use.

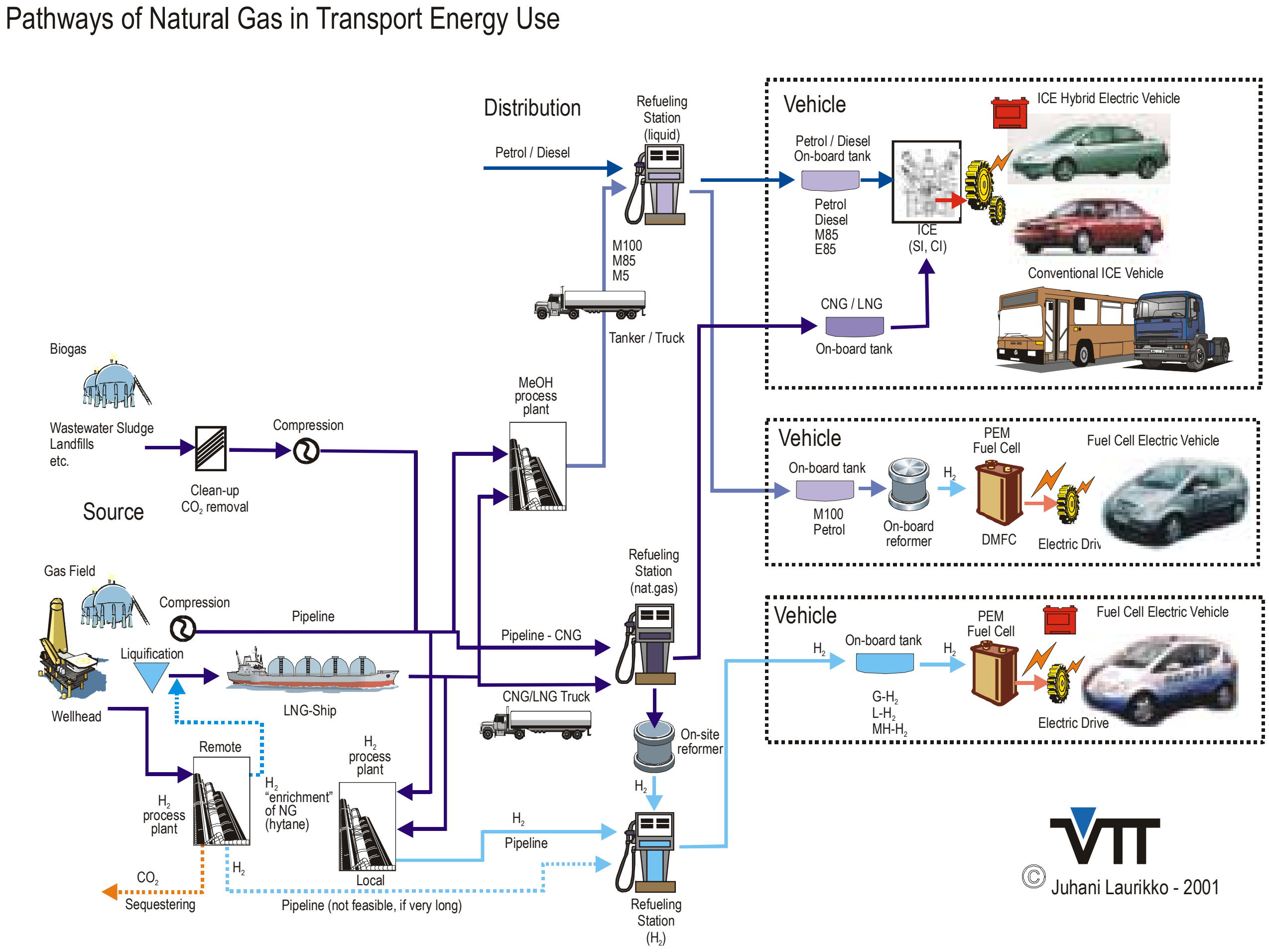

Figure 1.3. Possible pathways for natural gas into transport energy use.

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2. Review of vehicle and propulsion technology

Developments in vehicles powered by internal combustion engines have not yet reached the end of the line. There is still potential for both emission reductions and improvements in engine efficiency. The internal combustion engine powered vehicle has a history of more than a century. Current vehicles are highly refined, easy to use and in most cases have more than satisfactory performance. For spark-ignition engines, the emission levels have been so dramatically reduced that the specific emissions are well below those of ordinary power plants. In the case of gasoline vehicles, the emphasis of future activities will be put on improvements in engine efficiency. For the diesel again, most of the work will focus on emission reduction (particulates, nitrogen oxides).

The great improvements in engine performance, especially the reductions in exhaust emissions, have been possible by replacing simple mechanical control systems with electronics. This applies both for gasoline and diesel engines.

One of the basic problems with the internal combustion engine is that engine efficiency depends very much on engine load. This is especially true for spark-ignition engines. Figure 2.1 shows an example of an engine map (efficiency versus load and speed) for a medium-duty gas fuelled spark-ignition engine /2.1/. Light-duty vehicle engines are in general operated on very low average loads, which results in low efficiency.

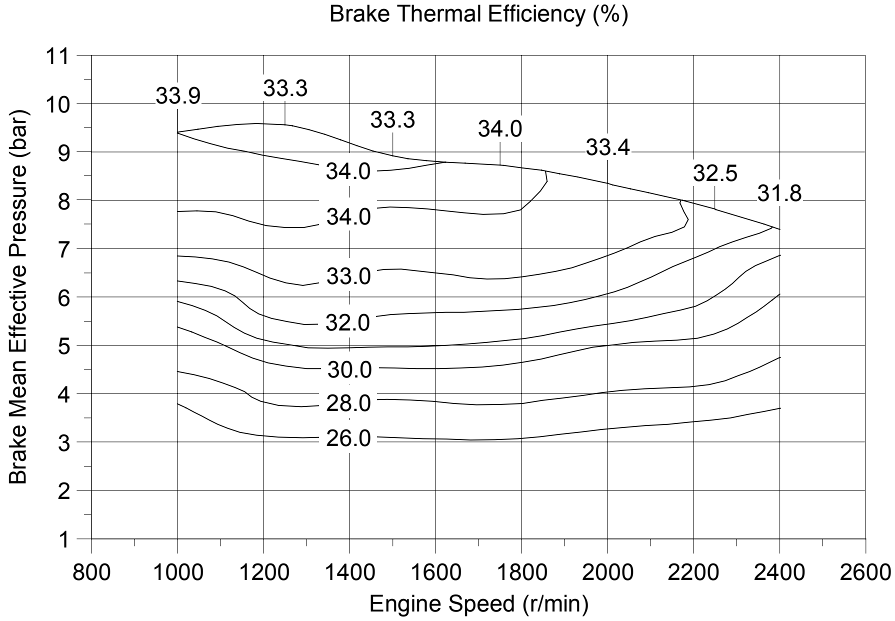

Figure 2.1. Engine map (efficiency versus load and speed) for a spark-ignition engine /2.1/.

This problem can also be alleviated with intelligent control systems. A hybrid vehicle combines two power sources, in most cases an internal combustion engine (ICE) and an electric motor. Earlier mechanical (flywheel) or hydraulic systems (hydraulic accumulator) were also considered. A hybrid system allows the ICE to operate on favourable loads for improved fuel economy. The electric system will boost performance when needed, and also in some case regenerate braking energy. There are several different levels of hybridisation, from minimal hybrids with integrated starter-generator for boosting accelerations to full serial hybrid vehicles with electric propulsion motors.

One of the main advantages of a fuel cell (FC) is that the efficiency of the fuel cell itself is rather independent of load. However, the efficiency of the total FC system including auxiliaries varies somewhat with power.

Figure 2.2 shows fuel cell, reformer and total FC system efficiency as a function of load in comparison with the efficiency of a gasoline engine /2.2/. The efficiency of the FC itself peaks at a very light load. The efficiency of the fuel reformer is more or less constant between 20 and 100 % load. As a result, the efficiency of the total system peaks at 20 % load, giving a benefit compared to the gasoline engine in the load range from 0 to 70 %. At full load, however, both systems give equal efficiency.

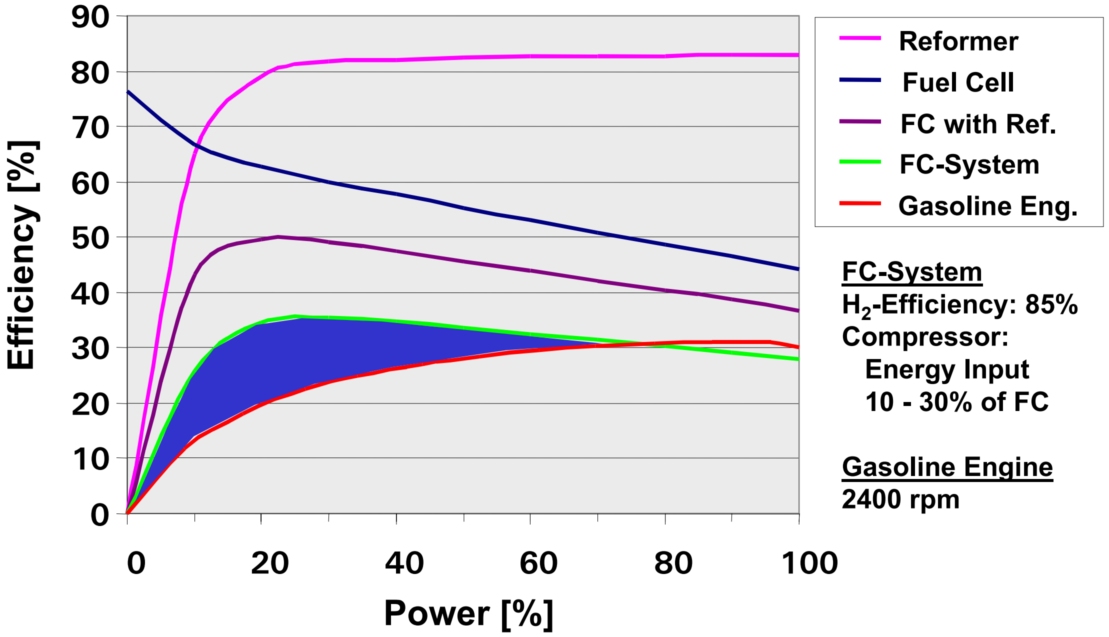

Figure 2.2. Efficiency comparison of FC with reformer vs. gasoline engine /2.2/.

The high low-load efficiency of the FC system gives a kind of built-in hybrid effect, and adding a battery pack for energy storage on a FC vehicle turns the FC vehicle into a full hybrid vehicle with the possibility of regenerative braking.

The total efficiency of any vehicle is much dependent of the duty cycle. Stop-and-go type of traffic consumes more energy than driving at moderate constant speeds. A hybrid or a FC vehicle may be more efficient than a conventional vehicle in urban driving, but the difference is reduced when running at constant high speeds, typical of extra-urban conditions.

The power requirement of auxiliaries (alternator, air conditioning etc.) in vehicles is increasing all the time due to increased sophistication of the vehicles. Especially in stop-and-go driving, including extended periods of idling, the share of power needed for the auxiliaries can be quite substantial. This power is mostly generated at worst possible engine conditions regarding efficiency, i.e. when idling. This has resulted in attempts to separate power generation for auxiliaries and power for propulsion. A good example of such a system is the BMW hydrogen powered demonstration vehicles, which are equipped with an IC engine for propulsion and a FC for auxiliary power production. Both power sources are fueled with hydrogen /2.3/.

Figure 2.3 gives an example of different powertrain alternatives.

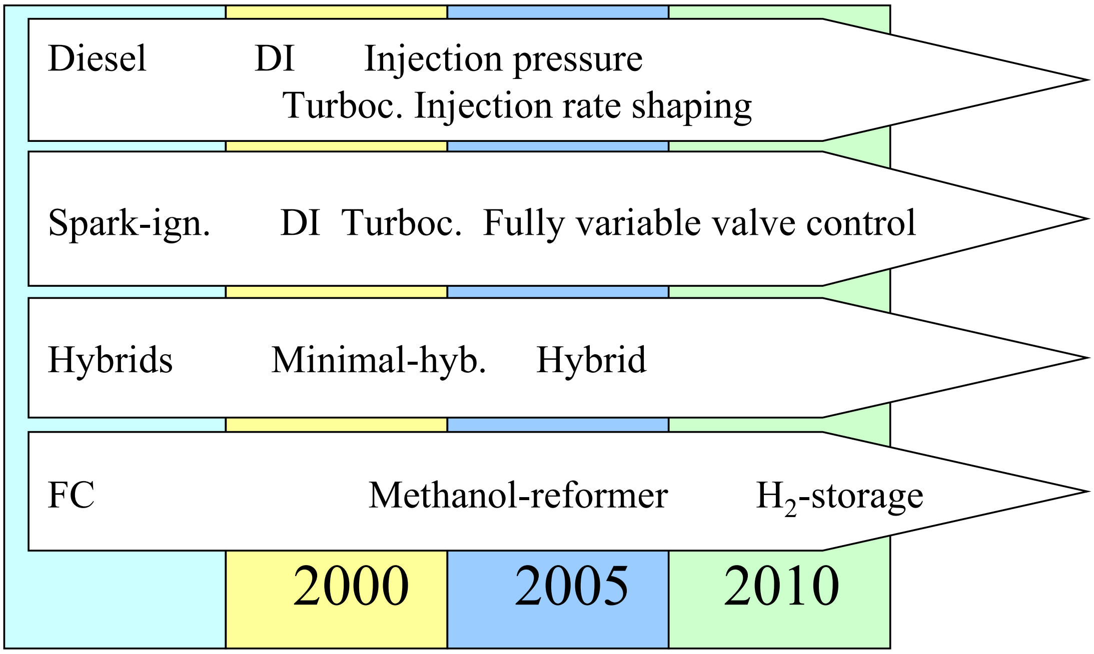

Figure 2.3. Powertrain alternatives for the future /1.4/..

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3. Internal Combustion Engine vehicles

3.1 Advances in ICEs

3.1.1 General

Several new features have been launched recently to improve the properties of the conventional internal combustion engine. Since the 1980's, tremendous improvements have been achieved regarding harmful tailpipe emissions. However, because of the global warming (greenhouse effect) issue, the most recent developments in engine technology have aimed at increasing the efficiency of the engine. This leads to better fuel economy and lowers CO_2 emissions. Also, the consumers' demands for higher torque and power have been another driving force behind recent development.

3.1.2 Manifold and valve train designs

To increase the low-rpm torque of the engine, the intake manifold configurations have been under deep investigation. Today, as a result of this, variable geometry manifolds are used widely. In these systems, a valve, located in the manifold, controls the intake air flow forcing the air to travel a longer distance at low rpm before reaching the combustion chamber. At high rpm, the route is shorter to increase high-end power. In some cases, this kind of manifold design can even provide a supercharging effect. These manifolds often lower also noise and vibration.

The multivalve engine (more than 2 valves per cylinder) penetration has grown significantly on the market. After this, the next step in valve train development was variable valve timing systems. At first, this applied to intake valves only. Recently, variable timing systems have been introduced also for exhaust valves. These systems have the capability of incorporating the so-called internal EGR (exhaust gas recirculation) principle, meaning that a part of the exhaust gas remains in the cylinder, needing no EGR valves or pipes, in order to lower the NO_X formation at certain driving conditions.

In spark ignition engines, the throttle valve causes pumping losses. To prevent this, in some recently designed engines, the throttle valve has been replaced by completely variable intake valves. These systems incorporate, besides variable timing, also variable valve lift. Engines utilising this system are available e.g. from BMW (Valvetronic) /3.1/.

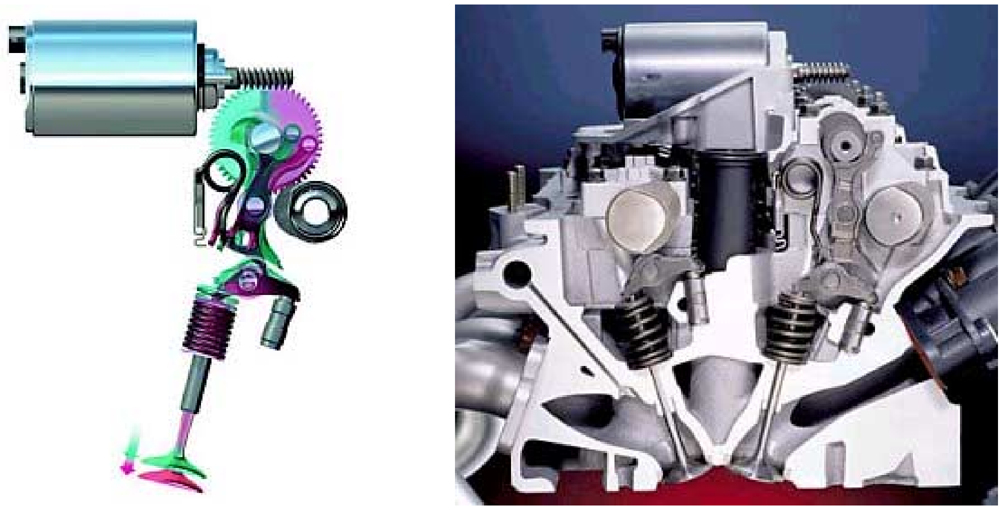

Figure 3.1 BMW Valvetronic system with variable valve timing and lift /3.1/

3.1.3 Direct injection engines

Direct injection diesel engines (CIDI = compression ignition, direct injection) have been used in heavy-duty applications for quite a while. Since the 1990's, the direct injection principle has also been utilised in small diesel engines. In these engines, the fuel is injected directly to the combustion chamber instead of a separate pre-chamber. This directs a greater portion of the fuel energy to push down the piston, rather than to heat up the cylinder head. This configuration increases the efficiency of the engine by some 10-20 % and provides extremely low fuel consumption. The drawback of these engines is that sometimes an auxiliary heater is needed at low ambient temperatures to keep the engine and the vehicle interior warm.

Also some spark ignition engines utilise direct injection systems (DISI = direct injection, spark ignition). Mitsubishi has been one of the pioneers in this field (the GDI engine). Direct injection systems require a specially designed intake manifold and piston to create the swirl needed for reliable combustion.

In DISI engines, usually lean air-fuel mixture is utilised instead of stoichiometric. This results in higher efficiency. In these engines, usually richer mixture is directed close to the spark plug to enable reliable combustion. The rest of the combustion chamber is filled with leaner mixture, so that the average air-fuel ratio of the charge is leaner than stoichiometric. The use of this kind of non-homogeneous mixture is often called stratified charge. The fuel injection pressures in DISI engines can be as high as 120 bar.

DISI engines usually require exhaust after-treatment for NO_X to reach sufficiently low emission levels. The De-NO_X catalyst systems are not yet at their mature commercial stage, and they usually operate only on low-sulphur gasoline, which is not available everywhere.

The recent developments in computer science and engine management electronics have enabled the implementation of direct injection engines. Also, the developments in turbocharging technology, and capability to manufacture high-pressure fuel injection systems are other factors behind this development. The modern CIDI engines utilise common rail fuel injection systems with injection pressures up to 2000 bar. With these systems, it is possible to inject very small amounts of fuel very precisely, and the combustion can be divided into several phases, incorporating pre-injection, main injection and post-injection periods.

A drawback of both CIDI and DISI engines is that deposits easily stick onto the intake valves, especially if conventional (external) EGR systems are used. This is due to the fact that the crankcase ventilation gases, and also recirculated exhaust (if equipped with EGR), are directed to the engine through the intake valves. However, the solvent properties of the fuel, as well as the influence of the dispersive and detergent fuel additives, do not affect the valves, since the fuel flows directly to the combustion chamber not touching the valves.

3.1.4 Turbocharging

Turbocharging has become fairly common, at least among many European car manufacturers. One or the pioneers in this field is Saab, who started using turbo engines as early as 1977. With a turbocharger, it is possible to reach the power level of a significantly larger engine without sacrificing the fuel effectiveness of a small engine.

The first turbocharged passenger cars were typically somewhat tricky to drive, since the turbo boost started very sharply at a certain, usually fairly high engine speed. This could result in losing control of the vehicle on a slippery surface, if the driver was not familiar with this phenomenon.

Today, the behaviour of turbochargers is much more refined. Many turbo engines are called low-pressure turbos, meaning that the turbocharger itself is quite small and delivers boost pressure already at very low rpm. This makes these engines pleasant to drive in everyday traffic, since there is plenty of power available at low engine speeds, with low noise and low fuel consumption levels. The maximum boost pressure of such systems is not very high. The sophisticated engine management systems control the by-pass valve mechanisms to prevent damage to the turbocharger at high rpm. The most recent developments incorporate variable geometry turbochargers.

In diesel engines, the turbocharger also has a critical role regarding emissions. With the help of the turbocharger, the smoke levels of diesel engines have come down significantly. At low rpm, the diesel engines used to emit plenty of smoke and particulates, because there was not enough air present in the combustion chamber. To prevent this, the amount of fuel injected had to be brought down, resulting in very low power at low rpm. With the help of a turbocharger, it is possible to increase injected fuel amount and power at low rpm without increasing smoke and particulate levels.

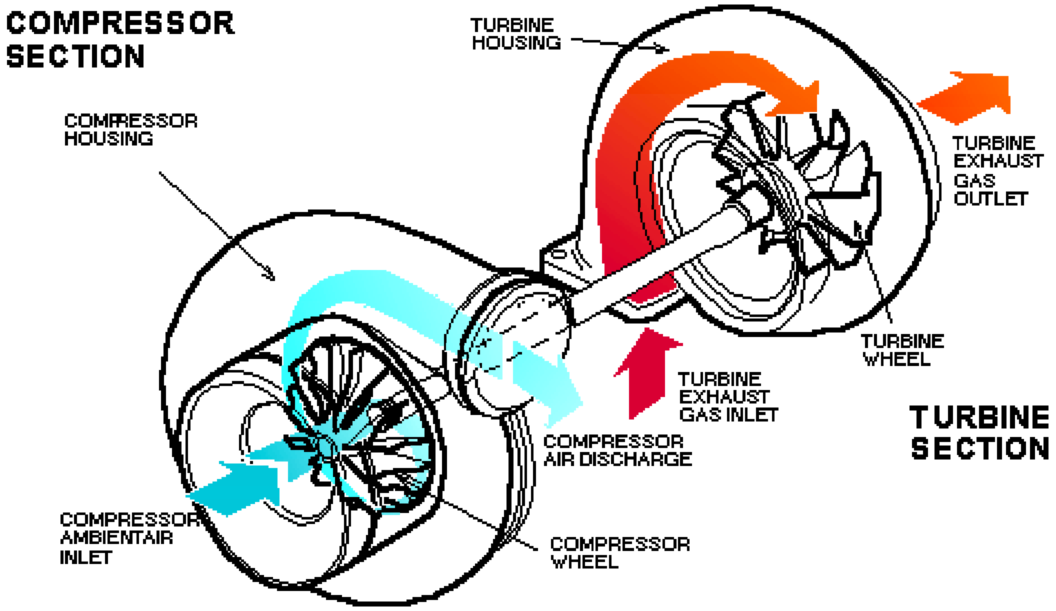

Figure 3.2 Turbocharger working principle /3.2/.

3.1.5 Variable compression ratio

One interesting engine concept is the Saab variable compression (SVC) engine. In this design, the compression ratio of the engine can be varied in the range of 8:1 ... 14:1 by inclining the cylinder block up to four degrees in comparison to the crankshaft. The 1.6-litre prototype engine, featuring 5 cylinders and a supercharger, is claimed to reach the fuel economy of an optimised 1.6-litre engine, while offering the power of a 3.0-litre displacement engine. This means 30 % fuel economy improvement compared to a conventional 3.0-litre engine /3.3/.

Figure 3.3 Saab Variable Combustion engine /3.3/

3.1.6 Increased electrical voltage

The electrical voltage of cars will eventually be increased from 12 to 42 volts. This provides several benefits compared to the present voltage level. The power-to-weight ratio of 42 V electrical components will be higher. Some auxiliaries, like power steering and water pump, can be electrical instead of mechanical, providing higher efficiency and better controllability. The starter and alternator can be integrated (ISG = integrated starter-generator) and combined with the engine flywheel. This saves weight and space, enables rapid and reliable automatic engine on/off systems, and the starter can even be used as a temporary power booster for accelerations.

One of the most promising improvements related to increased voltage is the possibility of controlling the engine valves electronically. In this case, the valve timing, lift and lift speed can be controlled unrestrictedly and steplessly, which gives completely new possibilities for engine design. Additionally, electrically controlled valves make disabling of individual cylinders possible, as well as reducing the amount of mechanical parts needed for valve operations by over one hundred.

3.1.7 OBD systems

The on-Board Diagnostics systems (OBD) were created to monitor all emission related components. In these systems, the Malfunction Indicator Light (MIL) will be turned on, if any problem or failure occurs that would increase the emissions. The purpose of the system is to alert the driver immediately, so he or she knows to have the vehicle checked as soon as possible. Another reason behind the OBD development is the system's capability to pinpoint the specific component that has malfunctioned, saving substantial time and cost compared to guess-and-replace repairs. The so-called OBD-II system has been required in the US for all cars built since January 1, 1996. In Europe, the EOBD (European On-Board Diagnostics) has been required for new certifications since January 1, 2000, and for all new vehicles since January 1, 2001 /3.4/.

However, the OBD systems are problematic if used in conjunction with natural gas operation. When a vehicle equipped with OBD is converted to natural gas operation, the OBD monitors will perceive incorrectly that a fault is present when the vehicle is operated on natural gas. This will trigger the MIL. This incompatibility applies especially to bi-fuel vehicles that can be operated on either gasoline or natural gas.

Originally, the European EOBD regulations did not take into account the alternative fuel issues. They required that alternative fuel vehicles also have to be fully OBD compliant. However, based on North American experience, a letter was sent to the European Commission by ENGVA (European Natural Gas Vehicle Association). The letter requested a waiver for specific OBD monitoring requirements for NGV's. As a result of this, it was decided that vehicles adapted to run on natural gas may have their OBD system permanently disabled until the end of year 2004.

However, this decision raised new concerns. If the OBD system is permanently disabled on a bi-fuel vehicle, it will also then be operated without OBD monitoring on gasoline. This means that alternative fuel vehicles, which are declared to be environmentally friendly, might become gross polluters if a malfunction occurs when driving on gasoline, because there is no warning to the driver

To prevent this, the OBD systems should be compatible with natural gas operation. Partnerships between CNG converting companies and OEM's could provide the opportunity to develop strategies for maintaining functionality of many OBD monitors when operating on gasoline, but turning off selected monitors when the vehicle is recognised to be operating on natural gas. The ultimate goal would be a fully functional OBD system for both gasoline and natural gas.

3.1.8 HCCI engines

In the future, we might see engines known as Homogenous Charge Compression Ignition (HCCI) engines. This engine type combines features from both spark ignition and diesel engines, promising the high efficiency of a diesel engine with virtually no NO_X or particulate emissions. This engine can operate using a variety of fuels, including natural gas.

In the HCCI engine, fuel is homogeneously premixed with air, as in a spark-ignited engine, but with a high proportion of air to fuel. When the piston reaches the top, this lean mixture auto-ignites from combustion heating, as in a diesel engine. Usually, auto-ignition causes an unwanted phenomenon, called knocking, in a spark-ignited engine. This may result in overheating and severe engine damage. However, in the case of the HCCI engine, the excess air present in the combustion chamber keeps the temperatures relatively low. When the danger of engine damage is eliminated, auto-ignition becomes a desired mode of operation.

Given the mix of advantages, it is not surprising that considerable research is going on around the world on the HCCI principle. Natural gas seems to be a very promising fuel option for HCCI engines. Among others, University of California, Berkeley, and Lawrence Livermore National Laboratory have performed successful research on a natural gas powered HCCI engine /3.5/.

3.1.9 Natural gas in advanced ICEs

High knock resistance is one of the indisputable advantages of natural gas as a motor fuel. The octane rating of natural gas is typically referenced to be as high as 130. High octane number can be utilised in engine design by using a higher compression ratio than with gasoline, resulting in higher efficiency. However, in bi-fuel engine configurations, it is not possible to increase compression ratio significantly, since the same engine has also to be operated on gasoline.

Nevertheless, benefits similar to increasing compression ratio can be reached, if the engine is equipped with an adaptive engine management system with knock sensors. This kind of engine control system increases ignition advance as much as possible until knocking is detected. In the case of natural gas operation, the knock limit is not reached until higher ignition advance values than for gasoline. This leads to higher efficiency and better fuel economy.

Using natural gas instead of gasoline in port-injected engines has at least two implications on the intake system. Firstly, the cooling effect of gasoline evaporation is lost. This means that volumetric efficiency (amount of combustible mixture going into the engine) is reduced and that temperatures in the combustion chamber are slightly elevated. This may have implications on the performance requirements for exhaust valves etc.

Secondly, no additive can be used in natural gas to keep injectors and inlet valves clean. This is a very important function of certain gasoline additives. In SI engines, which most of the time operate throttled, small amounts of engine oil leak through valve guides and seals. In gasoline engines, the fuel additives help to wash the potential deposits away.

For their natural gas models, Honda has put a lot of effort on oil control and emission stability. As a result, the 2001 MY Honda Civic has been SULEV certified for a useful service life of 150,000 miles /3.6/.

Several studies are going on to develop direct injection natural gas engines. The results are promising, but further research is needed to reach a mature commercial stage. Lotus Engineering found that DISI engine operation stayed more stable when running lean on CNG compared to gasoline. This means that natural gas is a very attractive choice for lean-burn operations. Engine-out emissions were reduced on CNG by 60 % HC, 26 % NO_X and 21 % CO_2 compared to gasoline /3.7/. In the case of port injected engines, it is relatively easy to fit in injectors for both gasoline and natural gas. For a DISI engine however, installing two direct injection nozzles into the combustion chamber might prove impossible.

Westport Innovations, Inc, has worked on natural gas powered CIDI engine concepts. Direct injection permits a natural gas engine to operate throttle-less and with high compression ratio, thereby maintaining the conditions that make diesels the most efficient engine platform. The directly injected natural gas can be ignited with either pilot fuel or hot surface, such as a glow plug. Westport has developed a patented, combined injection valve that injects both the diesel pilot and the natural gas. They have also developed a high-speed high-pressure injector with very good flow control for glow plug ignited natural gas engine operation.

According to Westport, NO_X emissions are reduced significantly (up to 40 %) over diesel operation, because natural gas burns with a lower flame temperature. Incorporating EGR systems, NO_X emissions can be lowered even further. With lower carbon content and lower propensity to form soot, PM emissions of natural gas are also reduced (up to 75 %) compared to diesel operation /3.8/.

3.2 Fuel requirements for advanced ICE's

3.2.1 General

The most important requirement for both gasoline and diesel engines, equipped with sophisticated exhaust after-treatment systems, is low sulphur level. Because of stringent emission regulations in all developed countries, all ICE's have to be equipped with exhaust after-treatment systems. Most of these devices do not work properly, if the fuel sulphur level is too high. This applies especially to the newest NO_X and particulate after-treatment devices.

The 3-way catalyst, oxidising CO and HC and reducing NO_X emissions has been used for spark ignition engines since 1980's. It can be used at moderate (100...500 ppm) gasoline sulphur levels, even though the conversion efficiency is lower and the age of the catalyst is shorter along with higher fuel sulphur content.

However, in the case of an oxidising catalyst used with a diesel engine, the fuel sulphur level has to be well below 100 ppm. At higher sulphur levels, particulate emissions usually increase due to sulfate formation in the catalyst. Also, if the newest technology particulate or NO_X after-treatment devices are used in either gasoline or diesel engine, the most preferable fuel would be sulphur-free. In practice, this means sulphur levels below 10 ppm.

3.2.2 Availability of sulphur-free fuels

Fuels of reduced sulphur content are already available in several countries. Japan has had sulphur-free premium gasoline for many years. Finland has had below 50 ppm and Sweden below 10 ppm sulphur diesel for about a decade. In Germany, the first sulphur-free fuels are already on the market, and tax incentives for sulphur-free fuels will be introduced by 2003. In the US, one-third of the gasoline pool in California is below 10 ppm sulphur, and officials are considering regulatory action to obtain ultra-low sulphur levels statewide. US federal officials are expected to reduce maximum allowed sulphur level in diesel fuel to ultra-low levels by 2006 /3.13/.

Gaseous fuels, like natural gas and LPG, are practically sulphur-free, and in this respect they are very suitable fuels for the most advanced internal combustion engine technologies and their sophisticated exhaust after-treatment systems.

The situation in many developing countries is significantly different compared to Japan, Europe and North America. Leaded gasoline is still used, and there is no control of fuel sulphur content. Thus it is impossible to operate vehicles with sophisticated exhaust control devices on certain markets. For developing markets, natural gas can provide a lead-free and practically sulphur free high-quality fuel option. Natural gas will result in emission advantages over conventional liquid fuels, especially low-grade fuels, both in vehicles without and with exhaust after-treatment systems.

3.2.3 European legislation

The European Union legislation (Directive 98/70/EC) sets limit values for properties of both gasoline and diesel fuel (Table 3.1). Two stages have been decided, of which the first one has been effective since 1 January 2000, and the second phase will be in force beginning 1 January 2005. The sulphur levels required by the Directive (last rows in the table) are much higher than values required by most advanced engine and exhaust after-treatment technologies /3.10/.

Table 3.1. European Union Fuel Specifications, years 2000 and 2005 /3.10/.

GASOLINE		2000	2005
RVP summer	kPa	max 60	-
Aromatics	% v/v	max 42	max 35
Benzene	% v/v	max 1	-
Oxygen	% m/m	max 2.7	-
Sulphur	mg/kg *)	max 150	max 50

DIESEL		2000	2005
Cetane number		min 51	-
Density at 15 °C	kg/m^3	max 845	-
Distillation 95 %	°C	max 360	-
Polyaromatics	% m/m	max 11	-
Sulphur	mg/kg *)	max 350	max 50

*) mg/km is commonly referred to as ppm

However, the European Commission has undertaken an analysis about the need to reduce further the sulphur level to below 50 ppm level, which is mandated for 2005. There is a proposal for a Directive to start marketing zero sulphur (meaning below 10 ppm) gasoline and diesel on January 1, 2005. The proposed deadline for full market penetration for zero sulphur fuels is January 1, 2011 /3.11/.

Also, a Directive dealing with biofuels and biocomponents in transportation fuels is under preparation. The proposal for a Directive on the promotion of the use of biofuels for transport deals with the following biofuels: bioethanol, biodiesel, biogas, biomethanol, biodimethylether and biooil. The proposal states that the Member States shall ensure that the minimum share of biofuels sold is 2 %, calculated on the basis of energy content, of all gasoline and diesel sold for transport on their markets by 2005. This share is supposed to increase in accordance with the schedule set out in Table 3.2 /3.12/.

Table 3.2. Minimum proposed amount of sold biofuel as a percentage of gasoline and diesel sold /3.12/.

Year	%
2005	2
2006	2.75
2007	3.5
2008	4.25
2009	5
2010	5.75

Biofuels will be permitted to be made available as pure biofuels, biofuels blended in mineral oil derivatives, or liquids derived from biofuels like ETBE. In the case of ETBE, 45 % of the amount used is calculated to be biofuel.

The proposal includes also requirements for minimum percentages of biocomponents blended with conventional gasoline and diesel (Table 3.3). These amounts are taken into account when calculating the minimum amounts indicated in the previous table.

Table 3.3. Minimum proposed percentages of biocomponents to be blended with gasoline and diesel /3.12/

Year	% in diesel	% in gasoline
2009	1	1
2010	1.75	1.75

Out of numerous alternative fuels and engine technologies, discussion of the European Commission indicates that there are four options appearing to have high volume potential over the next 20 years. These are hybrid vehicles, biofuels, natural gas and hydrogen/fuel cells /3.13/.

Concerning the alternative fuel options, an "optimistic development scenario" at this stage might look like the following:

Table 3.4. Scenario about the use of alternative fuels in Europe until year 2020 /3.13/

Year	Biofuel, %	Natural gas, %	Hydrogen, %	Total, %
2005	2	-	-	2
2010	6	2	-	8
2015	(7)	5	2	14
2020	(8)	10	5	(23)

We can see that natural gas is considered as the most widespread alternative fuel in Europe within the timeframe of 20 years from now.

3.2.4 World-Wide Fuel Charter

There is a significant number of fuel quality standards and Directives in different parts of the world regulating fuel quality, but no legal international harmonisation for fuel quality exists. Therefore vehicle and engine manufacturers around the world have released a World-Wide Fuel Charter (WWFC) which aims at the harmonisation of motoring fuels world wide. WWFC is supported by European Automobile Manufacturers Association (ACEA), Alliance of Automobile Manufacturers, Engine Manufacturers Association (EMA), Japan Automobile Manufacturers Association (JAMA), and numerous other vehicle manufacturing organisations world wide.

World-Wide Fuel Charter was first established in 1998 to promote greater understanding of the fuel quality needs of motor vehicle technologies and to harmonise fuel quality world wide in accordance with vehicle needs. The objective of the global fuels harmonisation effort is to develop common, world wide recommendations for fuel properties, taking into consideration customer requirements and vehicle emission technologies, which will in turn benefit customers of all vehicle and engine manufacturers and all other affected parties.

The WWFC is to be considered as a list of wishes from the auto manufacturers' side. However, the WWFC seems, along with other documentation, to have attracted the attention of decision-makers on the need to reduce sulphur content.

The newest edition of WWFC was published in April 2000, and a draft for a new version has been launched. The 2000 edition calls for reducing sulphur content in both gasoline and diesel fuel. Four different fuel quality categories have been established for both unleaded gasoline and diesel fuel. The categories are as follows /3.14/:

Category 1:
Markets with no or minimal requirements for emission control.

Category 2:
Markets with requirements for emission control (US Tier 0 or 1, Euro 1 and 2, or equivalent standards).

Category 3:
Markets with advanced requirements for emission control (California LEV, ULEV, Euro 3 and 4, or equivalent standards).

Category 4:
Markets with further advanced requirements for emission control, to enable sophisticated NO_X and particulate after-treatment technologies. (California LEV-II, US Tier 2, Euro 4 in conjunction with increased fuel efficiency constraints, or equivalent standards).

The Category 4 fuels have to be practically sulphur-free, meaning sulphur levels below 10 ppm. Only sulphur-free fuels enable the utilisation of the most advanced emission control technologies like the de-NO_X and SCR (Selective Catalytic Reduction) catalysts and sophisticated particulate traps.

3.2.5 Standards for natural gas quality

The ISO standard 15403 ("Natural Gas – Quality Designation for Use as a Compressed Fuel for Vehicles") sets limit values for certain properties for natural gas for road transportation use. The critical issues regarding gas composition are listed as follows /3.15/:

1. water content
2. sulphur compounds
3. particulate matter
4. higher hydrocarbons
5. CO_2
6. free oxygen
7. glycol / methanol
8. oil content
9. corrosive components

The standard clearly requires that the dew point of compressed natural gas in the containers must be low enough to preclude the formation of liquid under any circumstances of pressure and temperature. Water content of less than 0.03 g/m^3 is stated as satisfactory level for expected pressure and temperature.

To prevent corrosion, the limit value for sulphur is 120 mg/m^3, if there is water present. This value also avoids excessive poisoning of exhaust catalysts. Limit values for both CO_2 and O_2 are set at 3 %. No glycol or methanol shall be added. Method how to measure oil content has not yet been determined. So, no specification is given at this time. However, years of OEM experience suggests a range of 70 to 200 ppm of oil in the fuel.

SAE J1616 (Recommended Practice for Compressed Natural Gas Vehicle Fuel) calls for at least a 5 micron filter on the fuel line feeding the vehicle container to prevent particulates from entering the vehicle fuel system /3.16/.

The limit value for sulphur, 120 mg/m^3, originally set to prevent corrosion, translates into 165 ppm sulphur. Looking at the requirements set by the newest emission control (catalyst) technologies (Category 4 vehicles), this value is way too high, and this indicates that the specifications for natural gas for vehicle use should be modified. The same applies if natural gas is to be used for on-board reforming.

Sulphur in natural gas stems from the gas itself and also from the odorant (mercaptans). From the wellhead, sulphur is present mainly as hydrogen sulphide (H_2S). The hydrogen sulphide, however, is largely removed due to its toxicity. Thus a more significant source of sulphur is odorants added intentionally to natural gas /3.17/.

However, typical sulphur content of natural gas is much lower than the limit value of 120 mg/m^3. In the US, typical contract terms and industry practice limit total sulphur to 0.25-1 grains per 100 scf, or approximately 8-30 ppm on a mass basis. Results of over 2300 analyses indicate that the average sulphur content of all samples was around 10 ppm. A typical result was that 80 % of the sulphur found in the gas was from the odorant. At a total level of 10 ppm this would mean that 2 ppm is from H_2S and 8 ppm from the odorant /3.17/.

In Europe, the natural gas coming from the Siberian gas fields Urengoi and Jamburg contains sulphur less than 1 mg/m^3, i.e. less than 1.5 ppm S. In Finland, tetrahydrothiophene (THT) containing 36 % S is used as odorant in the low-pressure part of the natural gas pipeline system. The odorant concentration is 10-15 mg/m^3. At 15 mg/m^3 odorant concentration, maximum natural gas sulphur content is then 9 ppm /3.18/. This corresponds well to the US example.

Thus natural gas can meet the oncoming fuel sulphur limit of 10 ppm proposed for advanced vehicles. However, as the greater part of natural gas sulphur stems from the odorant, this clearly indicates that there is a need to develop sulphur free odorants. In the case of fuel cell vehicles, fuel sulphur will probably have to be limited to 1 ppm or even less.

If the natural gas industry wants to take part in the competition of clean transportation fuels, a new quality standard regarding maximum sulphur for automotive applications should be set.

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4. Hybrid vehicle technology

4.1 Advantages of hybrid vehicles

Striving for better efficiency has forced the automobile manufacturers to look at completely new technology concepts. One of these is hybrid technology, which means combining several propulsion systems, usually an internal combustion engine (ICE) and an electric motor (EM), in one vehicle.

The efficiency of the ICE is low at low loads. This applies especially to spark ignition engines. Most of the driving in urban areas includes plenty of idling and low-speed driving. Under these conditions, the ICE fuel consumption, in relation to the amount of power generated, is high. For this reason, the hybrid technology seems promising, since in a hybrid vehicle, the operation of the ICE can be independent of the instantaneous propulsion power need. One option is that the EM could be used mostly in cities and the ICE mostly on highways. Using the EM in cities would also be very beneficial regarding urban air quality.

In most hybrid vehicles, the ICE can be harnessed to charge the batteries at relatively high constant load levels and steady engine speeds, utilising the highest efficiency sections of the engine map. Additionally, under such conditions, the emissions are usually fairly low. In these cases, the power needed for vehicle propulsion is provided by the EM, whose efficiency is almost insensitive to load variations. This principle saves considerable amounts of fuel especially in stop-and-go driving that include substantial periods of standing still in congested traffic. Also, hybrid vehicles usually incorporate regenerative braking systems, turning the electric motor into a generator producing electricity, which is then stored in the batteries.

An additional advantage of hybrids is that combining the ICE with an EM enables the use of smaller ICE's (engine downsizing). Smaller engines use less fuel, partly because they are used on average at higher load levels than bigger engines, in relation to the maximum power of the engine. And due to the additional boost provided by the EM during accelerations, the downsizing can be implemented without sacrificing vehicle acceleration time or hill climbing capability.

4.2 First mass production hybrid vehicle

The first mass produced hybrid vehicle is the Toyota Prius (Figure 4.1). It went on sale in Japan in December 1997. It utilises a 1.5-litre 4-cylinder 16-valve ICE producing 43 kW at 4000 rpm. The power of the permanent magnet electric motor is 30 kW at 940 – 2000 rpm. The batteries are of NiMH type. Toyota says that the batteries should last for 10 to 15 years. The vehicle weighs 1220 kg (2700 lbs). Acceleration time from 0 to 100 km/h is 13 seconds.

The Prius meets the most stringent exhaust emissions standard, California's Super Ultra Low Emission Vehicle (SULEV) standard. Thus it is claimed to be 90 per cent cleaner than conventionally powered cars, producing about 50 percent less nitrous oxide and about 80 percent less of other greenhouse gases. It has also potential to become an AT-PZEV (advanced technology partially-zero emission vehicle) with a 0.2 credit value, that could constitute 2 % share of the 10 % ZEV mandate. Although it has pure electric drive, it cannot, however, be treated as a true ZEV-as its battery capacity does not allow it to operate on electric drive over the full FTP certification cycle.

Figure 4.1 The Toyota Prius hybrid vehicle (photo: Toyota Motor Co.)

Normally the vehicle starts using the electric motor, and during hard accelerations the microprocessor controls both of the power sources to obtain the required acceleration with best possible efficiency (Figure 4.2). The rated fuel consumption values are in the range of 4.5 – 5.5 l/100 km (40 to 50 mpg). A noteworthy detail is that unlike normally, the consumption is lower in city than in highway driving. This is a direct result of the Prius being designed for tight urban driving conditions, such as are encountered in Tokyo /4.1/.

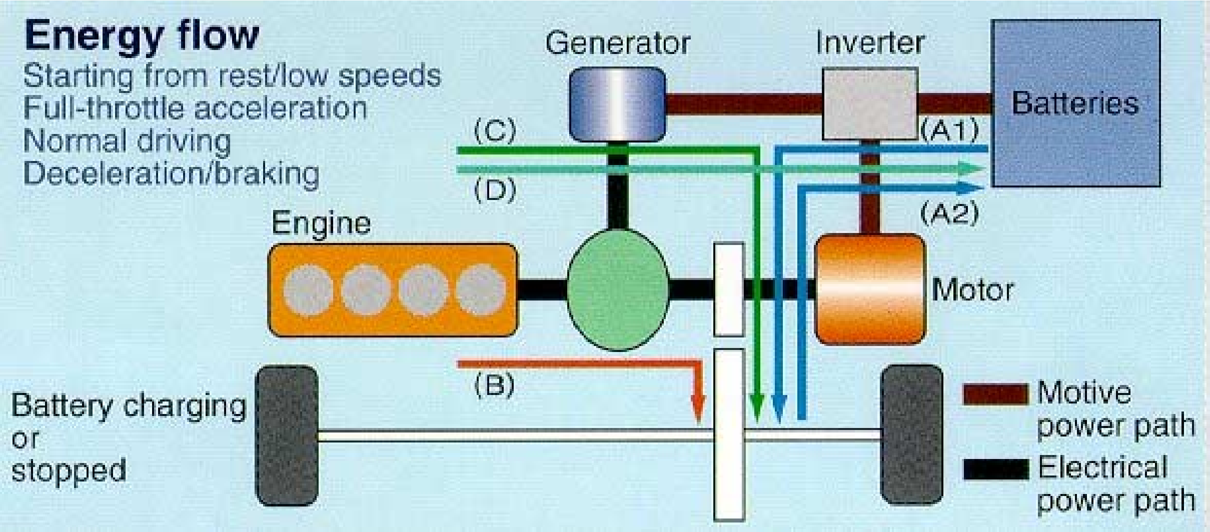

Figure 4.2 Energy flow chart of the Toyota Prius hybrid electric vehicle driveline /4.2/

4.3 Different types of hybrid vehicles

Several types of hybrid vehicle configurations exist (Figure 4.3). Depending on power delivery routing principles, the main types are known as parallel and series hybrids, but also several kinds of mixed configurations are in use (like in the case of the Toyota Prius). These are sometimes called combined hybrid-electric vehicles. In some cases, the driver controls whether the ICE or the EM is used. In some configurations, the vehicle management system takes care of this, and the driver does not have control over the selection of the propulsion system in use.

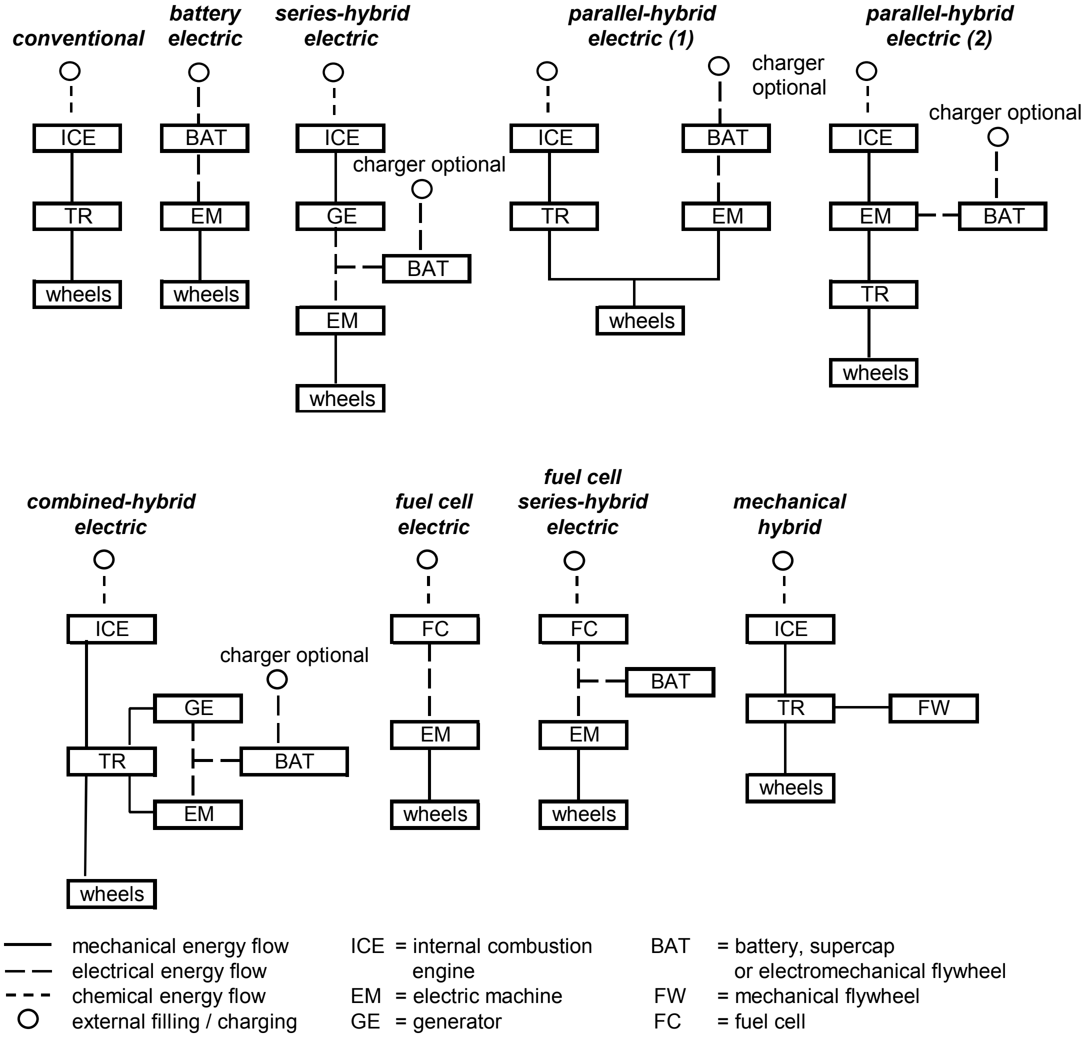

Figure 4.3 Schematics of various electric and hybrid propulsion system configurations /4.2/

Some configurations allow the EM and the ICE to work one at a time or together. Some configurations use the EM only as a temporary power boost in addition to the ICE, but never alone.

Electricity for the EM is stored in batteries. The capacity, weight, volume and type of batteries vary widely, as well as the strategy as to how the batteries are charged. Some hybrid vehicles use only the ICE for recharging (charge-sustaining hybrids), and some can be recharged also from the grid (charge-depleting hybrids). Most hybrid vehicles feature regenerative braking systems, meaning that during braking periods, the EM functions as a generator utilising the excess kinetic energy of the vehicle to charge batteries.

In the near-medium term for obtaining vehicle fuel economy and emission reduction, the minimal hybrid (also called as mild hybrid) vehicle can be an interesting solution. This kind of a drivetrain takes into account the constraints of low cost and the overall performance expectations from a general purpose vehicle. Figure 4.4 illustrates a typical minimal hybrid drivetrain schematic.

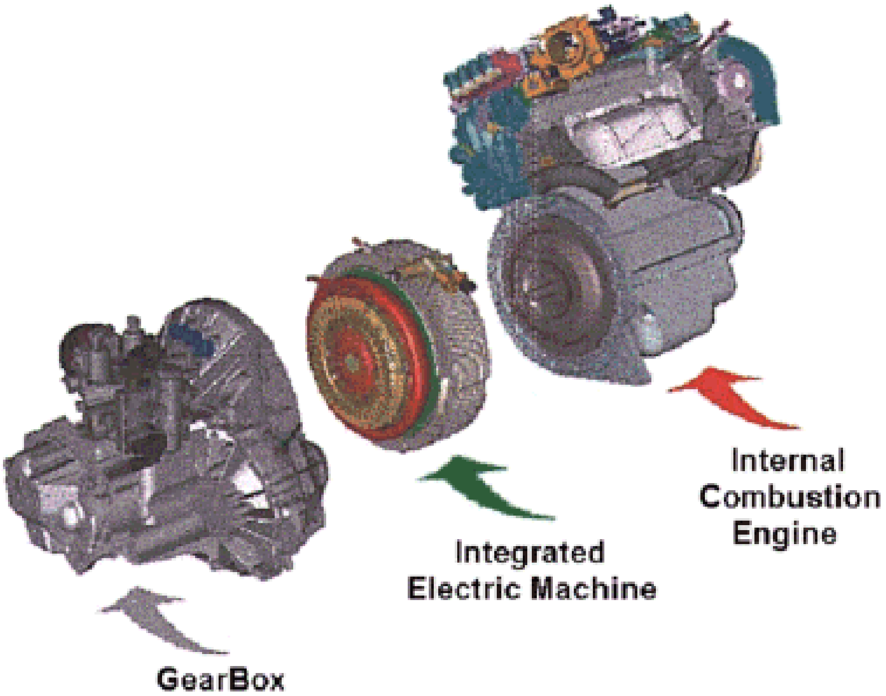

Figure 4.4 Typical minimal hybrid electric vehicle schematic /4.3/

The minimal hybrid system differs from conventional drivetrains only by having an integrated starter/generator (ISG) unit between the engine and the gearbox. In this system the electric motor is used as a supplementary power source to support the ICE. It also enables easily stopping of the ICE at traffic lights, because the powerful electric motor starts the engine smoothly and quickly without the noise generated by pinion engagement. Usually, this kind of vehicle is equipped with only a small extra battery pack to store energy captured by regenerative braking only.

An example of a series hybrid vehicle is the General Motors EV 1 series hybrid. This vehicle is based on the battery electric version of the vehicle. The biggest change from the EV1 electric design is the stretched wheelbase for added interior space and a long central tunnel for component storage. As for the series EV1, instead of the T-shaped battery pack for the battery-electric model, this car carries 44 advanced NiMH batteries in an I-formation down the centre of the car. This clears some of the space needed for a second propulsion system positioned at the rear of the vehicle.

Several new components were developed for this car, including a new rear suspension and new electronic controllers for the transmission, engine and motor/generator unit. In the front part of the trunk compartment, a turbine-powered auxiliary power unit is located. This small and lightweight turbine delivers 40 kW of electrical energy at 100,000 and 140,000 rpm. GM claims the vehicle is able to reach a top speed of 80 mph, almost 130 km/h /4.2/.

An example of a parallel hybrid-electric vehicle is the Fiat Multipla Ibrida. The vehicle uses many standard components. Making use of standard components produces a relatively cost effective hybrid vehicle.

The engine is a 1.6-litre gasoline engine. The parallel hybrid Ibrida works with a 29 kW 3 phase AC asynchronous electric motor, powered by NiMH batteries (19 kWh, 216 V). The Multipla has an automatically shifted 5- speed gearbox. A generator is separately connected to the engine (Figure 4.5).

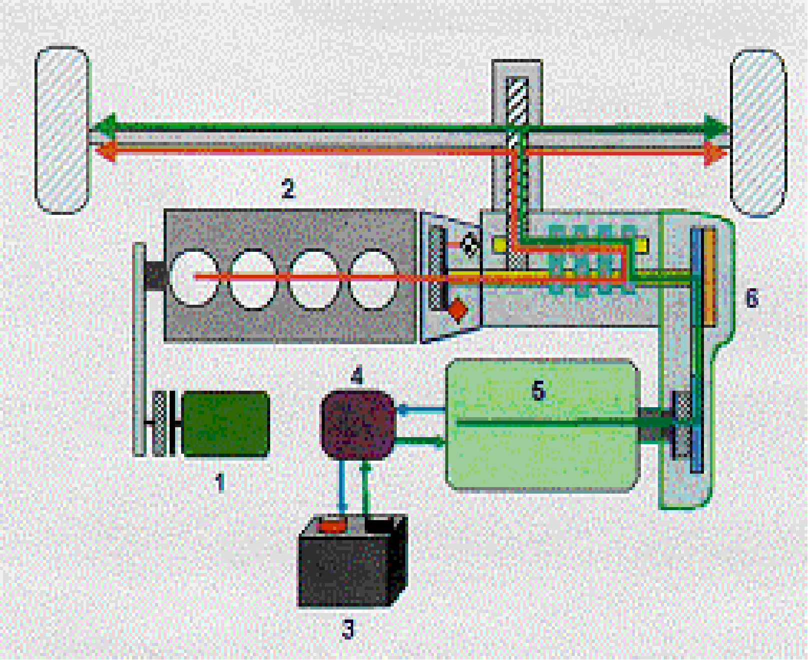

Figure 4.5 Fiat Multipla Hybrid configuration. 1 = AC alternator, 2 = ICE, 3 = Battery, 4 = Inverter, 5 = Electric Motor, 6 = Transmission. (picture from FIAT)

The vehicle has three modes of operation. The first mode is a parallel hybrid-electric mode; both the combustion engine and the electric motor drive the vehicle. At low speeds the system uses the electric motor whereas the combustion engine takes over as the speed increases. Another mode is the electric mode, when the vehicle runs as a Zero Emission Vehicle, ZEV, having a top speed of just 80 km/h. In this mode, the transmission system is locked in second gear. As a third mode, the vehicle is able to be operated in the electrical EA (extended autonomy) mode, which can be used to optimise the remaining range in EV mode in situations where the batteries have been depleted significantly. In this case, the ICE runs at low speed and high torque to drive the generator until the batteries are charged again. Afterwards, the engine shuts down and the system returns to pure EV mode again /4.2/.

4.4 Natural gas as a fuel for hybrid vehicles

Clean burning natural gas as such would be an ideal fuel for hybrid vehicles that are designed to produce as clean emissions as possible. However, there are some considerations that have to be made. Typically, a hybrid vehicle weighs more than its conventional counterpart. The difference can be several hundred kilograms. The factors contributing to the additional weight are the two separate propulsion systems and especially the battery pack. In some cases the extra propulsion system and batteries on board the vehicle also reduce usable passenger or luggage space.

Lack of space and heavy weight of a hybrid vehicle make the use of natural gas in these vehicles somewhat problematic, since the natural gas containers are larger and heavier than liquid fuel tanks. In some hybrid vehicles, there is hardly enough space for conventional fuel tanks, not to mention natural gas containers. And if the vehicle gets too heavy, part of the efficiency and emission benefits will be lost. In this respect, the most likely use for natural gas among hybrid vehicles would be in vehicles that are bigger than passenger cars. At this stage, however, hybrid vans or trucks are relatively rare.

In the case of a minimal hybrid vehicle with an ISG system, natural gas would work well, since there are no very large additional technical devices onboard the vehicle. Because minimal hybrids seem to be a near future option, natural gas would have potential for hybrid vehicles at least in the short term.

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5. Fuel cell technology

5.1 General

The fuel cell (FC) is considered to be one of the most promising power sources for future vehicles. With a FC, the chemical energy in the fuel can be transformed into electric energy without any moving parts (this applies to the stack itself, not to the auxiliaries). Many automotive manufacturers (OEM) have demonstrated their interest in FC vehicles. Included on this list are Daimler-Chrysler, Toyota, Honda, GM, Ford, Nissan, Volkswagen, Renault and PSA. In addition, the FC is an interesting alternative for decentralised power production.

A FC is an electrochemical device in which hydrogen combines with oxygen producing electrical energy. In a way it could be described as a dry battery, which is continuously replenished with fresh chemical energy. The operating principle of the FC was invented by William Grove as early as 1839. However, the first demonstrator was built by Francis T. Bacon in 1950.

The Gemini and Apollo space programmes by the U.S. space administration agency NASA in the 60's sped up the development of FCs considerably. The FC played an important role in the energy supply of spacecrafts, and is still used in U.S. space shuttles. Figure 5.1 shows the development in FC technology /5.1/.

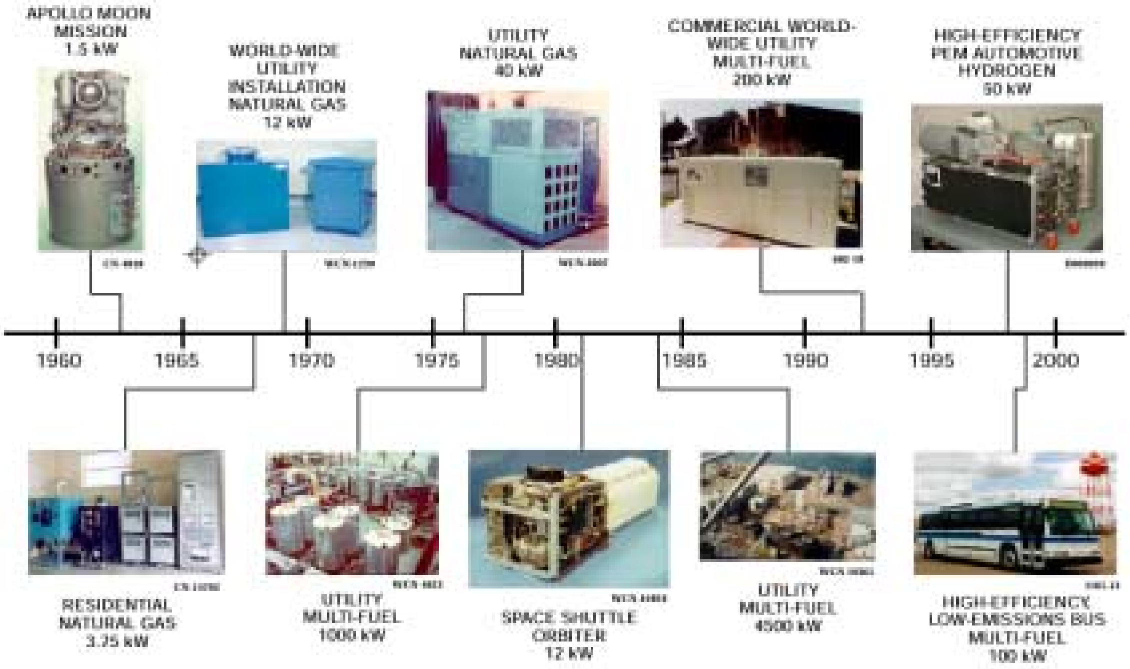


Figure 5.1. The development in FC technology /5.1/.

The most promising fuel cell type for automotive applications is the PEM (Proton Exchange Membrane) fuel cell (see 5.2). SOFC (Solid Oxide) type cells might be suitable for Auxiliary Power Units (APUs), as they also provide heat (heating of the vehicle).

The electrochemical reaction in a PEM type FC takes place when hydrogen and oxygen are supplied to electrodes, hydrogen to the anode and oxygen to the cathode. With the help of catalytic materials like platinum and semi-permeable membranes, the hydrogen molecules are stripped into protons (H^+) and electrons (e^-).

The protons are able to flow from the anode to the cathode through the electrolyte, but not the electrons. This results in a differential in potential between the anode and the cathode, and this in turn creates an electric current. The process is in principle a reversed process of making hydrogen by electrolysis. Figure 5.2 describes the structure and the chemical reactions of a PEM type FC /5.2/.

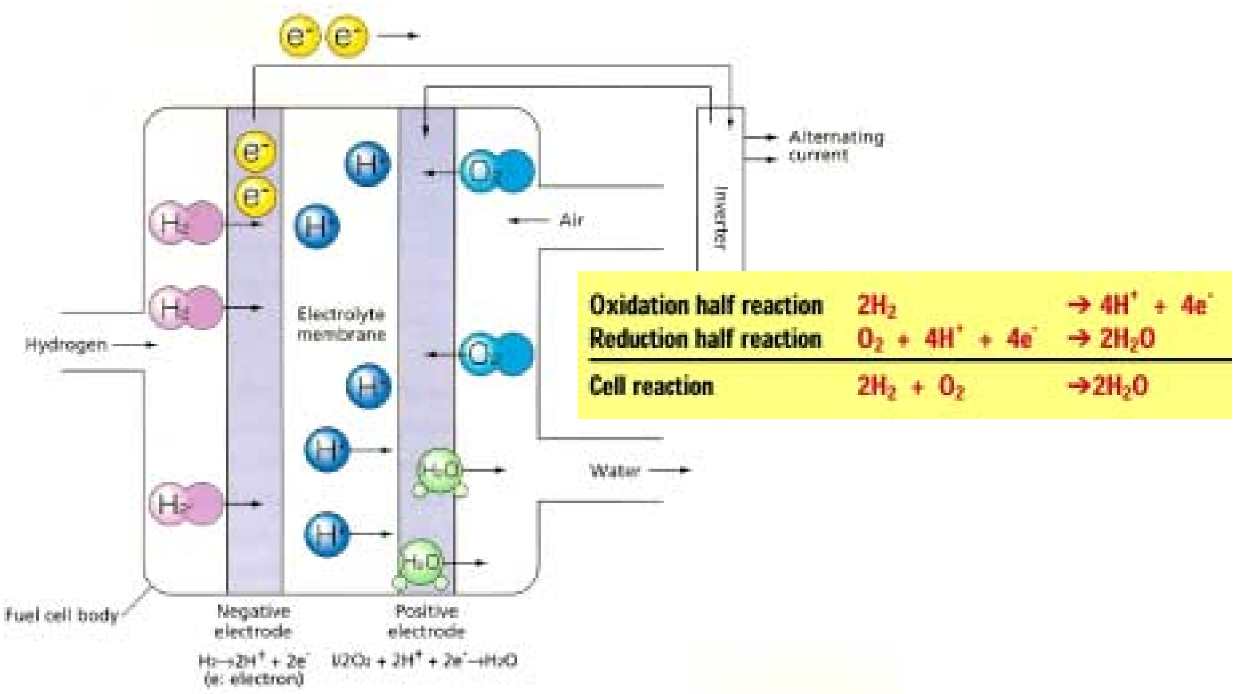


Figure 5.2. Structure and the chemical reactions of a PEM type fuel cell /5.2/

The voltage generated by one cell is low, typically below 1 V. Therefore, several cells have to be connected in order to obtain sufficient voltage and power density. This combination of multiple cells is called a **stack**. The optimum voltage range for electric propulsion motors is in the order of 200-300 V. Therefore a typical stack consists of some 250 to 350 cells.

If the fuel is pure hydrogen, the only emission from a FC is water vapour. The process temperature is also so low that no oxides of nitrogen are generated, even if air is used instead of pure oxygen.

The theoretical maximum for the thermal efficiency of the ICE is limited by the limit value for the Carnot cycle process. Depending on the compression ratio this limit value is in the 60-70 % range. However, the efficiency of a real world engine is far from that maximum. In addition to losses in the hot exhausts, energy is also wasted as internal friction, pumping losses, losses for cooling and losses by auxiliaries as the cycle used deviates from the Carnot ideal. Therefore, the maximum efficiency of automotive diesel engines is typically 40-45 %.

The fuel cell process has no similar restrictions. Therefore, it is claimed that FCs can reach efficiency values of 60-70 %, when converting pure hydrogen into electric energy /1.15/. However, if the hydrogen is less pure and contains non-reactant species like CO_2, the FC efficiency is lower. Some estimates are in the range of 40-45 %.

5.2 Fuel cell types

FCs have been built in many different ways using different types of electrolytes. Table 5.1 summarises the characteristics and key properties for different kinds of FCs. Comparing technologies is somewhat difficult as the "target is constantly moving", i.e. such a comparison is valid only for a given time. This comparison was made in 2000. PEM and PAFC (phosphoric acid) cells were considered the most suitable types for automotive applications according to /1.16/. MCFC (molten carbonate) and SOFC (solid oxide) cells operate at high temperatures, and are therefore more suited for stationary power production than for automotive applications. However, BMW has demonstrated the use of SOFC type APUs.

For light-duty vehicle applications a low operating temperature is more or less a must due to space constraints. Some heavy-duty applications with more space available could allow also systems working at high temperatures.

Table 5.1. Properties of different FC types /1.16/.

FC type	PEM Proton Exchange Membrane	AFC Alkaline FC	PAFC Phosphoric Acid FC	MCFC Molten Carbonate FC	SOFC Solid Oxide FC
Operating temperature (^{o}C)	70-80	80-100	200-220	600-650	800-1000
Current density	High	High	Moderate	Moderate	High
State of development	Early prototypes	Space applications	Early commercial applications	Field demonstrations	Laboratory demonstrations
Likely applications	Electric utility, portable power and transport	Military and space	Electric utility and transport	Electric utility	Electric utility
Advantages	• Low temperature • Quick start-up • Solid electrolyte reduces corrosion and management problems	• High performance	• High efficiency for co-generation • Can use impure hydrogen fuel	• High efficiency • Flexibility of fuels	• High efficiency • Flexibility of fuels • Solid electrolyte reduces corrosion and management problems
Disadvantages	• High sensitivity to fuel impurities • Requires expensive catalysts	• Expensive removal of carbon dioxide from fuel and air supplies	• Low current and power • Large size and weight	• High temperature enhances corrosion and breakdown of cell components	• High temperature enhances corrosion and breakdown of cell components
Prospect for high efficiency	Good	Good	Good	Good	Good
Prospect for low costs	Good	Good	Fair	Fair	Fair-good

Key features for automotive applications are:

- high power density for acceptable weight and space requirements
- good dynamics (fast response, short warm-up)
- estimated low production costs and possibilities for future mass production.

Therefore, the PEM FC is generally considered to be the most promising option for vehicles. It has good power density and good dynamics. Good dynamics means that the best available cells can follow the fluctuations in power demand that occur in normal traffic. This means that a FC vehicle based on a PEM stack can actually operate without a battery pack as energy buffer. However, stored energy can be needed for other reasons, for subsystems and start-up of both fuel processor and FC stack. In practice, most FC vehicles will have some kind of energy storage. Energy storage is also needed to enable regenerative braking.

Figure 5.3 shows a schematic structure of a PEM fuel cell /1.15/.

A fuel cell stack alone is not enough, auxiliary systems for air and water handling are also needed. This so called **“balance-of-plant”** sub-system must supply the cathode continuously with air (oxygen), and remove the generated water. Additionally, cooling is necessary to prevent the stack from overheating.

The efficiency of the subsystems will affect the total efficiency of the FC system. Therefore, it is important to design the balance of plant for optimum heat utilisation and recovery. Furthermore, if any other fuel than hydrogen is used, then also a **fuel processor** is needed as a part of the total system (see 5.3.2).

5.3 Fuelling the fuel cells

5.3.1 General

Principally all the fuel cell types presented in Table 5.1 operate on gaseous hydrogen. However, stacks operating at medium or high temperature are capable of “internal reforming”. A SOFC can also use CO as fuel. Table 5.2 lists the need for fuel reformers for different fuel cells.

Table 5.2. Need for fuel reformers for different fuels /5.3/.

Fuel cell type	Reformer required?
PEM	Yes
AFC	Yes
PAFC	Yes
MCFC	Yes[a]
SOFC	Yes[a]
DMFC[b]	No

a: Except when natural gas is used as the fuel
b: Direct Methanol Fuel Cell

The PEM FC, which has the lowest operating temperature of all FC types is also the one which is most critical regarding the fuel. The catalysts used in PEM cells are very sensitive to carbon monoxide poisoning, and thus the PEM FC in most cases (at current levels of technology) needs a very pure hydrogen fuel.

However, in addition to “normal” hydrogen-fuelled FC’s, stacks that operate on liquid methanol have been demonstrated. Even if this may sound promising, these so-called direct methanol fuel cells (DMFC) are, however, still in the early development stage; they have inferior performance compared to H_2-PEM stacks, giving only 1/5 of their power density /5.3/.

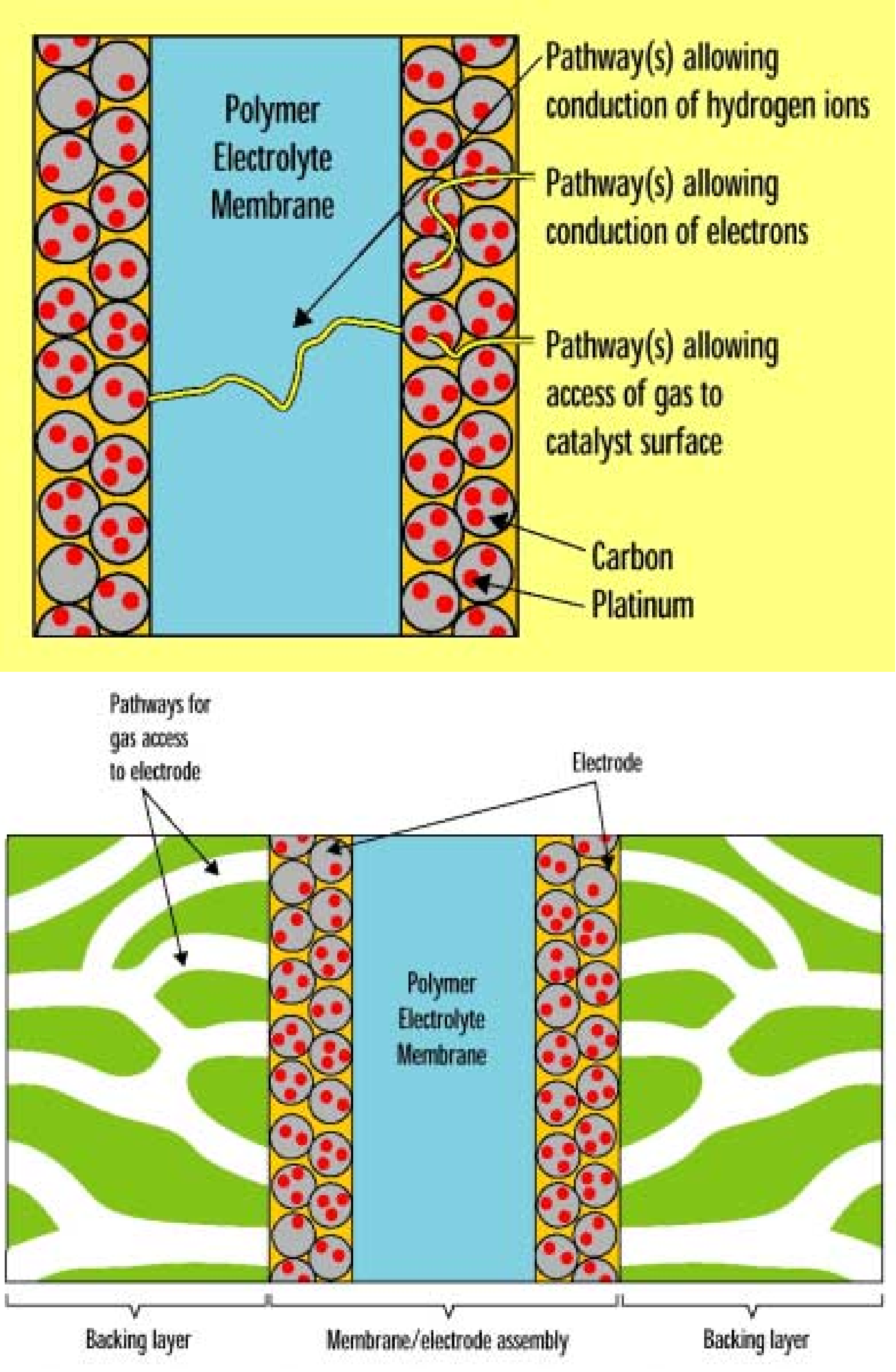


Figure 5.3. The structure of a PEM fuel cell.

Also the efficiency of a DMFC is lower than for a PEM stack, in the order of only 30%. When evaluating the total efficiency of a FC system operating on other fuels than pure hydrogen, the losses in the fuel processor should also be taken into account. Thus, the competitiveness of a direct methanol system is raised.

Even if it is estimated that commercial applications of DMFCs lie a minimum 10 years ahead, the first vehicle equipped with a DMFC was already presented by Daimler-Chrysler in late 2000. However, it was only a small Go-Cart equipped with a 3 kW DMFC /5.4/.

The question of fuel is one of the most important ones in bringing FC vehicles with PEM stacks on the market. A commercial infrastructure for hydrogen production and distribution does not yet exist. Apart from the associated cost of building new infrastructure, widespread public distribution of hydrogen presents also some technical difficulties. Gaseous hydrogen has very low energy density in storage, liquefied hydrogen in turn requires very low temperatures.

However, some of the automotive manufacturers have stated that they will launch FC vehicles in 2003 or 2004. This means that these vehicles will have to rely on fuels other than hydrogen, or as one option, hydrogen produced locally. If any other fuel than hydrogen is used, then the fuel has to be processed into hydrogen, either on-site at the refuelling station or on-board in the vehicle.

5.3.2 Fuel processor technologies

Because hydrogen supply and distribution is not readily available, most of the automotive companies involved have also built FC demonstrator vehicles that include on-board fuel processors that can produce hydrogen-rich gas to fuel the FC.

The most important processes for hydrogen production from hydrocarbons using the chemical route are /5.3/:

- steam reforming (STM)
- partial oxidation (POX)
- water gas shift (WGS), needed in all reforming
- autothermal reforming (ATR), a process which combines STM and POX, utilising process heat for neutral energy balance (POX is exothermic, STM is endothermic, supplementary energy is needed for start-up)

Steam reforming of hydrocarbon fuels, described in equations 1, 2 and 3, is an efficient method for producing hydrogen /5.5/:

$$C_nH_m + n\,H_2O \rightarrow nCO + (n + m/2)\,H_2 \qquad \Delta H° < 0 \qquad (1)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H° = -41\text{ kJ/mol} \qquad (2)$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \qquad \Delta H° = -206\text{ kJ/mol} \qquad (3)$$

The major products observed in steam reforming are CO, CO_2, CH_4 and H_2. At low temperatures and pressures, CO_2 and H_2 are the favoured products, and the concentration of CO increases as the reaction temperature increases. Equation (2) is the reversible water gas shift reaction.

The STM process is endothermic, so the STM reactor needs to be heated. The required temperature level when operating on methanol is around 200 ^{o}C /1.15/, and some 800-1300 ^{o}C for hydrocarbons /5.6,5.7/. For this reason methanol is the preferred alternative. Part of the fuel is burned in a separate burner to provide process heat.

In partial oxidation the fuel itself is partly combusted to produce a synthesis gas that consists of H_2, CO and CO_2. Thus the process is exothermic. The synthesis gas can be converted into pure hydrogen by converting the carbon monoxide and water into carbon dioxide and hydrogen (water gas shift) and by subsequently separating the carbon dioxide.

An idealised equation for the combustion of any hydrocarbon fuel can be written as /5.8/:

$$C_nH_mO_p + x(O_2+3.76N_2) + (2n-2x-p)H_2O = nCO_2 + (2n-2x-p+m/2)H_2 + 3.76xN_2 \quad (4),$$

where x is the oxygen-to-fuel molar ratio .

This ratio is a very important parameter because it determines:

a) the amount of water required to convert the carbon to carbon dioxide
b) the hydrogen yield (moles)
c) the concentration (mole-%) of hydrogen in the product, and
d) the heat of reaction

When x = 0, Equation (4) reduces to the endothermic steam reforming reaction, when x = 12.5, Equation (4) is the reaction for complete combustion. The partial oxidation reactor should be operated in a manner that the overall reaction is exothermic, but at a low value of x, so that higher hydrogen yields and concentrations are favoured.

A POX reactor operates at a temperature level of around 1000 ^{o}C or in a catalytic version at 700 ^{o}C /1.15/.

The water-gas shift reactor is a critical component of the fuel processor. It reduces the carbon monoxide concentration and increases the yield of hydrogen. Commercial catalysts used for water-gas shift reactions are unsuitable for transportation due to their insufficient reactivity (high weight and volume) and their tendency to degrade under the severe conditions encountered in an automotive system. Meeting the need for water-gas shift catalysts is critical to the commercial success of automotive PEM fuel cell systems /5.9/.

The feed gas to the FC stack may contain hydrogen and carbon dioxide, but not carbon monoxide, as carbon monoxide is poisonous for precious metal catalysts of PEM- type FC. Final CO clean-up takes place in a catalytic PrOX (preferential oxidation) reactor after the reformer. The PrOX reactor lowers carbon monoxide levels below 10 ppm. To optimise total efficiency, the heat from this “clean-up” oxidation reaction should also be utilised as process heat.

All three processes (STM, POX, ATR) can be used in automotive applications. The configuration will depend on the fuel to be used. Top-of-the-line fuels at this moment for this purpose are methanol and gasoline, although commercial gasoline grades of today might not be suitable, for reasons described later on in the next chapter. For example, sulphur will hamper the performance or even destroy the catalysts needed in the fuel processors. Other fuels discussed in this context are ethanol, DME (di-methyl-ether) and for obvious reasons also natural gas.

Figure 5.4 shows the schematics of a fuel STM processor system and Figure 5.5 the schematics of a POX/PrOX system. Figure 5.6 gives an example of prototype fuel processor.

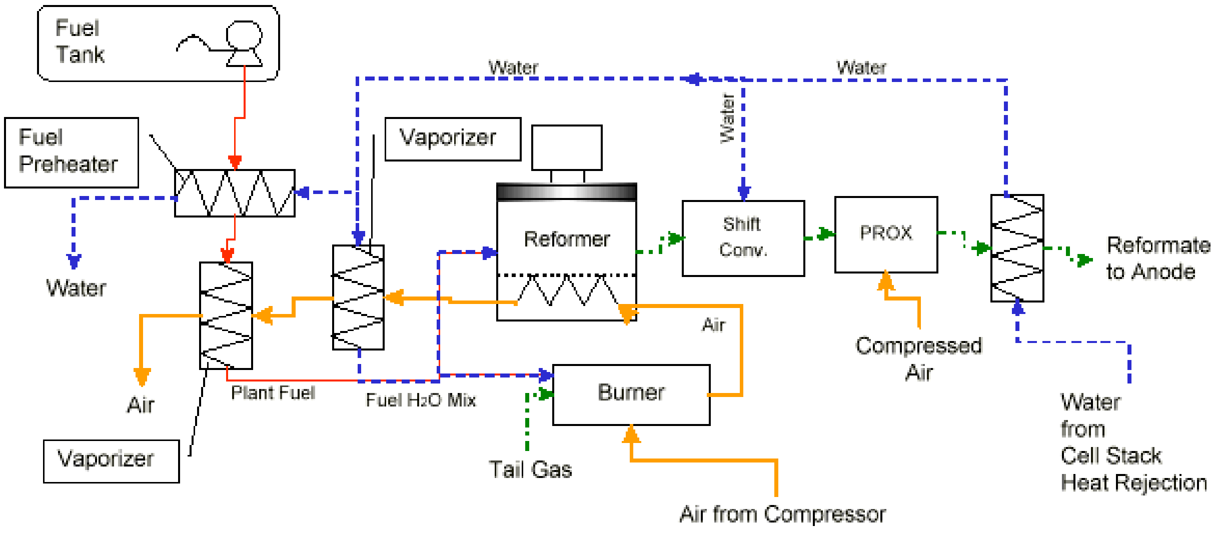
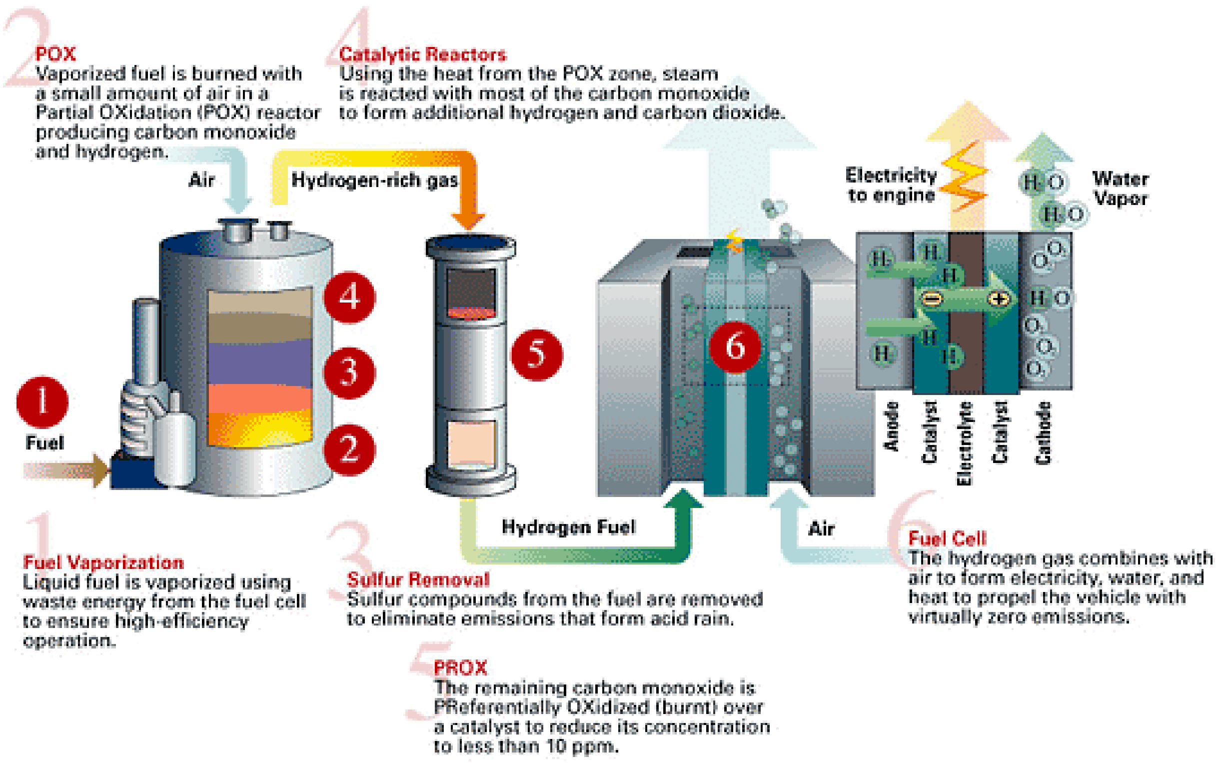


Figure 5.4. A STM fuel processor system /5.3/.



POX
Vaporized fuel is burned with a small amount of air in a Partial OXidation (POX) reactor producing carbon monoxide and hydrogen.

Catalytic Reactors
Using the heat from the POX zone, steam is reacted with most of the carbon monoxide to form additional hydrogen and carbon dioxide.

Fuel Vaporization
Liquid fuel is vaporized using waste energy from the fuel cell to ensure high-efficiency operation.

Sulfur Removal
Sulfur compounds from the fuel are removed to eliminate emissions that form acid rain.

Fuel Cell
The hydrogen gas combines with air to form electricity, water, and heat to propel the vehicle with virtually zero emissions.

PROX
The remaining carbon monoxide is PReferentially OXidized (burnt) over a catalyst to reduce its concentration to less than 10 ppm.

Figure 5.5. Schematics of a POX/PrOX fuel processor system /5.10/.

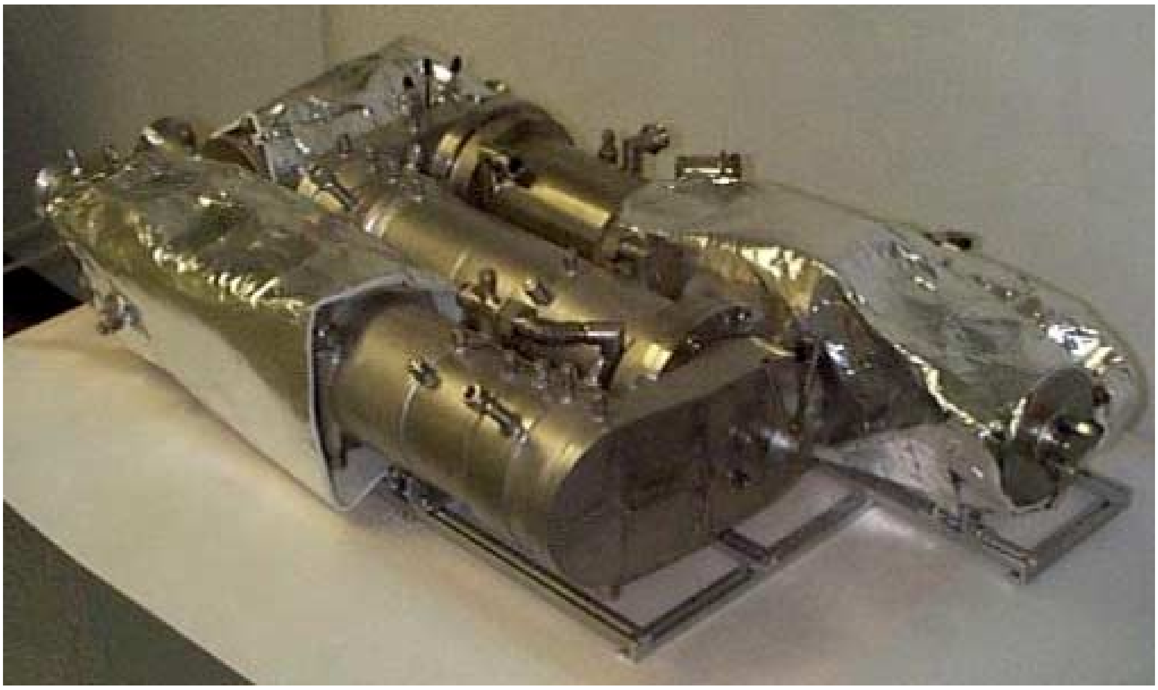


Figure 5.6. GM's 3rd generation prototype fuel processors for gasoline /5.20/.

The system in Figure 5.4 contains the following major parts:

- burner for process heat
- steam reformer
- water shift reactor
- preferential oxidation reactor
- heat recovery systems

There is work going on to simplify reformers. One idea is a single step reactor combining a steam reformer with hydrogen-permeable membranes so that the hydrogen produced can be extracted through the membranes. As a result, the reactors can be smaller and operated at lower temperature. Furthermore, a membrane reactor delivers pure hydrogen to the fuel cell, eliminating the need for additional shift and PrOX reactors to remove the CO /5.5/.

5.3.3 Fuel options for fuel processors

Liquid fuels have many advantages over gaseous fuels regarding distribution and storage. Therefore, **methanol** has been listed as one potential fuel option. Even if methanol is produced in large quantities and is a common industrial chemical, no widespread "retail" distribution system exists at the moment. However, introducing methanol at refuelling stations would present a smaller problem and lower cost burden than building a hydrogen distribution system based on centralised hydrogen production.

There are also fuel processors that can handle **gasoline**, or perhaps more correctly, **hydrocarbon blends**. However, current commercial gasoline qualities are not necessarily suitable for FC applications. This is partly due to the high sulphur content, partly due to the fact that ICE engines require gasoline with a certain octane level, specific evaporation characteristics, additives for inlet system cleanliness etc. These properties are not of any significance, if the gasoline is used for fuel processor feed, and would in a sense be wasted. Sulphur-free diesel might also be a fuel option.

Therefore, it is difficult to see that gasoline could be fully optimised for use in both ICE and FC vehicles. Perhaps the fuel for FC vehicles could be some special very low sulphur hydrocarbon cuts. This, however, would again mean that an additional, parallel refuelling system would be needed for FC vehicles.

Natural gas (NG), on the other hand, could play a significant role in fuelling FC vehicles. This could be accomplished either through on-site or on-board reforming. Some areas in the world have an extensive natural gas pipeline network both for household and industrial purposes. The number of NG refuelling stations is also increasing steadily. Relatively small on-site reformers could conveniently be placed at natural gas refuelling stations or other locations alongside the natural gas pipeline network. The equipment to refuel gaseous hydrogen is in principle similar to equipment used for compressed natural gas.

Natural gas is well suited for reforming. Many oil refineries use natural gas for hydrogen production by steam reforming. Hydrogen is used for upgrading processes like hydrocracking and desulphurisation to produce high-quality transportation fuels /5.12/. Methane would in many ways be an ideal hydrocarbon feed for reforming. However, at the current technical level of natural gas storage (CNG, LNG), in an on-board application this may lead to problems with space requirements and weight, especially for light-duty vehicles.

There are, however, quite substantial variations in natural gas composition and quality in different parts of the world and even within certain regions. This sometimes creates problems using natural gas as an automotive fuel, and would have to be taken into consideration also considering natural gas as a fuel for FC vehicles or as a source for hydrogen production by reformation.

Even in conventional ICE vehicles, it can sometimes be difficult to fit in CNG cylinders to give adequate operating range. Some of the prototype FC systems are rather bulky and heavy, combining this with CNG tanks could result in excess complexity, weight and space problems. On the other hand, a FC system should give better fuel economy than an ICE and this would mean that for equal range, smaller CNG tanks would be needed on a FC vehicle than in an ordinary vehicle. One could also elaborate on the idea of having LNG as a fuel for FC vehicles.

Furthermore, considering the use of NG as FC fuel, SOFC offers considerable advantages, as it can be fuelled directly with NG. Hydrogen is produced with internal reformation process, because of the high working temperature. As solid-oxide electrodes are also well tolerant to CO (actually CO serves as fuel), partial impurities contained in the reformate gas would not harm the cell. The NG must, however, be free of sulphur. High operating temperature and slow start-up make SOFC less desirable for automotive use, but in heavy-duty applications, it could present a viable alternative.

Appendix 1 gives an example of a table listing different fuel options for fuel cell vehicles /1.15/.

5.3.4 Comparing reformation efficiencies

Reforming of methanol and hydrocarbons differ from each other regarding not only temperature but also energy requirement and product gas composition and purity.

Table 5.3 gives the chemical formula, heating value, hydrogen to carbon ratio, hydrogen mass content and calculated hydrogen energy yield for different fuels/compounds. Two different values for the hydrogen yield are calculated:

- steam reforming, no water gas shift reaction, equation (1) only
- steam reforming + water gas shift reaction, the WGS reaction calculated with low yield, (1) + (2)

Table 5.3. Chemical formulae, hydrogen-to-carbon ratio, hydrogen content and the energy share of the hydrogen part. Heating values based on /5.13/, WGS efficiency /5.9/.

Fuel/component	Formula	Heating value MJ/kg	H/C-ratio (-)	Hydrogen content (mass-%)	H_2 energy yield STM only MJ/kg fuel (% of feed)	H_2 energy yield STM +WGS (low yield) MJ/kg fuel (% of feed)
Methanol	CH_3OH	19.7	4	12.6	15.1 (77)	15.8 (81)
Methane (natural gas)	CH_4	50.0	4	25.1	30.0 (60)	46.7 (93)
Propane (LPG)	C_3H_8	46.3	2.67	18.3	22.0 (48)	40.1 (87)
Iso-octane (gasoline)	C_8H_{18}	44.6	2.25	15.9	19.1 (43)	37.8 (85)
Cetane (diesel)	$C_{16}H_{34}$	43.5	2.12	15.0	18.1 (42)	37.0 (85)

The energy yield for STM only corresponds to the reaction (1) without watergas shift reaction. This value varies from 77 % (methanol) to 42 % (diesel). For hydrocarbons, the WGS reaction increases hydrogen yield considerably, and the WGS is the more important the longer the carbon chain is.

The highest hydrogen yield, over 90 % of the energy in the original fuel, can be achieved with methane. Methanol gives a high yield from the STM reaction, but the WGS reaction does not improve the overall yield very much.

These calculations are theoretical and do not take into account the energy needed to heat the STM reactor. The actual differences in efficiency between the fuels could be smaller, as there are differences in temperature needed for the STM reactor (methanol having the lowest reaction temperature). Independent of the fuel, hydrogen yields corresponding to some 80 % of the original fuel energy content should be achievable. The reformer efficiency curve shown in Figure 2.2 (source Volkswagen) gives reformer efficiency values of some 80-85 % for the greater part of the load range.

Table 5.4 gives another estimate on the hydrogen yield of reforming processes (STM and POX, including water gas shift) for different fuels according to /5.3/. In this case the energy yield values for STM is over 100 %, which indicates that the WGS must have been calculated at a theoretical maximum, and that heat for the STM reactor is not accounted for. The energy yield for the STM varies in a very narrow band for all fuels. The partial oxidation route gives lower yields (process heat from the fuel itself). The efficiency values indicate that methane would be the preferred fuel.

Table 5.4. Hydrogen yield (in kg H_2/kg fuel) of reforming processes for different fuels /5.3/. A figure for relative energy has been introduced by taking into account the heating value of the original fuel.

Fuel	STM kg/kg	STM relative mass (%)	STM energy yield (%)	POX kg/kg	POX relative mass (%)	POX energy yield (%)
Methanol	0.189	100	115	0.126	100	77
LNG (methane)	0.503	266	121	0.377	299	90
LPG	0.456	241	118	0.316	250	82
N-octane	0.430	227	116	0.284	225	76
Diesel	0.424	224	118	0.279	221	78

Calculated on mass bases, nearly three times more methanol is needed to produce a certain amount of hydrogen compared to natural gas (methane). This is a detail that to some extent alleviates the problem of heavy CNG fuel storage on board a FC vehicle, as the mass of the fuel itself for a given vehicle range is only 1/3 with natural gas as compared to methanol.

5.4 The complete vehicle FC system

A complete FC system for a vehicle fuelled with methanol or hydrocarbons is, for obvious reasons, quite complicated. In addition to the FC stack itself, the system comprised the fuel processor, the air and water systems and the systems for heat transfer. Figure 5.7 is a schematic presentation of the main components and main flows in a methanol fuelled FC system. Figure 5.8 shows the complete system of a FC vehicle, including drive motor, power conditioner and batteries.

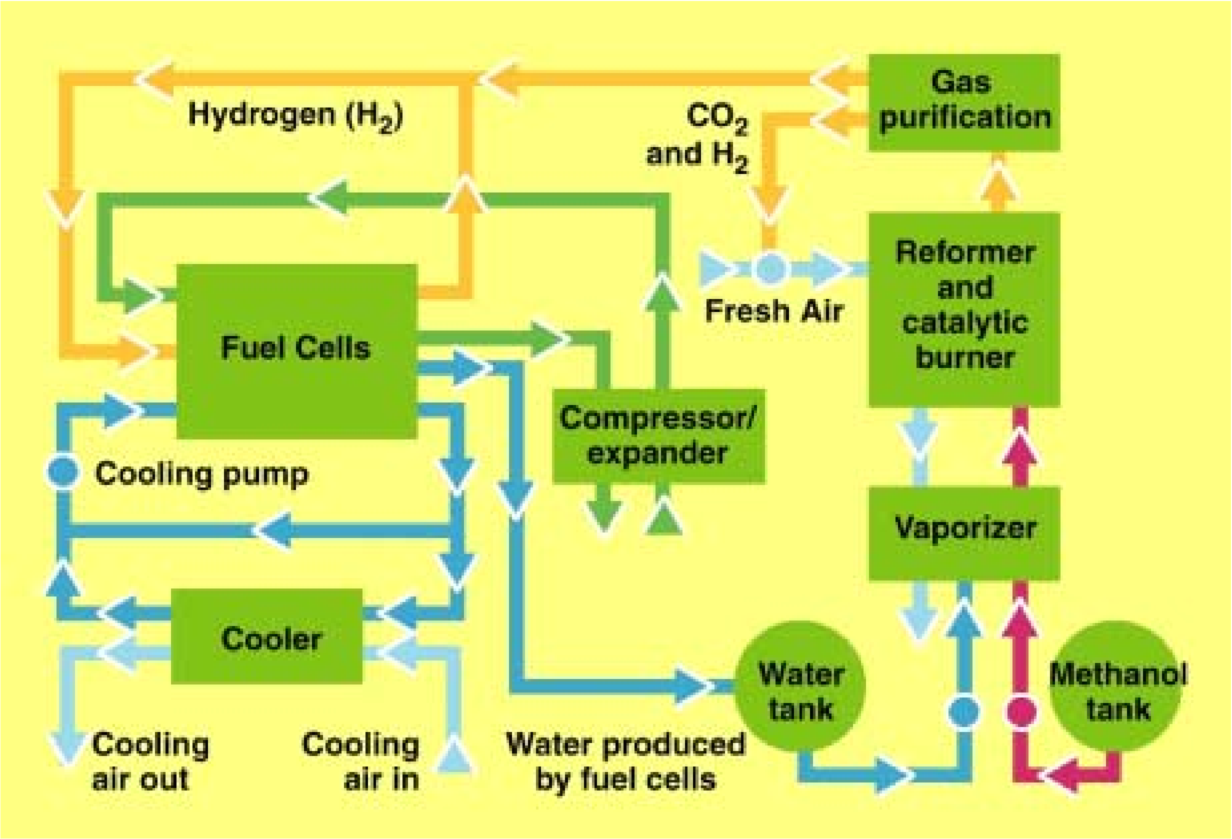


Figure 5.7. A schematic presentation of the main components and main flows in a methanol fuelled FC system /1.15/.

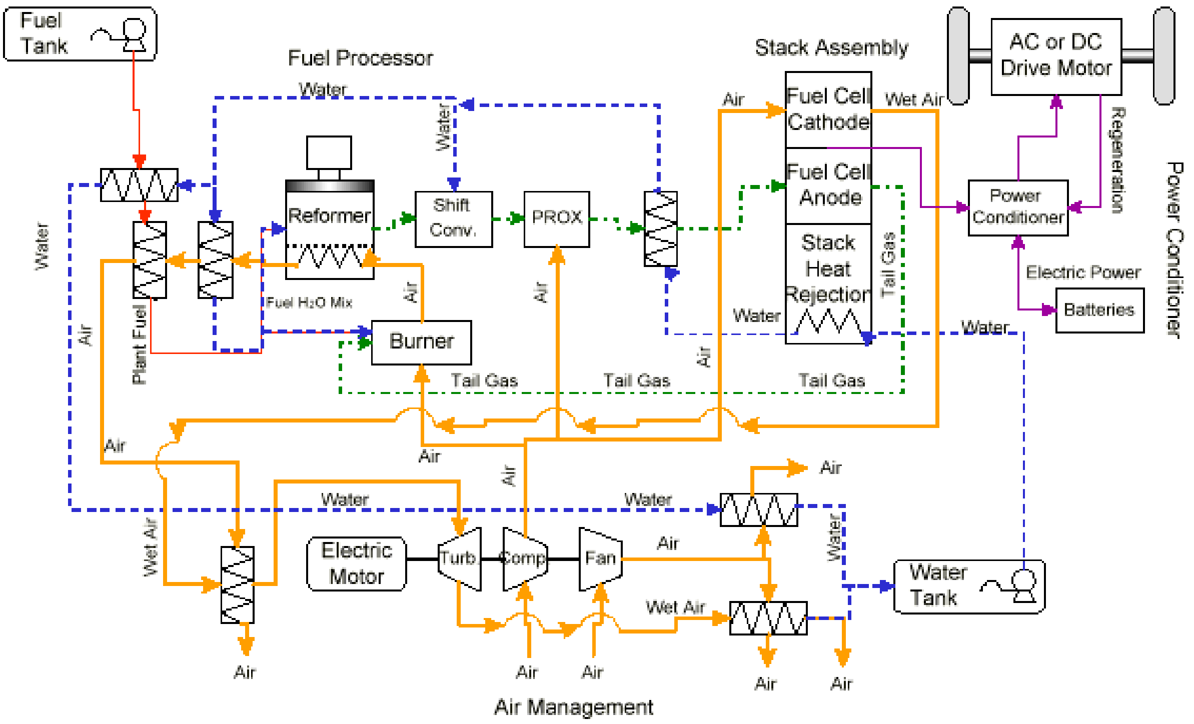


Figure 5.8. The complete system of a FC vehicle, including drive motor, power conditioner and batteries /5.3/.

5.5 Possibilities for distributed power

There are already commercial FC units for distributed power production. One example of such a unit is the 200 kWe PC 25 unit by IFC. This unit based on a PAFC and a fuel reformer is designed to run on natural gas or biogas. IFC states that it is also developing small PEM type FCs for light commercial and residential applications in the power range below 10 kW /5.14/. Figure 5.9 shows such a small FC unit. There is also a vision that small FCs could replace dry batteries in portable equipment like hand-held tools, radios, computers etc. The company Methanex is actively promoting methanol as a fuel for transportation, stationary power and portable power /5.15/.

A FC vehicle presents an interesting possibility of producing power-grid quality electricity for on-board and off-board applications. A FC vehicle could even supply a house.

Furthermore, a large number of FCs connected to the grid could even act as a distributed power system. Thus the expensive FC system would be used far more than its few running hours in transport use yielding to better payback. Also power grid load would be more balanced and distribution losses would lower. However, apart from pure technical difficulties in creating such a decentralised system, many institutional hurdles need to be removed, even if stationary FC based, small-scale combined heat and power (μCHP) units are already on the brink of commercialisation.

If FC vehicles were to contribute to distributed power, then the fuel would have to be methanol, gasoline, diesel or preferably natural gas. Using hydrogen produced by electrolysis in a decentralised on-site system would not add energy to the power grid, but would provide the possibility of equalising loads.

Figure 5.9. A small FC unit for residential applications /5.14/.

5.6 Alliances and joint-ventures for stack and fuel processor development

The industry leader in PEM FC stack development is Ballard Power Systems (Vancouver, B.C.). It started the R&D to build FC systems targeted mainly for transport applications as early as the 1980's. In the 1996, it formed an alliance with Daimler-Benz, another pioneering company in FC transport applications. Subsequently, Daimler was merged with Chrysler to become DaimlerChrysler, and a third major OEM, Ford, was also taken aboard. In 1999, this alliance resulted in a co-owned company now called XCELLSiS ("the Fuel cell engine company"), formerly known also as dbb. Its purpose is the development and commercialisation of fuel cell power for transport applications, both light and heavy duty. XCELLSiS is focussed on hydrogen and methanol as fuels for FC vehicles, and has teamed up with BASF, BP, Methanex and Statoil for methanol co-operation /5.16/.

Apart from XCELLSiS, this alliance has also founded another co-owned R&D company, Ecostar. It's mission is to develop traction-inverter modules (TIM) and electric traction motors (ETM) to be used in conjunction with FC to produce complete vehicle powerplants /5.14/.

The complicated cross-ownership relations between DC, Ford and Ballard in XCELLSiS and Ecostar were restructured in late 2001, when Ballard acquired sole ownership of these companies, but in this move, DC and Ford became direct minority shareholders of Ballard Power Systems (BPS).

BPS has also been active in acquiring exclusive rights to many technologies needed in fuel cell manufacturing. In this process it has joint operations e.g. with MicroCoating Technologies (MCT), from which company BPS bought exclusive rights for the manufacturing process in catalytic coating that MCT had developed /5.26/. Access to key materials in FC stack was secured by allying with UCAR International Inc., the developer of GRAFOIL® /5.27/ and Textron Systems, from which all carbon material operations were acquired by BPS in May 2001 /5.28/.

Among others GM /5.10/, Chrysler /5.17/, Argonne National Laboratory /5.18/ and AD Little /5.19/ have actively been developing fuel processors for gasoline type hydrocarbon mixes. GM already claims to have produced the world's first gasoline-fuelled FC vehicle /5.20/ using their Gen III fuel processor. However, the performance of this GM system is still rather modest, and it is far from being production-ready. It is, however, a clear signal of GM's commitment to use hydrocarbon fuels in FC vehicles.

AD Little founded a special company, Epyx, for fuel processor development. Epyx developed and demonstrated a fuel processor containing a stage for sulphur removal that was targeted to use Californian RFG2-type gasoline as feedstock. Furthermore, in late 2000, Epyx was merged with the Italian De Nora company to form a company devoted to complete FC system development called Nuvera Fuel Cells /5.21/.

The oil companies are also active. Since 1995 ExxonMobil has had an alliance with GM on the development of fuel processors for gasoline /5.22/. In 1998 this joint venture was augmented with Toyota Motor Co. /5.23/. The alliance between Toyota and GM has also been strengthening all the time /5.29/, /5.30/.

Furthermore, Shell has teamed up with the XCELLSiS to develop their own alternative process called CPO (catalytic partial oxidation) to produce hydrogen with high yield from hydrocarbon mixes /5.24/. This process is claimed to have a shorter start-up period than other types of processors.

In the fall of 2000, Shell Hydrogen US, a division of Shell Oil Products Company, and International Fuel Cells, a subsidiary of United Technologies Corporation, announced their intention to establish a 50-50 joint venture company to develop, manufacture, and sell fuel processors for the emerging fuel cell and hydrogen fuel markets. The establishing of this new company, HydrogenSource LLC, was announced in June, 2001. IFC claims that it has succeeded in developing a proprietary desulphurisation process that allows the use of today's pump-grade gasoline as a fuel for fuel cells. IFC demonstrated this technology in 2000, when it delivered to the U.S. Department of Energy a complete system capable of running an automobile-sized fuel cell on pump-grade gasoline /5.14/

In late 2001 Texaco announced the formation of Texaco Energy Systems that would specialise in fuel processing reforming technologies suitable for FC vehicles. It has also formed an alliance with Energy Conversion Devices (ECD), a notable patent holder and a potent developer of batteries for electric and hybrid cars and advanced hydrogen storage systems like Ovonics and other hydride-based technologies. Texaco owns a 20% share of ECD. Formerly, EDC was working closely with Shell Hydrogen, but this joint venture ceased in 1999 /5.25/.

5.7 Progress in performance and time to market scenarios

The development of fuel cell power plant for automotive use is quite active, and many major automotive OEM’s have already announced their plans to produce such vehicles in the near future. When DaimlerChrysler announced their NECAR 5 prototype in November 2000, they also stated that similar vehicles could be series produced and put on road in 2004. As Ford is strongly allied with DC and BPS, their plans are closely aligned. Furthermore, Toyota has recently announced /5.31/ that it has plans to produce 30 to 50 hydrogen-fuelled vehicles based on their of their FCHV-4 prototype, as soon as year 2003. A similar schedule, but without any numbers on vehicles, has also been released by Honda /5.33/.

However, these are only starting points, where cars to be placed in the hands of only some “qualified customers” will take part in different demonstrations and field tests. Higher production volumes and such vehicles could enter normal circulation are expected from 2010 onwards. Some experts see that it would be close to year 2025 before the FC could seriously challenge the ICE as the prime mover in automobiles, although in other vehicles and applications this could happen much sooner.

The race in FC stack performance is also on. The latest development stage of Ballard Power System's FC is called Mark 902, and it was announced publicly in November 2001 /5.32/. This 4th generation stack produces 85 kW, but Ballard has not disclosed any definite power-to-weight ratio for it. A new feature over the previous Mk 900 from January 2001, is that this same architecture could easily be used to scale the power between 10 to 300 kW.

Quite a close match is the GM2000 cell that was publicised in September 2001. It is powering their HydroGen3 FC vehicle based on the Opel Zafira body. Power output is 94 kW (continuous), and 129 kW (peak) /5.20/. It is developed by GM's GAPC (Global Alternative Propulsion Center), has 200 cells and measures 472 mm x 251 mm x 496 mm. Power density is 1.6 kW/litre and 0.94 kW/kg. The dynamics of this cell are so good, that it does not require buffer battery, as its predecessor in HydroGen2 did.

Both of these cells demonstrate that power densities are already quite close to what is an acceptable level to start speaking of powering real-world customer vehicles. What remains is the wide gap in costs/kW that still exists between ICE and FC power units, although the improvement has been continuous. There is still considerable expenditure in FC stack in precious metals, and currently only the cost of these essential catalytic layers cause the price of the whole stack to exceed some 50 USD/kW. Therefore, there is certainly much room for further improvement. But at least for the US based companies, the recent announcement of the Bush administration that it will waive all further public support for ICE based powertrain development in the PNGV (Partnership for New Generation Vehicles) initiative in favour of fuel cell power must be highly welcome.

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6. Hydrogen as a fuel

6.1 General

Although the hydrogen atom is the most commonplace element in the universe, it is found in nature only in compound form. Therefore, hydrogen gas must first be produced through the use of energy, before it becomes available to produce power. In production, both primary energy sources (NG, oil, coal) or secondary energy carrier (electricity, methanol) can be employed. In a sense, hydrogen is not a fuel, but an energy carrier, and depending on the production process, it can contain various amounts of "carbon-based energy", or even be totally "carbon-free".

The use of hydrogen as an automotive fuel is closely linked to the introduction of FC power, although a traditional ICE can also be converted to run on hydrogen. Perhaps the longest pioneering development of such technology has been carried out by BMW /2.3/ and Daimler-Benz, but others, such as Ford, have followed more recently /5.16/.

Because hydrogen is in gaseous form, its storage and distribution pose some difficulties as compared to traditional, liquid fuels. Since it is also highly flammable, a number of safety precautions are also called for, before it becomes a viable option for widespread use. However, since it has been used for industrial purposes for more than 100 years, technology and solutions to overcome most of these hurdles do exist.

6.2 Production

6.2.1 Volumes and sources

Today approximately 500 billion Nm^3 of hydrogen is traded worldwide. The vast majority of this volume originates from fossil fuel sources (NG, oil) or as a by-product in the chemical industry or from crude oil refining processes. The production of hydrogen as a by-product accounts for 190 billion Nm^3 worldwide (38 %), of which about 2 % or 10 billion Nm^3 stems from chlorine-alkaline electrolysis. /1.14/.

6.2.2 Electrolysis

The simplest way of producing hydrogen is electrolysis, where water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) by an electric current. Water is oxidised on the anode forming oxygen ($O_2 + 4H^+ + 4e^-$) and reduced at the cathode forming hydrogen ($H_2 + 4OH^-$) /1.14/.

The electrolysis process itself is well-known and quite simple, but rather energy intensive. Currently, less than 0.2% of world hydrogen is produced in this way. Electrolysis could also be used as a small-scale "household" device fuelling one or two cars (*see Figure 6.1*). This kind of technology is already commercially available /6.1/, /6.2/. However, this would put more load on the local electric grid and not contribute to the goal of decentralised, distributed power production, as described in 5.6.

In large scale operations electrolysis could also be further refined (e.g. by pressurisation), and used to exploit the electricity produced by renewable, but remote energy such as geothermal energy in Iceland /6.3/ and hydropower in Norway /6.4/. Even if hydrogen is rather cumbersome to transport, it can be seen as a plausible alternative for long-range transport of electricity. It has also been seen as having potential as a lucrative storage medium of electricity generated by photovoltaics, i.e. solar panels, solar thermal energy or wind turbines /6.5/.

Figure 6.1. Small "household" scale hydrogen generator /6.1/.

Another, and today also more important source than water electrolysis for industrial hydrogen is the H_2 formed as by-product from the chlorine-alkaline electrolysis, which is used e.g. during the manufacture of PVC.

6.2.3 Thermochemical reforming

6.2.3.1 Large scale, centralised production

As already stated, most of the world hydrogen is today produced from fossil feedstock using different thermochemical reforming processes.

The basic processes for thermochemical reforming have been described in 5.3.2.

Considering large-scale central off-site or even smaller size on-site production, the most important is **steam reforming of natural gas**. Steam reforming (STM) involves the endothermic, catalytic conversion of light hydrocarbons with water vapour. It produces a mix of hydrogen and carbon monoxide. Industry scale processes are normally carried out at temperatures of 850°C and pressures in the order of 2.5 MPa /1.14/.

Steam reforming is followed by the water-gas shift reaction, which increases the hydrogen yield by combining carbon monoxide and water into hydrogen and carbon dioxide. The energy released from this reaction cannot however be directly used for reformation. Using absorption or membrane separation, the carbon dioxide is removed from the gas mixture, which is further cleaned to remove other unwanted components. The left-over gas consisting of approximately 60% combustible parts (H_2, CH_4, CO) is re-routed to fuel the reformer /1.14/.

The process is technically well proven, and industrial scale steam reforming plants have capacities in the order of 100,000 Nm^3 H_2/h.

Another major production process is **partial oxidation of hydrocarbons.** Partial oxidation (POX) or gasification is an exothermic conversion of heavy hydrocarbons (e.g. residual oil from the treatment of crude oil) with oxygen and steam into synthesis gas. If the quantities of oxygen and water vapor are correctly controlled, gasification can continue without the need for external energy input, hence is autothermal. The synthesis gas can be used for hydrogen production or the production of liquid fuels (methanol, synfuels) or chemicals (ammonia). Compared with on-board reforming, the POX- route on an industrial scale uses low-grade fuels.

As with STM of NG, industrial scale production in partial oxidisers is carried out in plant capacities of the order of 100 000 Nm^3 H_2/h. This process is also technically well-proven /1.14/.

Should coal be available at low cost, **partial oxidation of coal** is also a viable option. Apart from the necessary initial preparation of the coal, the process elements of the plant as a whole are the same as for the gasification of oil. The coal is ground to a fine powder and then mixed with water to create a 50 - 70% solid content suspension suitable for pumping /1.14/.

This process is only carried out on a commercial basis in the coal rich countries of South Africa and China. As a matter of fact, a significant part of the transport fuels in South Africa is currently made by gasification of coal and the Fischer-Tropsch synthesis to produce liquid synthetic fuels.

Large-scale production units would make it possible to recover carbon dioxide, and thus give a carbon free fuel cycle even if the original fuel is a fossil fuel. Obviously, biomass could also be used as a starting point for hydrogen or synfuels production.

The Norwegian energy company Norsk Hydro has plans for carbon dioxide free production of fuels, chemicals and electric power based on natural gas. /6.6/, /6.7/. The basic idea is to separate the carbon dioxide and to pump it and store it in oil and gas wellheads. This would both prevent the carbon dioxide ending up in the atmosphere and also increase the yields of oil and gas wells. Norsk Hydro also has a long history in producing hydrogen through electrolysis. Figure 6.2 shows the principle of carbon dioxide removal and storage (sequestering) and Figure 6.3 the Norsk Hydro view on why hydrogen is interesting as an energy carrier.

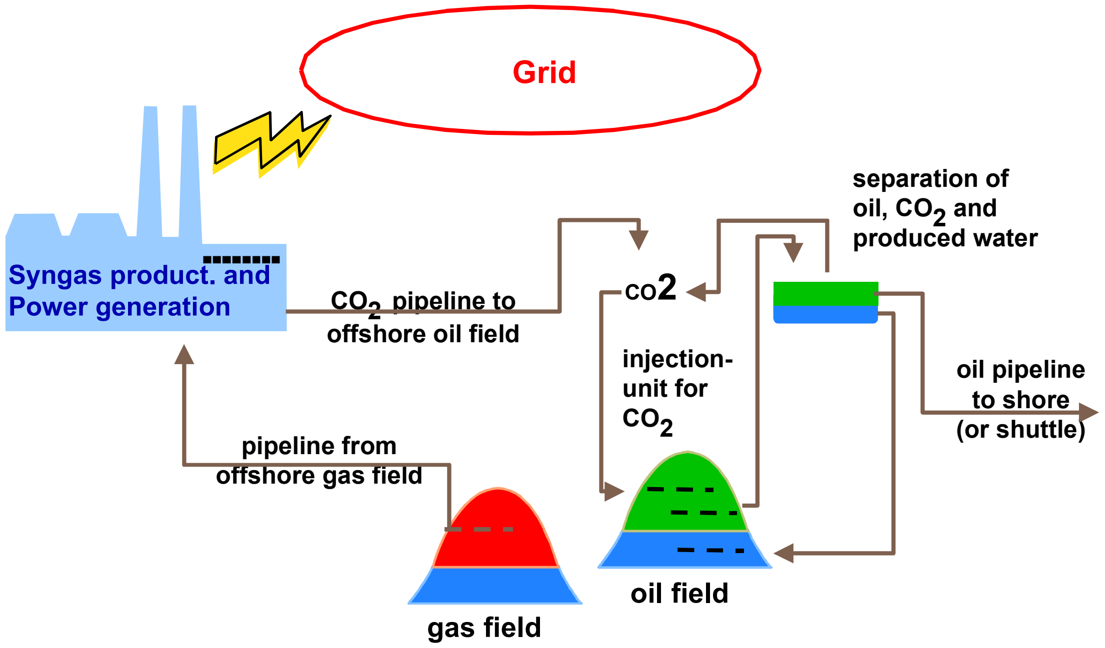

Figure 6.2. Carbon dioxide sequestering for carbon free production of electricity and fuels /6.6 /.

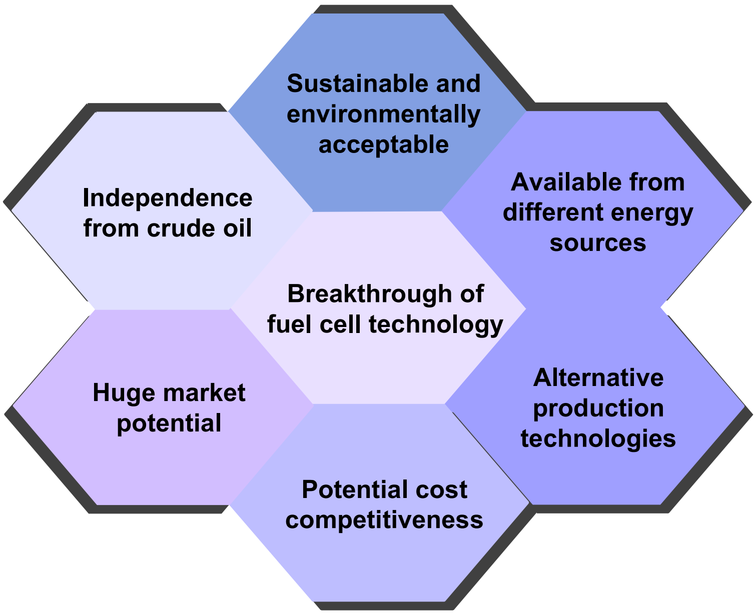

Figure 6.3. The Norsk Hydro view on why to promote hydrogen /6.6/.

6.2.3.2 Small-scale, on-site/on-board production

As described in Chapter 5.3.2, small-scale reactors called "*fuel processors*" have been developed to produce hydrogen on board a vehicle. As discussed in Chapter 5.4.3, various candidates are offered as feedstock for these devices. Because the best energy density is probably achieved with liquid fuels, gasoline and methanol are of prime interest. However, new kinds of H_2 storage technologies could also spur the use of NG, as many of them like ultra-high pressure compression or cryogenic liquefaction could even be used with NG.

Whereas NG may not be the first option for on-board reforming, it is highly advantageous as feedstock for local, on-site reformers that can convert NG distributed via pipeline to hydrogen. Such technology is announced as being almost readily available /6.8/, /6.9/, /6.10/, /6.11/ and could form an important backbone for the building of a hydrogen infrastructure. Figure 6.4 gives a schematic lay-out example.

When on-site and especially on-board reforming is used, there are little or no possibilities for carbon dioxide recovery. Thus, if the main target is a carbon free fuel cycle, the only viable options are hydrogen production by reforming in large units in combination with carbon dioxide sequestering, using biomass as feedstock for hydrogen production, or alternatively production of hydrogen by electrolysis using electricity generated from renewable sources or nuclear power.

6.2.3.3 Other possibilities

Gasification of biomass, **biomass fermentation** and quite recently, also **biological production** of hydrogen have been investigated. Among the options that are being developed are biological water gas shift reaction with some photosynthetic bacteria and production of hydrogen with special mutant strains of algae-bacteria /6.12/, /6.13/.

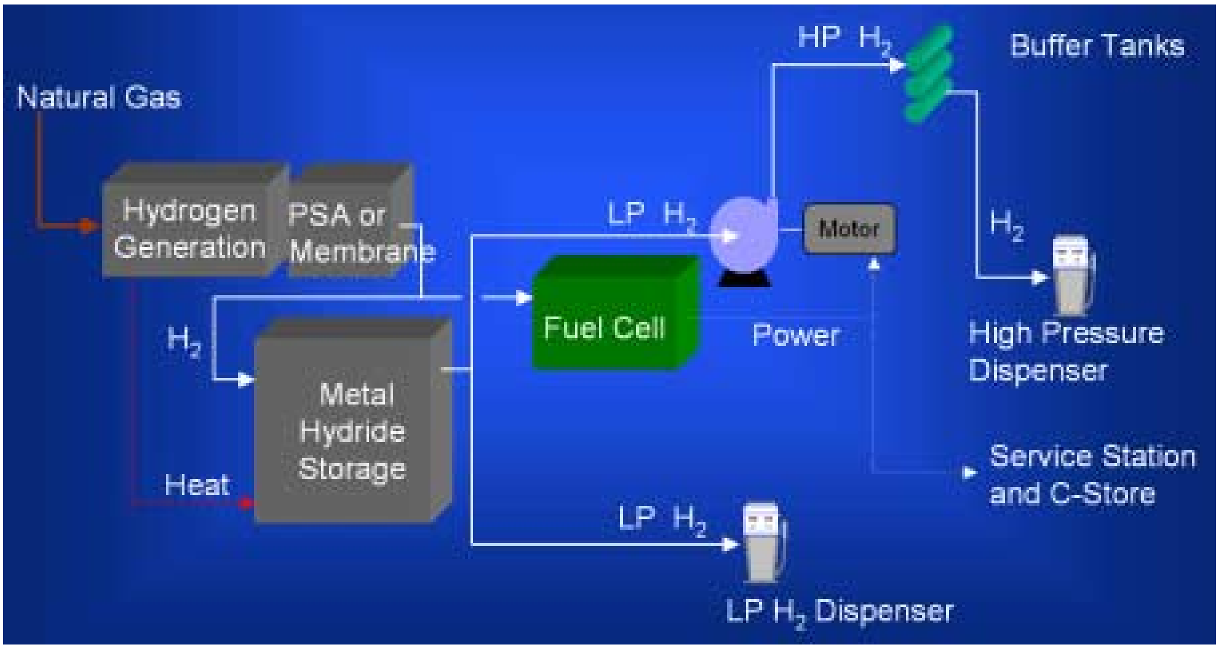

Figure 6.4. Hydrogen filling station based on local hydrogen generation from natural gas /6.10/

6.3 Infrastructure and storage of hydrogen

6.3.1 Storage options

The main three options for storing hydrogen, either stationary on-site, or on board a vehicle are:

- Gaseous, compressed H_2 [GH_2]
- Cryogenically liquefied H_2, [LH_2]
- Chemically bound hydrogen, e.g. in metal hydrides

A new and promising technology based on so called "*carbon nanotubes*" has been also announced. However, these are only on a laboratory-scale, and a viable "proof of concept" has not been shown yet.

One of the basic difficulties with gaseous hydrogen is the low energy density. This is demonstrated in Figure 6.5, which compares the driving distances derived from different 100 kg fuel and storage "packages".

6.3.1.1 Compressed H_2

A typical pressure level for compressed of H_2 is today some 20 MPa. However, this results in far too an low energy density, below 5 wt-% of the storage is H_2. Therefore, for compressed H_2 storage, the main development target is to raise the pressure level, but without unduly affecting the bulk of the tanks. Novel construction and materials are employed. According to /6.14/ companies such as IMPCO and its subsidiary QUANTUM have successfully demonstrated ultra-high pressure storage with pressure levels of 35 to 70 MPa (5.000 to 10.000 psi) yielding up to 11 wt-% H_2 density. However, national legislation may bar the use of such systems in some countries, as in e.g. in Germany, the maximum permitted pressure level is 24.8 MPa.

Figure 6.5. Simplified comparison of operating ranges with various energy storage systems /2.3/.

Raising the storage pressure is highly advantageous, as the energy requirement of the compression does not increase in a linear fashion, but in logarithmic scale. Thus the compression from 0.1 to 30 MPa needs only 10 % more energy than the compression from 0.1 to 20 Mpa /1.14/. Overall, one has to consider the fact that the compressor efficiency is about 65 to 70 % and the compression work is some 10 % of the energy of the pressurised H_2 /6.17/.

Hydrogen compression is carried out in the same way as compression of natural gas. However, appropriate sealing (e.g. Teflon) must be used and the compressed gas has to be guaranteed oil free. In principle, this stage of the chain is well tested and readily available.

Advances in high-pressure hydrogen compression and storage may well also benefit future CNG applications.

6.3.1.2 Liquid H_2

Another storage technology shared by NG and H_2 is liquefaction (see Figure 6.6). However, because of its characteristics, hydrogen requires a much lower temperature (-253 ºC compared to -167 ºC for NG). Therefore, more energy is also needed to maintain the status of the storage. The energetic losses are some 30% of the stored H_2 energy value /6.10/. Furthermore, boil-off of some 1 to 3% is expected. However, in a well-refined system, some of this “lost” gas could be used to fuel an on-site FC to produce electricity for the filling station or in an on-board APU (auxiliary power unit) that makes electricity and runs cars’ accessories and sub-systems, such as air conditioning.

6.3.1.3 Hydride H_2

Metal hydrides can be used to store hydrogen yielding quite high energy densities. However, present systems are rather bulky and heavy. Furthermore, this process needs some +300 to +350 ºC temperatures to release the gas from storage. On the other hand, this could be seen as an inherent safety feature, as the risk of an accidental release of hydrogen would then be minimised. (see also Chapter 6.3.5).

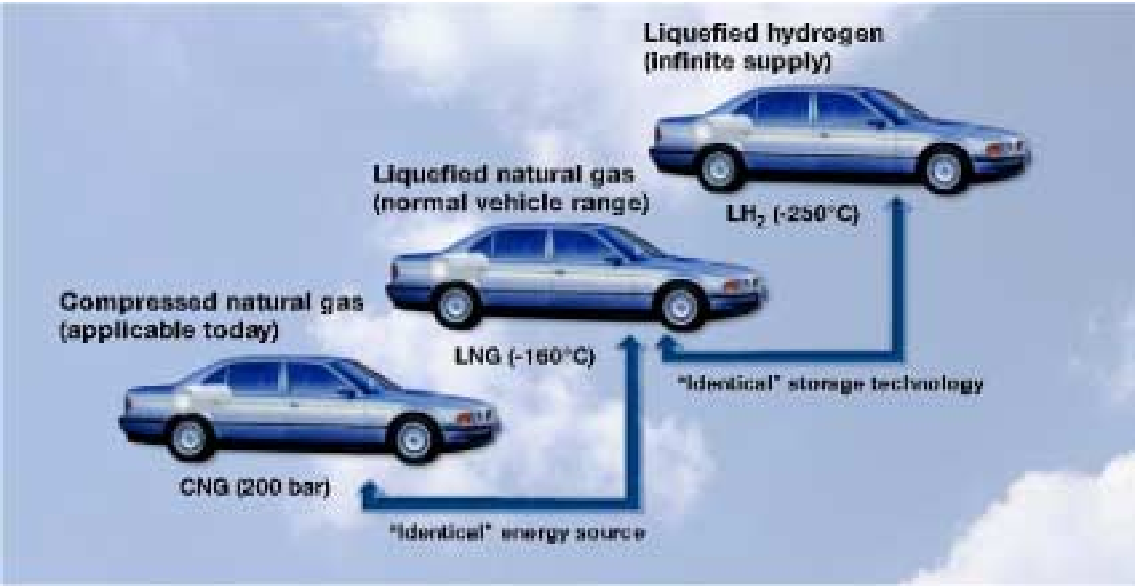

Figure 6.6. Technology is shared between NG and hydrogen /2.3/.

Some of the most advanced systems of this kind are being developed by Energy Conversion Devices (EDC), Inc., which holds the patents for the "Ovonics" technology. Recently Texaco has been strongly allied with EDC (see Chapter 5.6).

Another similar potential carrier for chemically bonded hydrogen could be sodium. In a recent demonstration DaimlerChrysler was showing a fuel-cell vehicle using aqueous (water-based) solution of sodium borohydride ($NaBH_4$) as the storage media for the hydrogen on-board. This technology is sourced from Millennium Cell, Inc. (USA), developing it under the trademark "Hydrogen on Demand". After the hydrogen has been derived from the borohydride in a catalyst bed, the material (borate) can be retrieved and recycled. It is non-toxic and also otherwise environmentally quite benign.

Figure 6.7 and Table 6.1 show a comparison between the performance of different hydrogen storage technologies.

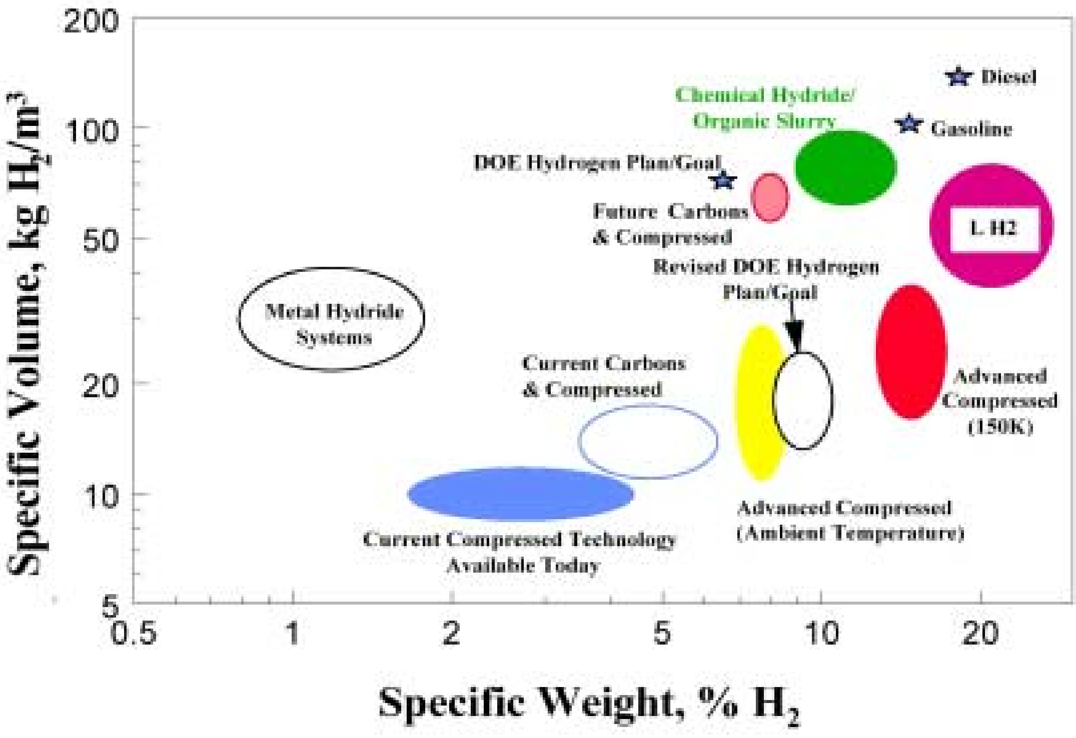

Figure 6.7. Comparison of different hydrogen storage technologies /6.15 /.

Table 6.1. Comparison between different hydrogen storage technologies /6.16/

	Gasoline	**Compressed Hydrogen**	**Liquefied Hydrogen**	**Metal Hydride (Ovonics Mg alloy)**
Btu	1,334,540	629,500	629,500	629,500
Fuel Weight (kg)	29.5	4.7	4.7	4.7
Tank Weight (kg)	13.4	63.3 - 86	18.6	120
Total Weight of Fuel System (kg)	43.2	67.9 - 90.5	23.3	124.7
Volume (liters)	40.1	408.8 - 227.2	177.9	120
Range (km)	600	600	600	570

Based on: Norbeck et. al., 1996; Pembina Institute for Appropriate Development, 2000; ECD Ovonics, 2000 and Stodolsky et al., 1999.

6.3.2 Transportation and distribution

Distribution of H_2 is fairly similar to NG. Pipeline network can be used for short and medium ranges. Such pipelines have low operating costs, but are a high capital investment. Some already exist in several industrial areas of the United States, Canada, and Europe, in the scale of 100 to 400 km in length. Typical operating pressures are 1-3 Mpa, with flows of 310-8,900 kg H_2/h /6.17/.

Long-range and low volumes can be transported in trucks either in GH_2 form or preferably as LH_2.

6.3.3 Refuelling

Commercial or at least pre-commercial stage technologies exist for vehicle refuelling, both GH_2 and LH_2. (Linde AG, ref /6.5/, *see Figures 6.8 and 6.9*). However, the present number of filling stations for hydrogen worldwide is still less than 20. Furthermore, none of them are yet open to the public, but are related to some demonstration projects or to R&D department of companies working in this field. However, a strategic plan has been made in Germany to determine how the number of public filling stations could be raised to 2000 by the year 2010. The expected penetration of H_2 fuelled vehicles in the German passenger car park is assumed to be some 2.5%, reflecting the 15 to 30 % share of new vehicle registrations after the year 2007 /6.5/.

Filling up a car with hydrogen, either with gaseous or especially with liquid hydrogen involves some technical difficulties, either because of the associated high pressures or extremely low temperatures. However, some demonstration units for “hands-off” operation of this task have been presented (see Figure 6.10), and it is believed that feasible solutions can be worked out, although dispensing hydrogen will never be as easy and straightforward as liquid fuels.

6.3.4 Similarities between CH_4/H_2

As already mentioned, there are a lot of similarities between NG and hydrogen in terms of storage, distribution and refuelling. The main differences are related to the lower density of hydrogen, and its high permeability. Lower density means larger storage volumes or increased pressure levels. High permeability poses some restrictions on materials used for tanks and their sealing. Compatible solutions, however, do exist.

Figure 6.8. Dispenser units for both gaseous (CGH_2) and liquid (LH_2) hydrogen; source Linde AG /6.5/.

Figure 6.9. Coupling for vehicle refueling with liquid hydrogen, source: Linde AG /6.5/.

Figure 6.10. Demonstration of a "hands-off" hydrogen filling station at Munich airport; /source: ARAL/.

6.4 Safety issues

Using hydrogen as a transport fuel poses some issues related to safety. Most of these are concerned with the unintended release of hydrogen into the atmosphere. Because the hydrogen molecule is so small, it has a greater tendency to escape through small openings than other gaseous fuels. However, based on properties of hydrogen, the propensity of hydrogen to leak through holes or joints of low pressure fuel lines may be only 1.26 to 2.8 times faster than a natural gas leak through the same hole, and not 3.8 times faster as frequently assumed based solely on diffusion coefficients /6.18/ (*see table 6.2*).

Table 6.2 Properties and leak rates of hydrogen and natural gas

Flow parameters	Hydrogen	Natural gas
Diffusion coefficient (cm^2/s)	0.61	0.16
Viscosity (m -poise)	87.5	100
Density (kg/m^3)	0.0838	0.651
Sonic velocity (m/s)	1308	449
Relative leak rates (-)		
- Diffusion	3.8	1
- Laminar flow	1.23	1
- Turbulent flow	2.83	1
- Sonic flow	2.91	1

Furthermore, if a leak occurs, natural gas contains more than three times the energy per unit volume than hydrogen, thus if ignited, the resulting energy release of a leak would be greater in terms of NG than in the case of hydrogen /6.18/.

However, if liquid storage technology is used for hydrogen, the boil-off of the gas must be handled correctly and with due precautions, because it is highly explosive in confined spaces, and it has a high flame speed. The shape of the space in which the hydrogen is confined also plays an important part, as does the mode of ignition. However, it also has a very high dispersion coefficient and this lowers the risk of reaching concentrations at the explosive level. This means that it is almost impossible to cause a hydrogen explosion in an open area. For the same reason, a hydrogen fire will burn out much more quickly than a gasoline or methane fire /6.19/.

Hydrogen is not intrinsically explosive, and it must be mixed with air or oxygen before detonation can occur. Furthermore, hydrogen is flammable and explosive over a much wider range of mixtures than any conventional fuel, but its lower limits of 4% and 13% respectively in air are wider than gasoline (1% and 1.1%) and similar to natural gas (5.3% and 6.3%) /6.19/ (*see table 6.3*).

Table 6.3. Some ignition-related properties of hydrogen, methane and gasoline

Property	Gasoline	Methane	Hydrogen
Density (kg/m^3)	4.4	0.65	0.084
Diffusion Coefficient In Air (cm^2/s)	0.05	0.16	0.61
Specific Heat at Constant Pressure (J/gK)	1.2	2.22	14.89
Ignition Limits In Air (vol %)	1.0-7.6	5.3-15.0	4.0-75.0
Explosion limits in Air (vol %)	1.1-?		13-56
Ignition Energy In Air (MJ)	0.24	0.29	0.02
Ignition Temperature (^{o}C)	228-471	540	585
Flame Temperature In Air (^{o}C)	2197	1875	2045
Explosion Energy (g TNT/kJ)	0.25	0.19	0.17
Flame Emissivity (%)	34-43	25 –33	17-25

When burning, hydrogen flame causes lower heating of the surroundings than “regular” fuels, because when a carbon-based fuel like gasoline burns, glowing hot soot particles transfer the heat to the surroundings, but since hydrogen contains no carbon, it burns cleanly without a residue of hot soot, producing little radiant energy /6.20/. However, this lack of carbon particles makes the flame almost invisible, which in turn can cause hazards. As table 6.3, shows, hydrogen has also higher flame temperature than NG. This is a further consideration, because the low heat dissipation around the hydrogen flame bears a lower “warning signal” than with carbon-containing fuels, where the heat can be felt further away from the flame, and thus one can enter the hot hydrogen flame zone almost without knowing.

Furthermore, on the positive side, hydrogen is totally non-toxic and so light that it immediately scatters rather than pooling as does LPG or polluting ground water, as liquid fuels often do /6.19/.

Most of the safety-related issues are actually false public perceptions and can be overcome with proper education and information distribution. The most common of these false perceptions of hydrogen’s inherit danger are related to the accident of the large German airship Hindenburg in 1937, where the hydrogen-filled airship was caught fire causing 37 deaths. However, according to /6.25/ the reason for this explosion was later established to be the ignition by a sudden, unexpected electrical discharge of the highly flammable paint that was used on the canvas of the dirigible and not the hydrogen that was used for buoyancy.

Those storage technologies that bond hydrogen to some media and produce gaseous hydrogen on-board only for almost immediate use, are also contributing to a safer system, because the amount of potentially leaking gaseous hydrogen is minimised.

6.5 Standards for hydrogen use in transportation

Most of the safety-related issues are best solved with standards or other proper codes of practice. Work is underway on several fora to establish necessary - and hopefully also widely harmonised - regulatory bases for successful commercialisation and deployment of hydrogen energy systems. One of the efforts is being undertaken by the International Standardization Organization (ISO) on its Technical committee ISO TC 197. At present, TC 197 has set up eight working groups, each for a different task. Those WG's and tasks are /6.22/:

• TC 197/WG 1	Liquid hydrogen - Land vehicles fuel tanks
• TC 197/WG 2	Tank containers for multimodal transportation of liquid hydrogen
• TC 197 WG 3	Hydrogen Fuel Specification (not active?)
• TC 197/WG 4	Airport hydrogen fuelling facility
• TC 197/WG 5	Gaseous hydrogen blends and hydrogen fuels - Service stations and filling connectors
• TC 197/WG 6	Gaseous hydrogen and hydrogen blends - Land vehicle fuel tanks
• TC 197/WG 7	Basic considerations for the safety of hydrogen systems
• TC 197/WG 8	Hydrogen generators using water electrolysis process

Concurrently, the National Hydrogen Association (NHA) in the U.S.A. has also been developing hydrogen standards and safety codes since 1995 /6.21/.

Furthermore, regarding motor vehicles, the European Integrated Hydrogen Project (EIHP) has produced drafts of two new regulations that considered liquid and gaseous tanks for hydrogen storage on board road-going vehicles. For further drafting, these were then presented to WP 29 of the UN Economic Commission for Europe (ECE). At the WP 29 meeting in March 2001, the Administrative Committee of WP.29 proposed including these draft regulations in their work programme at the next meeting in June 2001 /6.23/.

The two draft regulations were referred to GRPE (Working Party on Pollution and Energy), which is one of six subsidiary bodies for WP 29. It considered the matter at the end of May 2001. At that meeting, it concluded that GRPE did not contain the expertise to evaluate these regulations and could not complete the regulatory review in a timely manner. Therefore, a GRPE ad hoc group was set up under German leadership to work on both draft regulations. WP 29 endorsed this approach at its June 2001 meeting.

The first work group meeting was held in Bonn at the end of November 2001, with the presence of ISO TC 197 Chairman. At that meeting, it was decided that this ad hoc committee would:

- Draft regulations for liquid and gaseous hydrogen fuelled vehicles and present them for consideration as ECE documents as a first step under the 1958 Agreement;
- As a second step, develop a process to apply to global technical regulations (GTR) under the 1998 Agreement;
- Develop a closer relationship between ISO and the GRPE ad hoc group, mostly for the purpose of identifying the differences between the EIHP draft regulations the ISO draft standards.

Work of this ad hoc expert group continues, and the latest meeting was held on February 19, 2002, in Munich. According to the agenda /6.24/, it concentrated especially on BMW's experience with liquified gas storage technology, and a visit to the hydrogen filling station at Munich airport (see figure 6.10) was also arranged.

6.6 Cost issues

It is difficult to estimate the cost of hydrogen as a transportation fuel, both in terms of the fuel cost itself and the cost for infrastructure. In the Sustainable Mobility project of the World Business Council some figures are given. The figures are partly based on work that has been done by Argonne National Laboratory /6.26/.

The projections are made for the year 2030. The cost for hydrogen is estimated at some 45 US$/GJ, whereas costs for all other fuels are estimated at 5-15 US$/GJ (Figure 6.11). Strangely enough, CNG is predicted to be more expensive than conventional gasoline and diesel and even more expensive than a diesel blend containing 50 % FT diesel. The correct way to interpret the figures might be just that hydrogen is expected to be significantly more costly than all other alternatives.

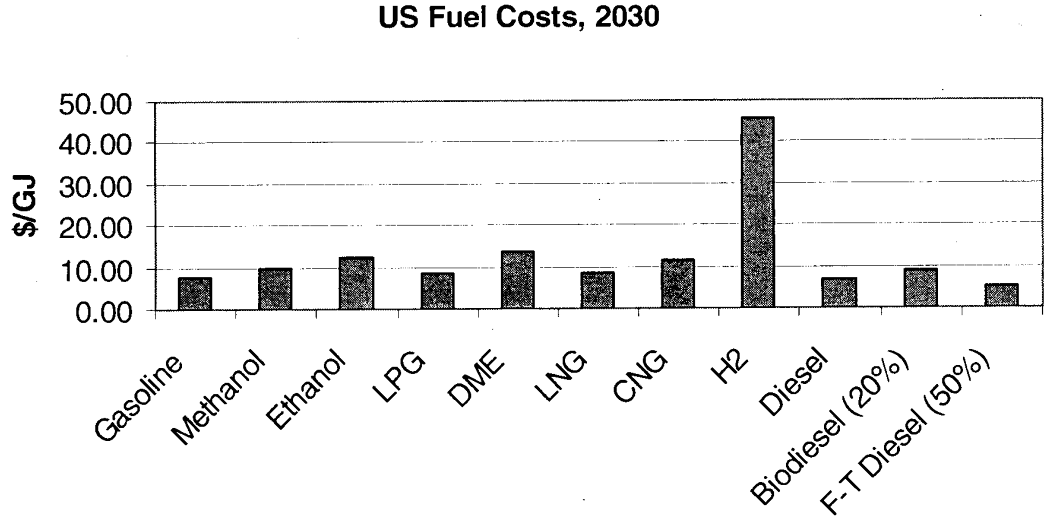

Figure 6.11. Estimated US fuel costs in 2030 /6.26/.

Figure 6.12 shows estimated investments needed for different fuels for a 30 % market share. The capital investment for CNG infrastructure is estimated at 19 Billion US$, hydrogen infrastructure at more than 60 Billion US$. The investment for LNG infrastructure is estimated to be roughly 1/3 of that of CNG. Here again the message given is clear; hydrogen is far more expensive than any other alternative.

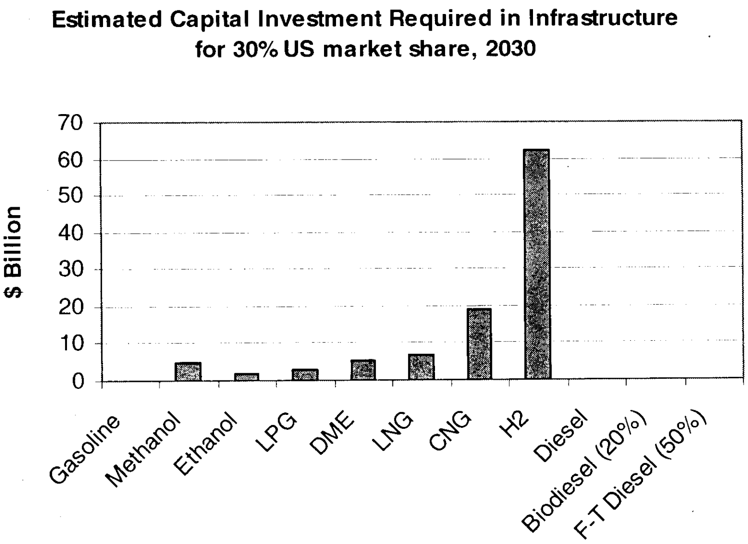

Figure 6.12. Estimated capital investment needed for a 30 % market share in the US /6.26/.

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7. Ways and possibilities of introducing NG into the transportation energy supply

7.1 General

Methane (natural gas) is a highly versatile light hydrocarbon that can be utilised as such or as feedstock to different processes to make other products that can be used as fuels and energy sources in the transport sector (Figure 7.1). Natural gas can also provide energy (both heat and electricity) to be used in fuel processing. Some of the options have already been mentioned in previous chapters. This chapter will summarise the different options for the introduction of natural as transportation energy. Detailed system efficiency and emission assessments are presented in Chapter 8.

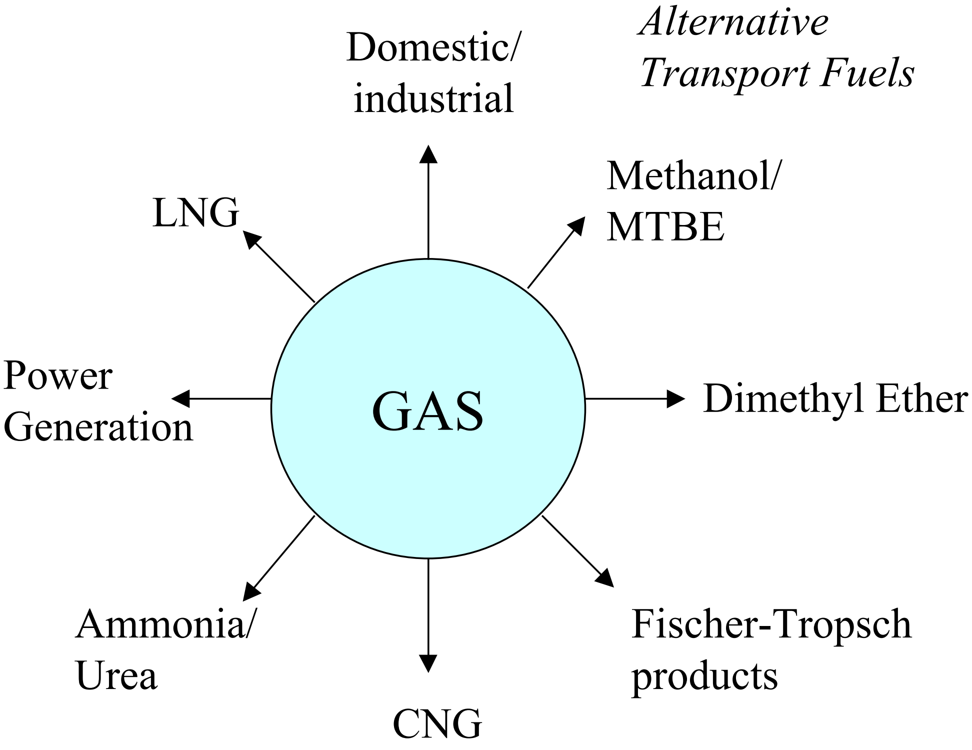


Figure 7.1 Natural gas utilisation options /7.1/.

In principle, there are many options for transportation energy. Figure 7.2 shows an example of potential forms of energy for vehicle propulsion. This particular presentation starts with a division into fossil (exhaustible) energy and renewable energy. Methane can be of either fossil (natural gas) and renewable origin (biogas).

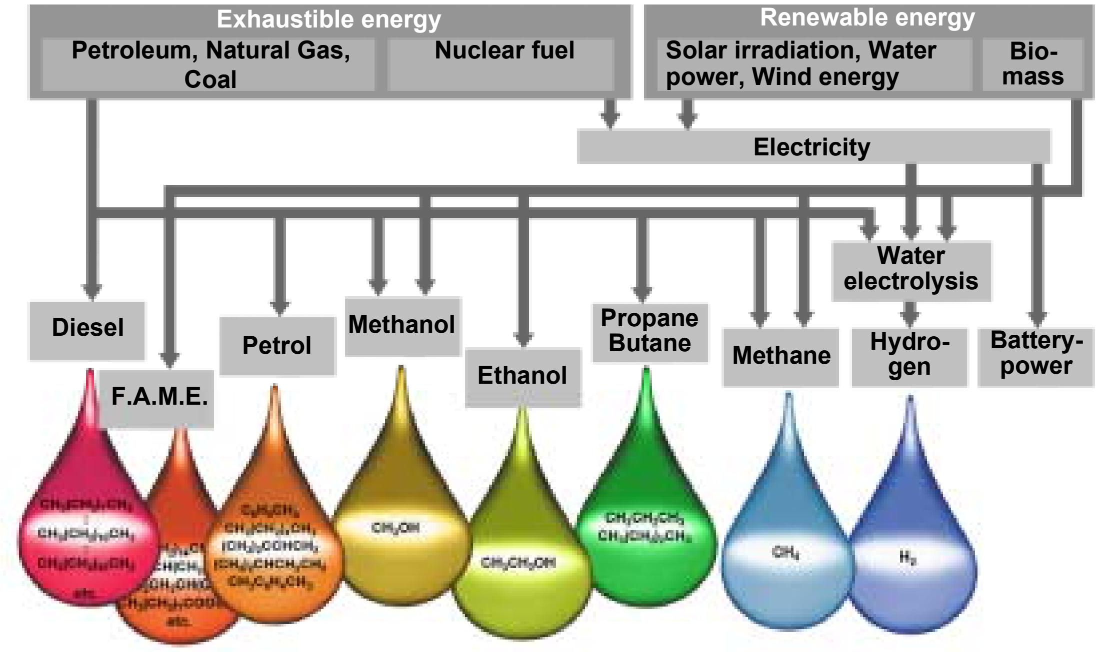


Figure 7.2. Energy options for vehicle propulsion /2.3/.

There is also a number of technology options for the propulsion system of the vehicle. Volkswagen divides the options into two main categories, conservative and alternative (Figure 7.3). The conservative route includes gasoline and diesel engines but also modifications to the transmission system (including different kinds of hybrids). On the conservative route, products derived from natural gas (hydrogen, oxygenates, synthetic fuels and fuel components) can be used to upgrade fuel quality and improve performance. Listed on the alternative route are electric drive, hydrogen and natural gas. Volkswagen does not believe in batteries only as a source of power, so the electric vehicle is actually a FC vehicle. Natural gas could either be used to fuel dedicated NG vehicles or to provide a source for hydrogen, either for FC or ICE vehicles.

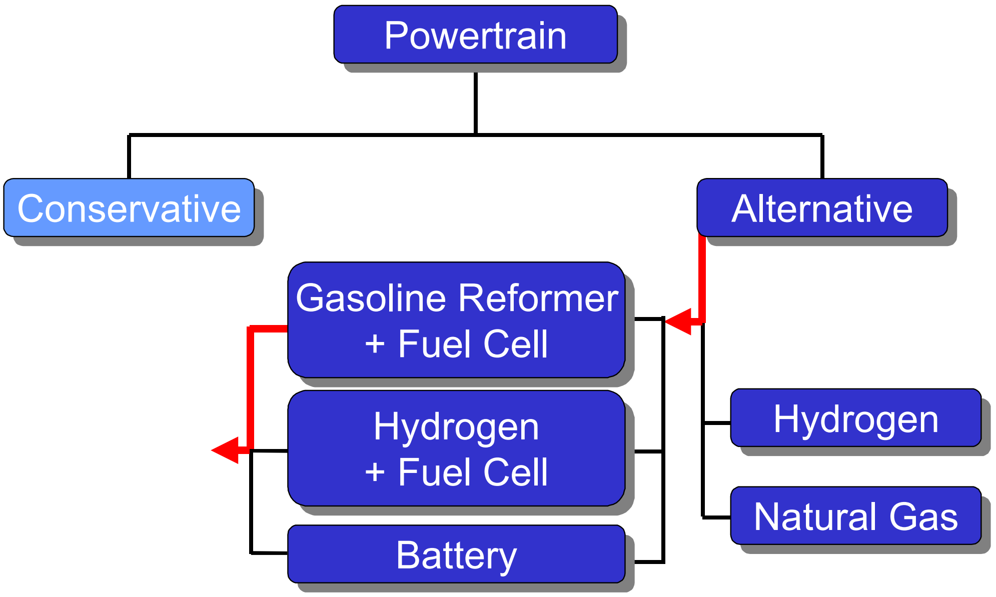


Figure 7.3. Propulsion technology scenarios /2.2/.

There is a drive to increase the share of natural gas in transportation energy. For this there is a number of reasons:

- energy security and diversification of energy sources
- reduction of CO_2 emissions
- reduction of toxic emissions

The European Commission is discussing a new biofuels directive, which would mandate a certain share amount of biofuels in the transportation sector. Included in the proposal is also a requirement that natural gas and hydrogen should account for certain shares of transportation energy. The figures proposed for 2020 are biofuels 8 %, natural gas 10 % and hydrogen 5 % /3.11/.

Figure 7.4 shows the evolution in environmental thinking. In the early 90's, the emphasis was on the reduction of toxic emissions. In the late 90's greenhouse gas emissions became the major concern. Neither the desire to reduce toxic emissions nor the need to reduce greenhouse gas emissions will disappear. However, we are entering a new era when supply of energy, especially based on crude oil, and the sustainability of the whole energy system will become major concerns. Looking at all three issues, toxic emissions, greenhouse gas emissions and energy diversification, natural gas can make a significant contribution to each.

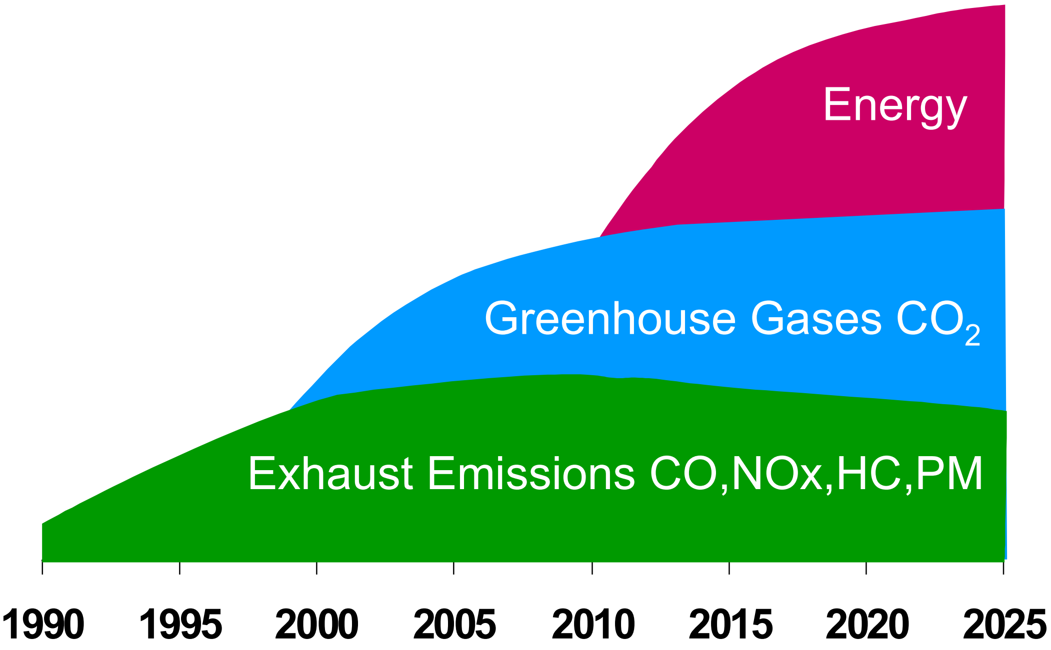


Figure 7.4 The evolution in environmental thinking /2.2/.

Figure 7.5 shows motivations for the use or promotion of alternative fuels at different time periods. During the energy crises of the 70's alternative fuels were discussed from an energy security point of view. Then came the reduction of harmful emissions and greenhouse gas emissions. For the future, new vehicle technologies like FC vehicles will bring new fuels to the market. Regulated emissions will be controlled by advanced engine and after-treatment technologies, whereas the issues of energy security and greenhouse gas emissions will remain.

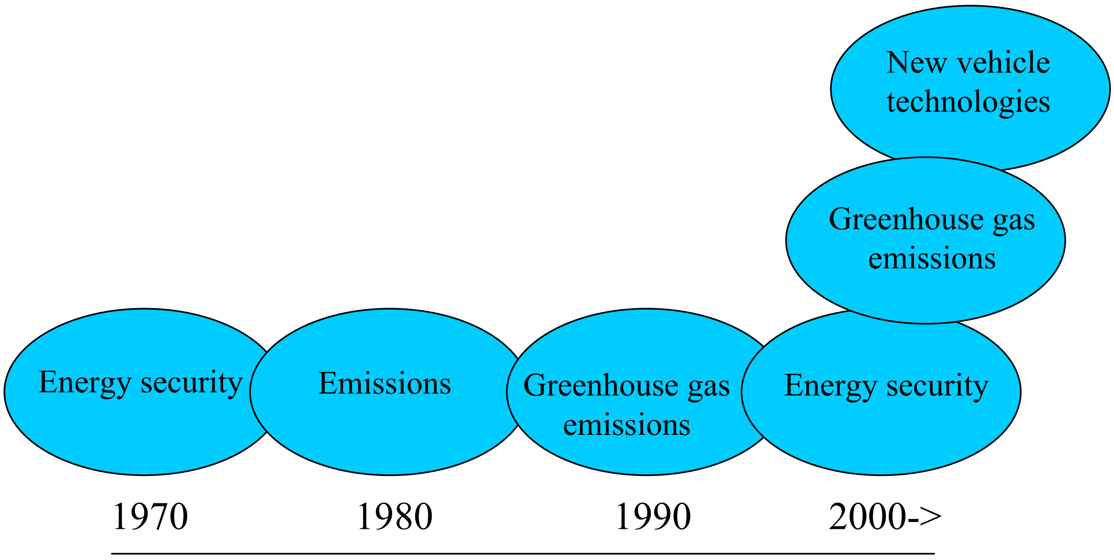


Figure 7.5 Motivations for the introduction of alternative fuels /7.2/.

When evaluating different fuels and fuel pathways one has to take into account many aspects /7.2/:

- adequacy of fuel supply
- location of fuel source
- process efficiency
- ease of transport and storage
- modifications needed in the distribution/refuelling network
- modifications needed in the vehicles
- fuel effects on vehicle performance (energy, emissions, ease of use)
- life cycle energy consumption and emissions, including greenhouse gas emissions

No single fuel can meet all requirements in an optimal way. That is why we will probably have a certain mix of different fuel options in the future.

7.2. Conventional fuels /7.3,7.4,7.5/

The fuel alternatives for conventional, unconverted vehicles, are rather limited. For unmodified gasoline vehicles, gasoline, synthetic gasoline and blends of gasoline and alcohols or ethers can be used. Most vehicles can tolerate some 10 % of ethanol blended into gasoline, corresponding to an oxygen content of some 4 %.

For unmodified diesel engines diesel, synthetic diesel and biodiesel can be used. Biodiesel (typically rapeseed methyl ester) can be used as a blending component or with some limitations, as such. There have also been demonstrations with emulsion-type fuels (diesel + ethanol or diesel + water) for diesel engines.

Natural gas or natural gas derived products can be brought into conventional fuels in several ways. The energy demand of oil refining is equivalent to some 10-15 % of the crude supply. This energy can be taken from oil, or if natural gas is available at the refinery, also from natural gas. Natural gas can generate both electricity and heat needed within the refinery, and thus reduce the demand for crude. Thus natural gas can make a contribution of a maximum of 15 % to conventional oil streams. This would also reduce total refinery CO_2 emissions by some 3-4 % when substituting oil with natural gas for process energy.

Diesel oil needs less processing than gasoline; its production only consumes some 40-55 % of the energy needed for gasoline processing. Refinery energy consumption has recently trended upwards because reformulated gasoline and desulphurised diesel need more energy than traditional fuel qualities /7.5/.

Hydrogen is used for desulphurisation and upgrading of fuels, especially diesel fuels. Hydrogen is typically produced by steam reforming of natural gas. Some refinery processes, like reformation of gasoline components, produce hydrogen, and this hydrogen can then be used in other processes.

Another route is to add synthetic components to the fuels. For gasoline these are typically ethers produced from alcohols and olefins. The most widely used component in gasoline is MTBE, which is based on methanol. Methanol again is produced from natural gas. California will ban the use of MTBE in gasoline starting in 2002 because of problems with ground water contamination (MTBE is readily soluble in water, and can be detected at very low concentrations) /7.6/. The California case might have impacts on world-wide MTBE use.

Synthetic components like high-cetane natural gas based Fischer-Tropsch components could be used in diesel fuel to enhance fuel quality (see 7.3). Modifications made to the conventional fuels do not necessitate modifications in the existing vehicle fleet nor in the fuel distribution infrastructure.

Well-to-tank efficiency for conventional liquid hydrocarbon fuels is roughly 85 %, slightly higher for diesel and slightly lower for gasoline. Hydrogenation of a fuel just to increase the heat content is an energy consuming and CO_2 adding process, even if the hydrogen is generated from natural gas. Therefore such a process should always involve improving the fuel quality for better end-use efficiency in the engine or for reduced emissions /7.7/.

7.3 Synthetic fuels (diesel, gasoline)

Synthetic fuels have a long history. Synthesis gas conversion technology- the Fischer-Tropsch (FT) process was commercialised in the late-30's in Germany. The company Sasol in South Africa started the production of synthetic fuels from low-grade coal in the 50's. Sasol's current plants were started in 1980 and 1982. One disadvantage with the Sasol process is a rather non-selective output including a mixture of different hydrocarbons and alcohols /7.8/. The coal is gasified (partial oxidation) to produce synthesis gas.

Most current synthetic fuel scenarios are based on the use of remote or stranded natural gas. Many energy/oil companies have discovered gas while exploring for crude oil. Often gas is found in remote locations with a very small proximate user market. Since the markets are far away, pipeline transportation is unrealistic and expensive. Liquefaction on site makes transportation of the fuel much easier, and would make it possible to utilise natural sources, which otherwise would remain unused or even be flared. This applies to synthetic diesel (gasoline), methanol and DME.

The first GTL (gas-to-liquids) plant operated on natural gas was built in Texas in the 50's. This operation, however, was not a commercial success. The same applies to the units built in New Zealand in the 80's and in South Africa and Malaysia in the early 90's. The New Zealand plant built by Mobil was designed to produce gasoline from natural gas via methanol, MTG (methanol-to-gasoline). This plant was soon turned into a methanol plant /7.9/.

Steam reforming or partial oxidation (or a combination of these two processes) can be used to turn methane into synthesis gas (see also 5.3.2). In the Fischer-Tropsch process synthesis gas is converted into long-chain paraffins, light olefins, high molecular waxes and water.

Upgrading processes yield desired products like such as low-sulphur diesel, naphta, waxes and lubricating oil base oils. Waxes can be converted in middle distillates using mild hydrocracking /7.10/. The straight-run gasoline components have a low octane number due to high linearity and low aromatic content, which make them unattractive as such for gasoline engines /7.11/. These components could, however, be used to fuel FC vehicles with on-board reformers.

In general, the FT process is better suited to produce middle distillates. The quality of diesel produced by FT synthesis far exceeds typical diesel fuel specifications. Table 7.1 gives a comparison of typical diesel against FT diesel. This makes FT diesel attractive both as fuel and blending component.

Table 7.1. Comparison of diesel fuel qualities /7.10/.

Parameter	Conventional diesel	FT diesel
Cetane no.	45	>70
Aromatics (% vol.)	10	<1.0
Sulphur (ppm)	500	<1.0

FT diesel reduces both gaseous and particulate emissions. Figure 7.6 shows a comparison between conventional diesel, reformulated diesel and FT diesel emissions.

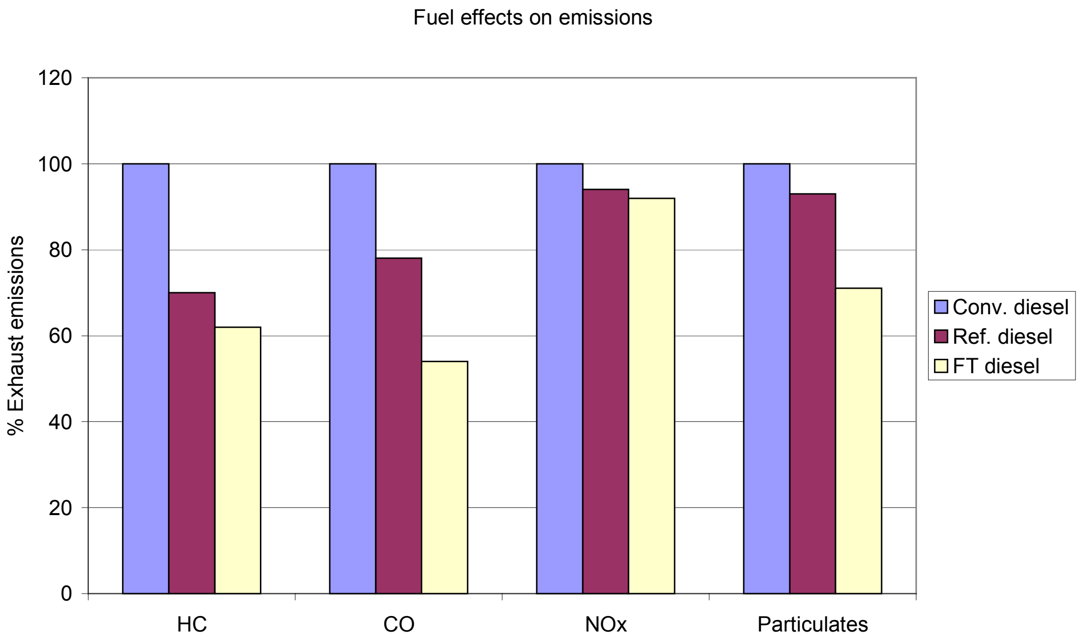


Figure 7.6. Fuel effects on diesel engine emissions /7.10/

Estimating the overall energy efficiency for FT diesel is somewhat difficult, as diesel fuel is not the only end product. Energy efficiency for production of conventional from crude is close to 90 %, whereas the figure for FT diesel from natural gas is in the order of 55 % /7.13/.

FT diesel has a great advantage over most other alternative fuels in the sense that no modifications are needed to the fuel distribution or to the existing vehicle fleet. FT diesel is also superior in performance qualities compared to ordinary diesel fuel.

7.4. Direct methane

Natural gas is an excellent fuel for spark-ignition engines. Natural gas can also be used in the diesel process, provided that the gas is ignited, for example, by a pilot diesel fuel spray. Issues related to the use of natural gas as a motor fuel are extensively discussed in the year 2000 IANGV Emissions report /1.10/, and to some extent in Chapter 3 of this report.

Basically, vehicle conversions from gasoline to natural gas are quite simple. However, if the vehicle has to comply with the latest emission and OBD requirements, the modification or the conversion has to be supported by the auto manufacturer. CNG storage is heavier and more space consuming than gasoline storage, and this can result in a slightly higher energy consumption for a CNG vehicles compared to a gasoline vehicle. This difference can, however, be reduced if the CNG vehicle is a dedicated vehicle taking full advantage of the high octane rating of natural gas.

Regarding exhaust emissions, vehicles without any exhaust gas after-treatment benefit from a switch from gasoline to natural gas. Thus converted vehicles using rather simple gas technology can be a good solution for many developing markets. In vehicles equipped with sophisticated exhaust gas after-treatment, the substitution of gasoline for natural gas results in rather limited absolute reductions in regulated emissions. The main benefits are reduced exhaust toxicity and reactivity. The desire to diversify transportation energy will probably continue to be a strong argument for the promotion of natural gas for transportation both in North America and within the European Union.

Hybrid vehicles are entering the market. The first vehicle to be produced in large numbers was the Toyota Prius, with its rather complicated and heavy propulsion system. Natural gas, especially in the form of CNG, may not be a feasible fuel alternative for “full” hybrid vehicles, both due to weight and space considerations. However, it can be foreseen that most manufacturers will take the “minimal hybrid” route. Such a system utilises an integrated starter/generator, which can both boost accelerations and recover brake energy. The battery needed is roughly 1.5 times the size of a normal start battery. Thus the minimal hybrids do not have the same weight and space constraints as full hybrids, making it possible to have CNG as a fuel option also in this vehicle category.

Most natural gas engines for heavy-duty vehicles are diesel engines converted to spark-ignition. A typical feature for these engines is low emissions compared to diesels, on condition that sophisticated engine control and exhaust after-treatment is applied. The main drawback is high energy consumption, considerably higher than for a corresponding diesel. High-pressure direct injection technologies giving diesel-like efficiency have been developed, but these engines have not yet been demonstrated in large numbers in the field.

Figure 7.7 shows some pathways for natural gas. Well-to-tank efficiency for compressed natural gas is roughly the same as for diesel, and slightly higher than that for gasoline. Values can vary somewhat depending on the source of the information.

When CNG is substituted for gasoline, overall efficiency is roughly the same or somewhat better. Well-to-tank efficiency of CNG is somewhat better, tank-to-wheels efficiency might be somewhat lower. Due to fuel chemistry, CO_2 emissions will be reduced by some 25 % /1.10/.

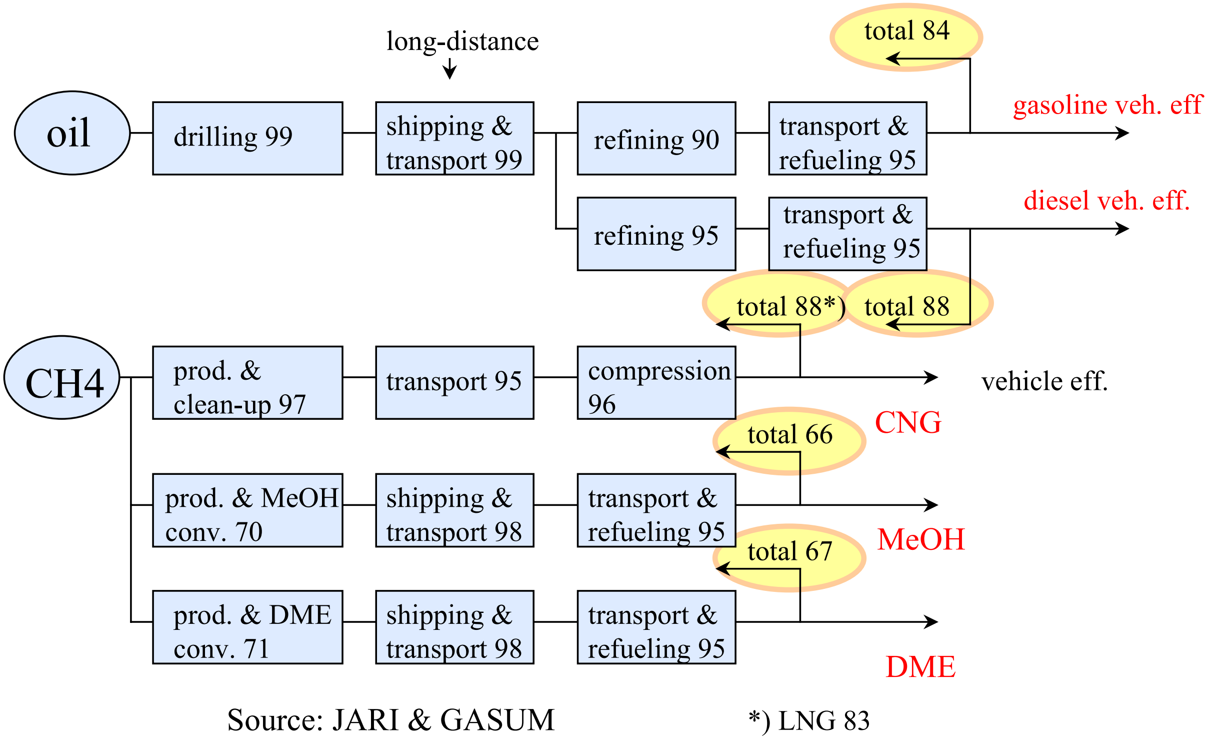


Figure 7.7. Some pathways for natural gas into transportation fuels /1.10/.

In the case of natural gas substituting for diesel, the overall efficiency of the fuel chain is determined by vehicle efficiency. If CNG is used in a spark-ignition engine, overall energy consumption will increase some 20-35 % compared with diesel operation. This means that a switch from diesel to CNG is close to CO_2 neutral in the best case, and in the worst case CO_2 emissions will increase some 10 %. If natural gas could be burned in the engine with the same efficiency as diesel (i.e. using direct injection of natural gas), the outcome would be the same as for gasoline substitution: the same overall efficiency and CO_2 emissions reduction of 25 %.

For city buses, the combination of CNG fuelling and full hybrid propulsion should be possible, as space and weight are not so limiting as for light-duty vehicles.

LNG gives a possibility to significantly increase energy density in natural gas storage. LNG technology also makes it possible to transport natural gas by ship or by tank trucks. However, the vast majority of natural gas vehicles are still CNG vehicles. LNG is cryogenic, which increases both system complexity and energy use compared to piped natural gas and CNG technology. LNG is predominantly found in some US heavy-duty truck and bus applications.

Both CNG and LNG require dedicated refuelling systems and dedicated or at least converted vehicles. Thus the infrastructure and vehicle costs are relatively high. In many markets, inadequate refuelling infrastructure hampers the growth of the natural gas vehicle population.

The main advantage of direct methane use is that the fuel itself (if not the refuelling infrastructure) is readily available in many areas. Natural gas is a high quality fuel for use in engines. It is also an efficient fuel in the sense that rather little processing, upgrading and energy is needed to put the fuel into the vehicle fuel tank.

In theory, it could be possible to use methane also for on-board reformer equipped FC vehicles. The great advantage of this would be that the existing CNG (or LNG) refuelling network could be used to fuel FC vehicles. The sulphur level of most natural gas distributed is so low that it would be suitable for on-board reforming. However, at this stage of reformer and FC technology, a combination of natural gas storage, reformer and fuel cell stack, seems to be a troublesome combination regarding both weight and space requirements.

7.5 Methanol

Methanol is a commodity chemical used widely in the chemical industry. This alcohol is usually made from natural gas via synthesis gas. The process is more selective and less energy consuming than the FT process. The efficiency of methanol production is close to 70 %.

Methanol can also be produced from biomass or coal using gasification. The biomass route is technically but not yet economically viable.

Characteristics of methanol are high octane rating, high heat of evaporation, low energy density (compared to gasoline) and low vapour pressure. In addition, methanol is highly corrosive and toxic. Methanol can be used in adapted spark-ignition engines. Fuel Flexible Vehicles (FFVs) can operate on blends containing 0-85 % methanol (or ethanol), the balance being gasoline. Running on methanol, the fuel flow has to be increased considerably. Methanol requires a fuel tank almost twice as large as does gasoline. Fuel system materials have to be wear and corrosion resistant. Cold start properties of methanol are poor, and this is one reason why methanol is seldom used straight, but is blended with hydrocarbons /7.5/.

Methanol (or ethanol) as such is not suitable for diesel engines, as the ignition properties of alcohols are poor. Either the fuel has to be treated with ignition improving additives, or the engine has to be modified with pilot- or glow-plug ignition assistance.

The interest in methanol fuelled vehicles peaked in the late 80's and early 90's. Since then, most activities have died away. In the US, the local manufacturers still produce FFV vehicles. Most of the vehicles sold are, however, operated on gasoline.

Spark-ignited methanol engines can achieve a higher efficiency than gasoline engines. Heavy-duty diesel cycle alcohol engines have an equivalent efficiency to normal diesel engines. In diesel engines, alcohols reduce both nitrogen oxide and particulate emissions. Drawbacks with methanol fuel are high fuel toxicity and high formaldehyde emissions in some driving conditions.

Overall efficiency using methanol in spark-ignited engines is some 10-15 % lower compared to gasoline, a figure which is slightly compensated for by increased engine efficiency. In diesel operation, overall efficiency is some 20 % lower compared to normal diesel operation.

Methanol can also make a contribution to fuels chains in the form of MTBE as discussed earlier, or as a component in biodiesel. Biodiesel, typically rape seed methyl ester (RME) in Europe, is produced by esterification of triglyceride (oil) and methanol. The energy contribution of methanol into RME is some 10 %.

At present, methanol receives much attention because its suitability for on-board reforming in FC vehicles. Methanol requires lower temperature in reforming than hydrocarbons, and if only ease and efficiency of reforming on board the vehicle were considered, methanol would most probably be the preferred liquid fuel alternative for FC vehicles. Some fuel cells can also use methanol directly (DMFC).

Looking at efficiency from well to hydrogen, including on-board reforming, the natural gas to methanol to hydrogen path seems less efficient (some 60 %) than crude to gasoline to hydrogen (some 65 %).

7.6 DME /7.5,7.14/

DME (dimethyl ether) is a fuel option, which has emerged recently. Like FT diesel or methanol, DME is produced via synthesis gas. The DME synthesis (oxygenate synthesis) has slightly higher efficiency than the methanol synthesis. DME is not toxic, and is used as a propellant in aerosol canisters.

DME is a gas that can be liquefied at moderate pressure (6 bar), and in this sense it is similar to LPG. DME, however, has excellent ignition properties (high cetane number), and is therefore suited to the diesel process. DME has potential for even bigger emission reductions than FT diesel.

DME has extremely low viscosity and lubricity. It also reacts with certain elastomers. The high vapour pressure means that fuel transfer pumps must be mounted within the fuel tanks. All these factors mean that constructing a complete high-pressure injection for DME is technically rather challenging. Prototype engines with Common-Rail type fuel injection systems have been demonstrated, but the technology has not yet been commercialised.

DME would require a new refuelling system and new vehicles. In this respect it is similar to the direct use of natural gas. The benefit of DME is that in diesel operation, DME gives the same or even better efficiency than conventional diesel. The drawback compared to direct use of natural gas is that energy is lost in the fuel conversion process. At this moment it seems that the first wave of enthusiasm over DME has vanished, and that activities around this fuel option are a little bit on hold.

7.7 Natural gas to hydrogen

Hydrogen can be produced either in centralised, decentralised on-site or in on-board reforming systems. The primary energy for hydrogen production can be either fossil or renewable. Looking at hydrogen production, three different development stages regarding both time frame and the need for development efforts can be identified (Figure 7.8). The ultimate goal might be centralised sustainable hydrogen production, but also decentralised systems may play an important role in the future.

Most probably hydrogen production will start in decentralised systems. In areas with existing natural gas networks, natural gas reforming will compete with electrolysis. The use of natural gas for on-site hydrogen production will have a good chance as long as the electric power grid is undersized and most power is generated from fossil energy. Decentralised systems (on-board or on-site) based on natural gas or any other fossil fuel provide no possibilities for CO_2 recovery.

Centralised systems based on natural gas would make CO_2 sequestration possible, thus creating an energy system which, in theory, would not contribute to greenhouse gas emissions. Such a system would, however, not meet the definition of a sustainable energy system.

Fulfilling the requirement of sustainability would call for the use of renewable primary energy. This could be biomass, biogas, solar energy, hydropower etc. Hydrogen production via gasification of biomass in centralised units would fulfil this requirement, as well as the use of biomethanol in decentralised systems. Electricity from renewable energy sources can provide “sustainable” hydrogen in both centralised and decentralised systems.

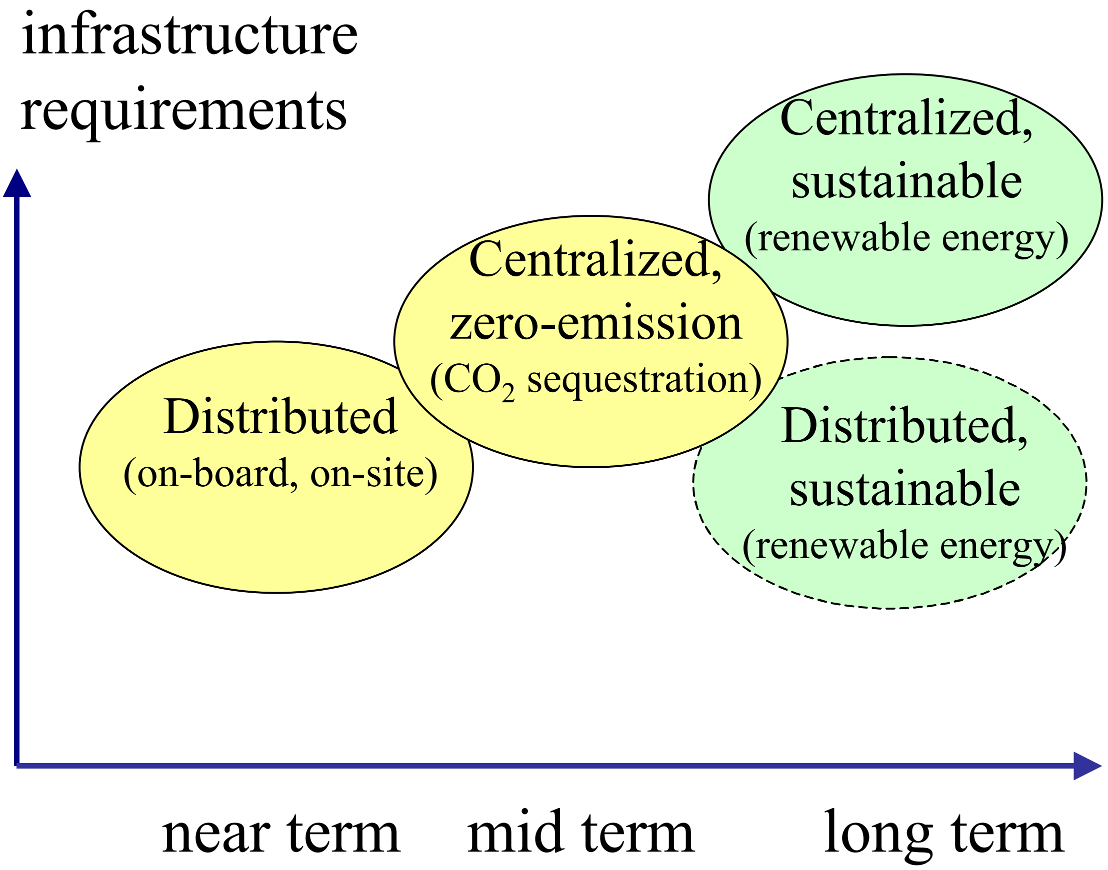


Figure 7.8. Hydrogen production scenarios.

The efficiency of electricity production from natural gas is in the range 30-50 %. The efficiency of electrolysis is in the range of 60-80 %. These values combined, not taking into account other losses, gives an efficiency range of some 20-40 %. The efficiency of natural gas steam reforming is in the order of 60 %. This means that the route from natural gas to electricity to hydrogen does not make sense from an energy efficiency point of view.

Figure 7.9 shows an example of how natural gas as such and hydrogen derived from natural gas could be used in decentralised fuel systems. The figure also presents hydrogen use in domestic systems.

Figure 7.10 and 7.11 show natural gas and methanol outlets in continental US. For reasons of availability, natural gas is a noteworthy alternative source for hydrogen, either for centralised or distributed systems. If on-board reforming of natural gas were a technically feasible alternative, existing CNG or LNG refuelling systems could play a major role in fuelling FC vehicles in the introductory stage. Methanol would require a widespread distribution network to be built.

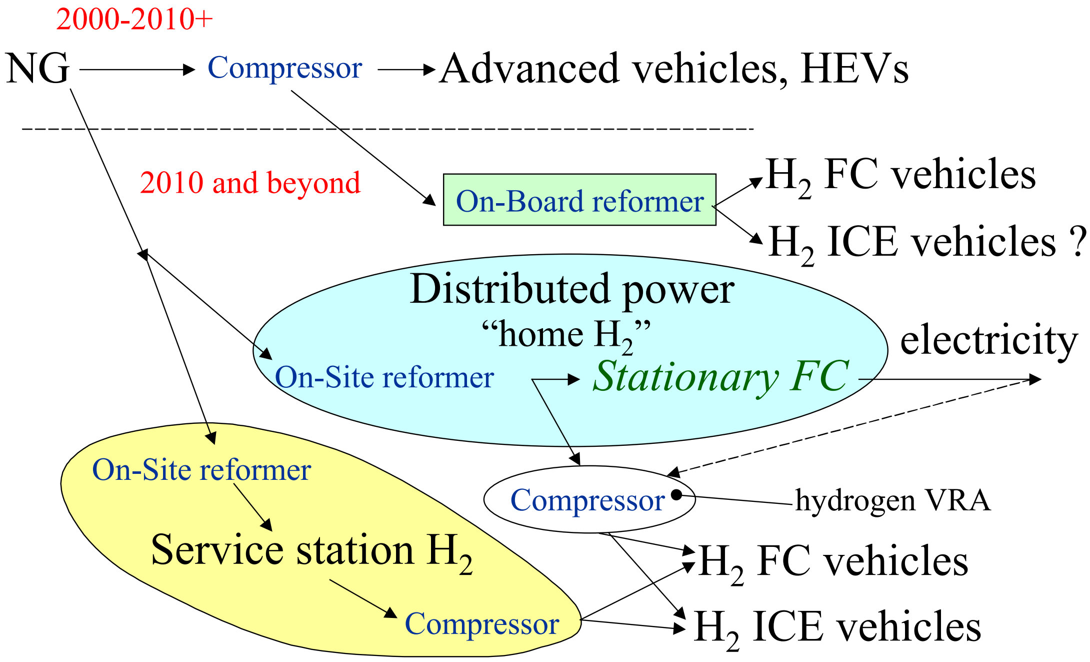
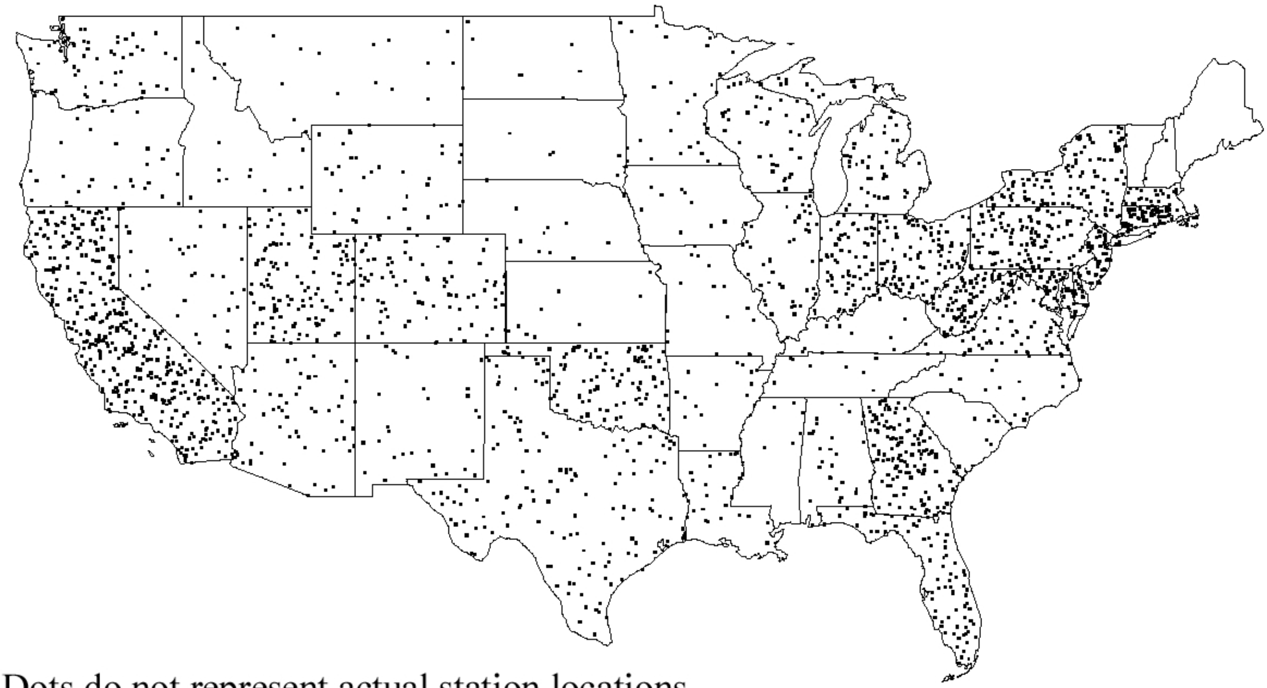


Figure 7.10. Natural gas pathways in decentralised systems (idea by Alex Lawson).



* Dots do not represent actual station locations

Figure 7.11. Natural gas outlets in continental US /1.16/.

* Dots do not represent actual station locations

Figure 7.12. Methanol outlets in continental US /1.16/.

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8. System efficiency – a "well-to-wheels" analysis

8.1 General remarks

Although the overall efficiency of a given fuel pathway is certainly an important figure, it is not the only dimension considered, when decisions are made for future transport energy sources and carriers. Items such as diversity, security and costs are certainly also on the table. Sometimes also local conditions can be such that the global rank order needs to be revised. Also in the long-term, using more and more renewable energy becomes necessary, and that alone can necessitate a new set of assessment criteria that put more weight on zero carbon emissions.

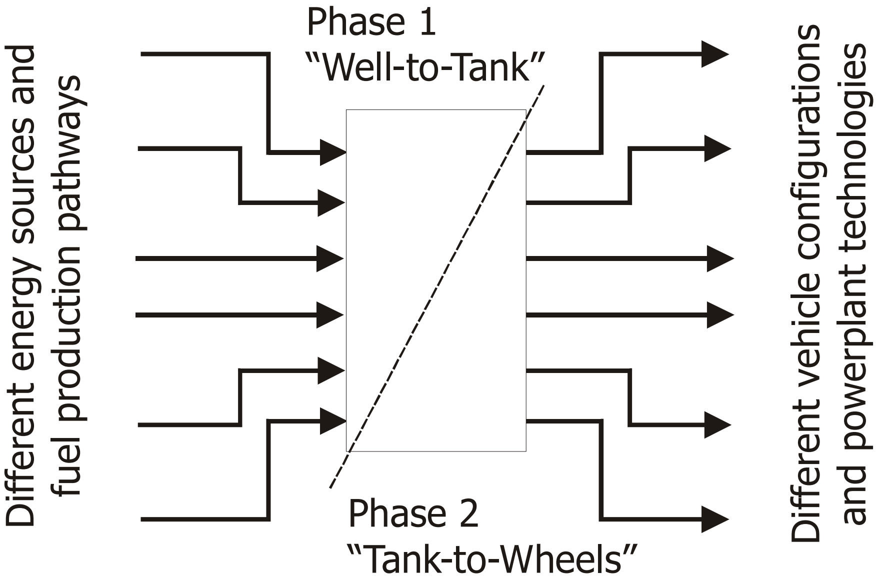
8.2 General description of the procedure and references to data sources

The "well-to-wheels" (WTW) system efficiencies are assessed in a two-phase process. First, a "well-to-tank" (WTT) analysis is performed, where different energy sources as well as different alternative fuel processing options are assumed. The result of this phase is fuel production efficiency (%) and total energy use in [MJ/MJ$_{\text{fuel}}$] put in the tank of a vehicle, for each of the applicable pathways from primary source to the given fuel. This phase shall also contain the energy required for distribution, storage, refuelling etc., as well as losses in these stages.

The second step is then a "tank-to-wheels" analysis, where different applicable powertrain options and vehicle technologies are catered for. This stage should render the eventual gross energy use in [MJ/km] and computed WTW efficiency (%), which often also gives the basis to make the first estimate of CO_2 emissions for different fuel options, as only the specific factor for kgCO_2 /MJ fuel is needed.

The focus is on natural gas (NG) and those derivatives based on NG as the feedstock.

Figure 8.1 is a schematic representation of the process.



Fuel options & storage technologies considered:
- gasoline (reformulated, low sulphur)
- diesel (reformulated, low suphfur)
- methanol
- natural gas (CNG, LNG)
- hydrogen (GH_2, LH_2, MH-H_2)

Powertrain options:
- Spark-ignition ICE (SI-ICE) + hybrid configuration
- Compression-ignition ICE (CI-ICE) + hybrid configuration
- Hydrogen Fuel Cell (FC) + hybrid configuration
- Direct Methanol Fuel Cell (DMFC)

Figure 8.1 Schematic flowchart of the "well-to-wheels" assessment process.

Several studies has been made and published recently on WTW efficiencies. Among these are the one made by Breakthrough Technologies Institute and published by the Methanol Institute /8.1/, one made by (S&T)^2 Consultants Inc. and published by Methanex Corporation /8.2/, both concentrating heavily on the use of methanol to fuel FC vehicles, but contain references to other fuels, as well.

A more broad-based study, mainly from the perspective of U.S.A. and passenger cars, has been made and published by Massachusetts Institute of Technology (MIT) /8.3/. Technologically much broader, but still very much a U.S. view is presented in /8.4/. This report (for some reason still only available in draft form) prepared by persons from several U.S. national laboratories in collaboration and published by the OTT of U.S. Department of Energy.

Perhaps the most comprehensive analysis in terms of full fuel-cycle emissions and energy use is presented in a series of reports /8.5/, /8.6/, /8,7/, prepared by Argonne National Laboratory (ANL) in collaboration with GM, BP, ExxonMobil and Shell. The two earlier reports from ANL /8.8./, /8.9/, are also quite substantial and reviews the use of natural gas extensively.

The State of California is different from the rest of the U.S. in many ways, and runs in the forefront of many new vehicle technology exploitation initiatives. The report /8.10/ by the Californian Energy Commission, and /8.11/ by Californian Fuel Cell Partnership that review the Californian situation regarding future transportation energy options and fuel alternatives for FC vehicles. A U.S. wide study on the FC vehicle technology options is presented in /8.12/.

Even more specific to the FC vehicle issues are scientific reports /8.13/, /8.14/, /8.15/, /8.16/, /8.17/, that contain either scenario analysis of FC options in transportation, or specific data of FC related technologies that can be used in fuel pathway calculations.

A Swedish study (by Ecotraffic ERD[3]) was released quite recently (October 2001) by Swedish National Road Administration /8.18/. It brings the use of biomass and other renewables into the assessment. This is a perspective taken only by /8.7/ among the U.S. studies mentioned above. The report contains also a review and comparison to the previous studies including those U.S. studies mentioned above. As it appears to be the most recent and in some ways most broad-based, we have chosen to use data mainly from this study, and the comparisons made below are mostly based on the numbers derived from that report. However, there seem to be some areas where we do not totally agree with the authors of the Ecotraffic study. Therefore, we have provided some critical notes when presenting and reviewing the results.

Table 8.1 lists the results for different fuel pathways and propulsion power alternatives, based on either crude oil or natural gas. Those biomass based fuel paths that the report also contains are not presented here, as for the short-term context mostly discussed here, their contribution is only modest, although in the long term the target is to increase the share of renewables quite considerably.

8.3 Efficiency and energy use of selected fuel/powertrain options

8.3.1 Crude oil to gasoline and diesel

The baseline case is considered to be crude oil refined to reformulated, low sulphur gasoline (RFG), which is the current “de facto” standard for new road-going motor vehicles using positive-ignition internal combustion engines (SI-ICE) for propulsion power. A parallel path is to make reformulated, low sulphur diesel fuel (RFD) and use diesel process in the ICE (CI-ICE), resulting in higher engine efficiency. As an option to gasoline-fuelled SI-ICE, an FC vehicle with an on-board reformer using gasoline is also considered. Although desulphurisation may not yet be needed in all market areas, future exhaust emission control is so heavily built upon the availability of low sulphur fuel that it must be taken almost for granted.

Table 8.1 Well-to-Wheels energy efficiency analysis for selected crude oil and natural gas (NG) based

Feedstock	Fuel	WTT	Reformer	Power-plant	PP Eff	WTW direct	rank	Hybrid. Gain	WTW hybrid	rank
Crude	**Gasoline**	**82.9 %**		**SI-ICE**	**14.9 %**	**12.4 %**	**8**	+ 23 %	**15.3 %**	**6**
			78 %	**FC**	**22.6 %**	**14.6 %**	**4**	+ 4 %	**15.2 %**	**7**
	Diesel	**87.9 %**		**CI-ICE**	**17.6 %**	**15.5 %**	**1**	+ 20 %	**18.6 %**	**1**
Natural Gas	**CNG**	**87.0 %**		**SI-ICE**	**14.9 %**	**12.9 %**	**7**	+ 23 %	**15.9 %**	**2**
			78 %	**FC**	**22.6 %**	**15.4 %**	**2**	+ 3 %	**15.9 %**	**2**
	LNG	**85.4 %**		**SI-ICE**	**14.9 %**	**12.7 %**	**8**	+ 23 %	**15.6 %**	**5**
			78 %	**FC**	**22.6 %**	**15.1 %**	**3**	+ 4 %	**15.7 %**	**4**
	G-H$_2$	**61.1 %**		**SI-ICE**	**14.9 %**	**9.1 %**	**14**	+ 22 %	**11.1 %**	**14**
				FC	**22.6 %**	**13.8 %**	**5**	+ 4 %	**14.4 %**	**8**
	L-H$_2$	**43.1 %**		**SI-ICE**	**14.9 %**	**6.4 %**	**17**	+ 23 %	**7.9 %**	**19**
				FC	**22.6 %**	**9.8 %**	**12**	+ 3 %	**10.1 %**	**15**
	EL > H$_2$	**37.0 %**		**SI-ICE**	**14.9 %**	**5.5 %**	**18**	+ 22 %	**6.7 %**	**20**
				FC	**22.6 %**	**8.4 %**	**16**	+ 4 %	**8.7 %**	**17**
	FTD	**55.0 %**		**CI-ICE**	**17.6 %**	**9.7 %**	**13**	+ 21 %	**11.7 %**	**12**
			78 %	**FC**	**22.6 %**	**9.7 %**	**13**	+ 4 %	**10.1 %**	**15**
	MeOH	**neat**		**SI-ICE**	**16.2 %**	**10.9 %**	**10**	+ 24 %	**13.5 %**	**11**
		67.3 %		**CI-ICE**	**17.6 %**	**11.8 %**	**9**	+ 21 %	**14.3 %**	**9**
			86 %	**FC**	**23.0 %**	**13.3 %**	**6**	+ 5 %	**14.0 %**	**10**
		G-H$_2$		**SI-ICE**	**14.9 %**	**7.1 %**	**15**	+ 23 %	**8.7 %**	**17**
		47.5 %		**FC**	**23.0 %**	**10.9 %**	**10**	+ 6 %	**11.5 %**	**13**

The study gives total WTW efficiency of some 12.4 % in case of the SI-ICE, and 15.5 % for the more efficient CI-ICE. These seem to be on the low side of such values referred in other studies, where 15 to 18 % are more commonly accepted.

A further improvement on the total efficiency is available for all of the options, if the ICE is augmented with a hybrid configuration. Then especially the poor low-load efficiency of SI-ICE can be improved and kinetic energy recovered via regenerative braking. Therefore, alternative results are presented, based on an assumption, that "hybridisation" can improve the powertrain efficiency by some 23 to 24 % in SI-ICE and by 20 % for CI-ICE, as it already has better part-load efficiency than its positive-ignition sibling. However, the drawback is that somewhat higher total weight for the vehicle needs to be assumed because of the added hardware. Whereas this will not affect WTW efficiency, it will raise the energy demand and thus render a lower total efficiency figure, while raising the vehicle weight.

The figures given in this study for an on-board reformer in a gasoline-fuelled FC are somewhat higher, as compared to those in other studies. The authors use 78 % for the reformer efficiency, probably a *partial oxidation* (POX) type reformer that is commonly used for gasoline type of hydrocarbons to produce hydrogen. The same value is also given in /8.14/. However, another reference /8.13/ gives a higher efficiency figure of 87 % for POX, but states that one has to take account also of the fact that product gas of such a system is less hydrogen rich, and a “fuel penalty factor” or “hydrogen utiliation factor” needs to be used. It gives a value of 80 % to this factor, resulting to a net efficiency of 69 %.

On the other hand, the combined efficiency figure (22.6 %) that this study assumes for a complete FC powerplant (stack+reformer) seems to be at the low side of any referred value. Thus the combined “vehicle-cycle” (reformer and the FC system combined) efficiency is only 17.6 %, resulting to WTW efficiency of some 15 %. However, the other studies suggest somewhat higher values reaching a WTW efficiency between 19 - 22 %. Therefore, the FC option here should have somewhat higher total system efficiency than those given.

8.3.2 Natural gas

As a currently viable option, the direct use of natural gas in ICE is now considered. Here both liquefied (LNG) and compressed (CNG) storage technologies are catered. Table 8.1 lists main results also for these fuel options. As can be seen from the WTW efficiency figures, both NG options are slightly better than gasoline-fuelled SI-ICE, but because of the higher energy use in fuel distribution stage, LNG reaches a marginally lower WTW (12.7 % LNG vs. 12.9 % CNG). The same kind of “boost” from hybridisation as for normal SI-ICE can be expected also here, so it will not change the relative ranking.

However, the combined efficiency of the FC and the reformer (most probably a *steam reformer* unit in this case) seems to be on the low side, as it is here exactly the same (17.6 %) as with the gasoline/POX case, whereas the literature usually gives higher efficiencies for STM reformers. Therefore, the combined reformer+FC efficiency should be higher in this case than with gasoline, and a more reasonable level for the combined vehicle-stage efficiency would be 35 %. Thus, the FC option should reach much better system efficiency than given in this study.

Furthermore, although these options are included in the table, using NG to fuel a FC vehicle with an on-board reformer may not be feasible. As the bulk of the gas storage is substantial, it may unreasonably add weight to the vehicle already loaded with the added weight of the reformer unit. Only if the vehicle is a heavy-duty vehicle like urban bus, the possibility of using existing fuel infrastructure to support the vehicle fleet could make this alternative sensible in some cases.

As stated earlier, major share of the current merchant hydrogen is produced from NG via steam reforming. This could also be a viable technology to produce fuel for FC vehicles. The hydrogen can be stored on-board either in liquid L-H_2 or gaseous form G-H_2. The difference in the fuel chain efficiency seems to split these options in such a way that a G-H_2 FC vehicle reaches WTW total efficiency of 13.8 %, which is 12 % better than baseline SI-ICE, but using L-H_2 yields to a lower value of 9.8 %, which is 12 % lower than baseline.

Again it must be stated that based on other literature, the combined powerplant efficiency for the FC (22.6) seems to be very low, and should be closer to 32 %. Thus, both direct-hydrogen FC options should render much better WTW figures than baseline SI-ICE fuelled with gasoline. For the G-H_2 the WTW efficiency should be over 26 %, and the net benefit of FC powertrain would then be nearly 60 %. Furthermore, even the L-H_2 case should be better than baseline by some 10 %.

Apart from central, large-scale production of hydrogen, it is also possible that NG is distributed via existing pipelines to retail refuelling stations, where hydrogen can be produced locally. Although for the sake of safety or simplicity, such distribution of natural gas would be preferred rather than distributing hydrogen, even if large-scale central production is considered to be somewhat more efficient than small-scale conversion at a retail station. Respectively, the liquefying or compression of hydrogen are also less efficient in small-scale local units. Therefore, while the most efficient pathway of this group is central production of hydrogen and using G-H_2, followed by locally produced G-H_2, the worst-case is then local site hydrogen production using L-H_2 for on-board storage.

Since ICE is less efficient as an energy transformer than FC, direct use of hydrogen in SI-ICE results in inferior WTW efficiency compared to baseline, although for technical point of view this option is valid, and is seen as a possibility to realise a motor vehicle with near-zero air-polluting emissions.

8.3.3 Natural gas to electricity and hydrogen by electrolysis (central and local production)

Hydrogen can be produced from water using electrolysis process. Using electrical energy to produce hydrogen opens also a gateway for renewable primary energy use, because electricity derived from hydropower or nuclear energy can be used.

Furthermore, the use of water electrolysis would enable both large-scale central and local, small-scale production, as well, but like with the reforming processes, smaller scale results in lower efficiency. At first it might seem lucrative to distribute the energy in the form of electricity and produce the hydrogen to fuel the FC vehicle at a site close to the consumer and without local emissions. However, the transmission losses of electricity (some 10 %) and the relatively low efficiency of the small-scale electrolysis devices (about 70 %) would rate this pathway as highly inefficent compared to other means of producing hydrogen. This option would also unduly transfer electrical load to the outer edges of the grid rather than putting it closer to the production sites.

On the other hand, an altogether different situation is created, if in the future distributed power production is realised. Then the loads should be equally distributed in order to lower the necessary transfer capacity of the grid, and from this viewpoint, local site electrolysis could be a viable option.

In terms of using NG as primary energy source, the total WTW efficiency of this pathway is, however, quite poor. Natural gas fired powerplants reach production efficiencies between 35 – 60 %, and combined with other upstream losses the throughput of energy as electrical energy to a site is in the order of 30 – 50 %. When the literature gives for electrolysis process efficiencies ranging from 60 % (small, local) to 76 % (large, central) the total fuel production efficiency would be 20 – 40 % which is considerably less than in the case of hydrogen reformed from NG. All total WTW efficiencies for this case are below 10 %, being the lowest from all the optional pathways considered in that study.

8.3.4 Natural gas to methanol to be used in FCV with an on-board reformer

As stated earlier, methanol makes a strong case when candidates for future transport energy carriers are sought. Because it is in liquid form, storage and distribution are less complicated than with gaseous fuels. The production of methanol is also a less complicated and capital intensive operation than building a large LNG installation for overseas NG transport. Therefore, for the exploitation of stranded gas reserves, methanol could offer a viable alternative. Production flexibility is also high, because apart from the production from fossil natural gas, renewable biomass can be used. Furthermore, a long-term option is to use hard coal, where world resources are quite substantial.

If methanol is used, the vehicle can utilise it either directly with ICE (both SI and CI are possible) or using an on-board reformer to produce hydrogen feed for an FC. Because of the high octane value of methanol, higher-than-usual compression ratio can be used to help SI-ICE reach higher thermal efficiency. This “boost” to the total powertrain efficiency is some 1 to 2 %. In a CI-ICE, no considerable difference in cycle efficiency is seen. Even if the TTW efficiency of these ICE options is comparable, the higher fuel cycle energy use in the case of methanol makes them somewhat worse than their baseline, where crude oil based gasoline or diesel oil is used.

Methanol is the easiest feed for reformate gas production, and the STM reactor in the on-board fuel reformer has the highest efficiency of its type. Literature gives it values from 62 % to as high as 86 %, which is the value used in this Swedish study. Nevertheless, the lower fuel cycle efficiency of methanol brings down the full WTW efficiency level close to baseline with some 10 % benefit over SI-ICE. However, as with the other FC vehicle cases, the FC powerplant efficiency seems to be somewhat underestimated here, and the eventual WTW efficiency should be higher, according to /8.13/ and /8.15/ in the order of 20 %, which raises the relative benefit over baseline to some 50 %.

8.3.5 Natural gas to Fisher-Tropsch diesel (FTD)

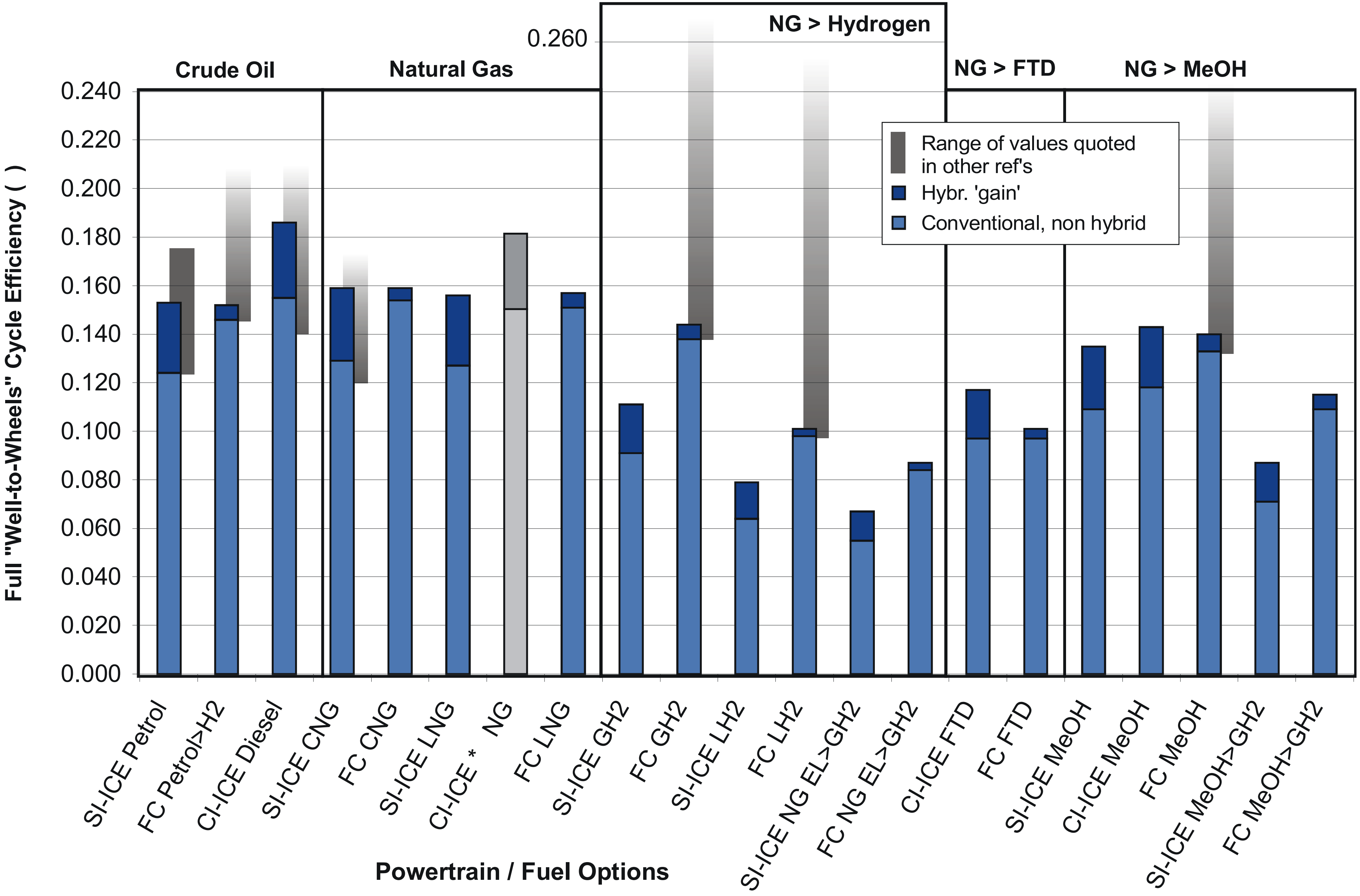
Apart from methanol, natural gas can be used as feedstock for the production of other liquid fuels, e.g. in the Fisher-Tropsch process. The products of this kind of process are similar to the existing crude-oil based fuels and very low in sulphur and aromatic hydrocarbons. Furthermore, FT-diesel (FTD) has a very high cetane number making it a superior CI-ICE fuel. Furthermore, when FTD is sulphur-free and low in aromatics, it is also a candidate fuel for FCV fuel reformer. However, due to the relatively high energy intensity of the FT-process, its fuel cycle WTT efficiency remains low. Therefore, both while using CI-ICE as powerplant or in case of a FCV, when a reformer must also be used on-board, the total WTW efficiency of this fuel pathway ends at a value of 0.1 which is lower than the baseline.

8.4 Discussion and a synthesis from the efficiency assessment

Total WTW efficiencies for those selected fuels and powertrain combinations are presented in figure 8.2. The base values are those that are commented on above and derived from /8.18/. However, as there seems to be some cases where other relevant studies suggest other, mainly higher, values for the efficiency, we have included those as a range to reflect the spread existing in the various estimates.

If we use only values from the reference study, the best total WTW efficiency is achieved with diesel fuel, diesel engine combination, especially in a hybrid configuration. It reaches a value of nearly 19 %. A close match, if such an engine could be realized, would be a NG-fuelled, direct-injected diesel engine (CI-ICE NG), as we calculate that it should produce WTW close to comparable diesel-fuelled engines, as the fuel-cycle efficiency of CNG is only slightly worse than for diesel fuel. However, such configurations exist today only at a demonstration level, and wider commercialisation is still underway.

The Swedish study ranks all hydrogen and methanol-fuelled alternatives much lower than crude oil or NG based combinations. However, if we take into account other relevant studies and see those ranges they give for fuel cell powerplants, a FCHV using centrally-produced H_2 from NG feedstock as GH_2 is the most efficient option reaching a WTW of over 26 %. It is closely matched by a methanol-fuelled FCHV using an on-board fuel processor for H_2 production (WTW up to 24 %). This combination is on the same level as a LH_2 -fuelled FCHV. Although the Swedish study ranked the petrol-fuelled FC as the best of all FC's, we see that this assessment could not be corroborated with values taken from the other studies listed and assessed here. Other references do give higher values for this option, but not reaching as high as the others already mentioned, but closer to 21 % WTW efficiency, thus matching the best ICE-based combination, which is in all studies CI-ICE in a hybrid configuration.



*) speculative, not in the study = Direct NG injection in CI-ICE (+hybridisation)

Figure 8.2 Total efficiency of selected fuel and powertrain pathways.

8.5 Emissions

8.5.1 GHG-emissions

A good first estimate of the GHG emissions from all the optional fuel/engine combinations discussed here can be obtained, if the total energy consumption of the given pathway is calculated, and then using the carbon content of the feedstock (crude, NG) to convert it to CO_2 emissions.

However, if NG is used in ICE, some emissions of methane do occur, even if catalytic converters are used, as methane is the most difficult of all hydrocarbons to oxidise. Furthermore, if an ICE is used, exhaust gases usually contain nitrous oxide, which also is a powerful GHG.

When a fuel cell powerplant is used, apart from CO_2 no other GHG emissions are generated if the hydrogen is produced in central, large-scale plants. Centralised production of hydrogen would also enable the capture of CO_2, if necessary. Furthermore, if an on-board fuel reformer is used, some local emissions are generated, but usually only at a trace level (*see 8.4.2*).

However, if electrolysis is used to produce hydrogen, there are some new elements which have to be considered. If the electricity to drive the electrolysis process is produced in a NG-fired powerplant, apart from CO_2, low levels of other GHG's are also emitted, but after this stage there will be no downstream emissions. Should the electricity be produced using hydro or nuclear power, it can yield to a totally carbon-free fuel chain. The same effect can be achieved, if renewable biomass is used as feedstock or fuel. However, it would not reach the same level, as it necessitates the use of fossil energy and thus the fuels would contain carbon emission "residues".

As a comparative example, Table 8.2 gives some values for GHG emissions over different fuel pathways. It is taken from /8.2/, and reflects the Canadian situation. Therefore, some numbers are probably different from their counterparts in the Swedish study.

Values from /8.5/ are also used to compute CO_2 emissions [in g/km] for most of the fuel/engine options discussed here. These values are illustrated in Figure 8.3.

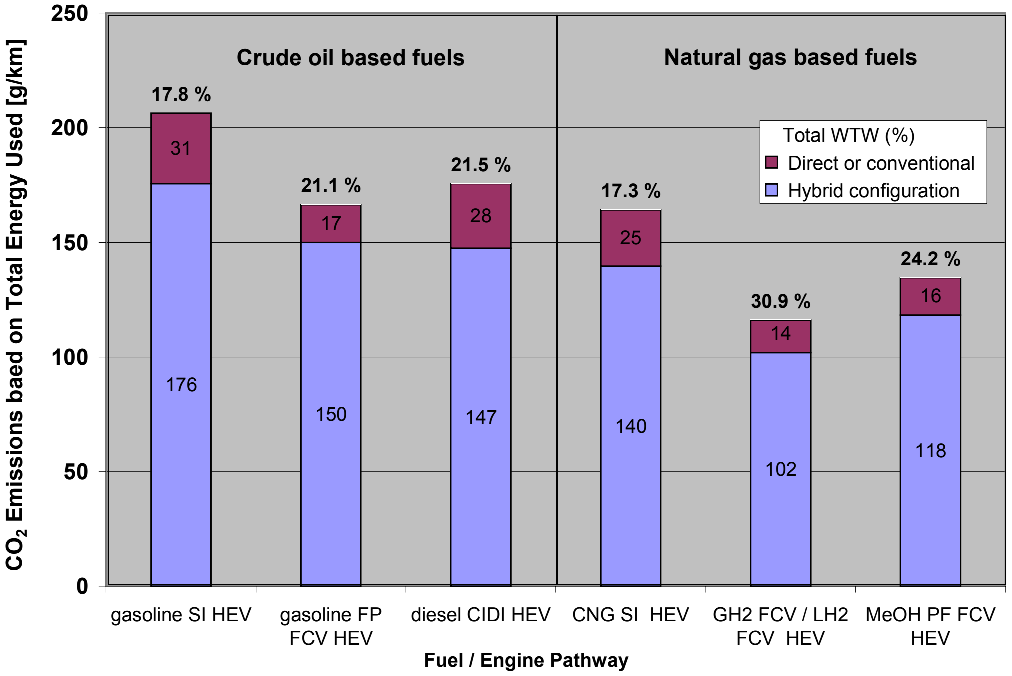
8.5.2 Toxic emissions and other air pollutants

As long as the ICE is used for energy conversion, the exhaust will contain toxic emissions and other emissions regarded as air pollutants. However, as a result of the strong progress in emission aftertreatment and control equipment technology, the levels of these emissions show a strong downward trend. But parallel to the increase in performance, the cost of such equipment has also increased. Therefore, it is becoming more and more expensive to produce low-emitting vehicles using the ICE as prime mover. This development is also fuelling the race of FC powerplant development. The fact is that as FC powerplants become less expensive, there becomes a cut-point, where it shall be more cost-effective to build a FC vehicle rather than an ICE driven one with a complicated and expensive emissions control system.

As already noted, when a fuel cell powerplant is used with an on-board fuel reformer, some air polluting emissions are generated; but are usually only at trace level, as the systems contain a unit referred to as a "tail gas combustor", which is essentially a catalytic converter to clean up the exhaust.

Engine	ICE	FC	FC	FC	FC	FC	FC
Fuel	Gasoline	CH_2	LH_2	CH_2	Methanol	Sulphur Free Gasoline	FTD
Source	Oil	NG (Small decentralize)	NG (Large centralized)	Electrolysis (natural gas to electricity)	NG	Oil	NG
Units	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile	Gm CO_2 eq/mile
Vehicle Operation	338.5	0.0	0.0	0.0	176.2	234.0	228.8
Fuel Dispensing	0.8	9.7	48.3	19.1	0.8	0.5	0.4
Fuel Distribution	5.8	0.6	1.7	0.6	15.6	4.0	8.9
Fuel Production	60.9	160.6	158.3	364.6	25.0	45.8	71.6
Feedstock Transport	1.0	7.1	7.1	0.0	1.1	0.7	1.6
Feedstock Production	42.5	11.9	11.8	0.0	15.0	29.4	22.3
Gas Leaks and Flares	12.8	14.4	14.5	0.0	10.8	8.9	16.1
Emissions Displaced by Co-products	0.0	0.0	0.0	0.0	0.0	0.0	-1.5
Sub Total	462.2	204.5	241.7	384.4	244.5	323.2	348.1
% Changes	**-**	**-55.8**	**-47.7**	**-16.8**	**-47.1**	**-30.1**	**-24.7**
Vehicle Assembly	5.3	5.4	5.4	5.4	5.8	5.9	5.9
Materials in Vehicles	28.4	29.2	29.2	29.2	29.9	30.4	30.4
Grand Total	495.9	239.1	276.3	419.0	280.2	359.5	384.4
% Change	**-**	**-51.8**	**-44.3**	**-15.5**	**-43.5**	**-27.5**	**-22.5**

Table 8.2 GHG emissions in CO_2eq for different fuel-engine pathways. (Source: /8.2/)



Source: Argonne National Laboratory Study (/8.5/)

Figure 8.3 CO_2 emissions for different fuel/engine combinations; data from Ref. /8.5/:

Only very limited data are available of the air pollutants from FC vehicles, but according to those few sources (some are shown in Figures 8.4 and 8.5), their emissions performance should be better than any known ICE-driven vehicle and very close to zero level of emissions during vehicle operation.

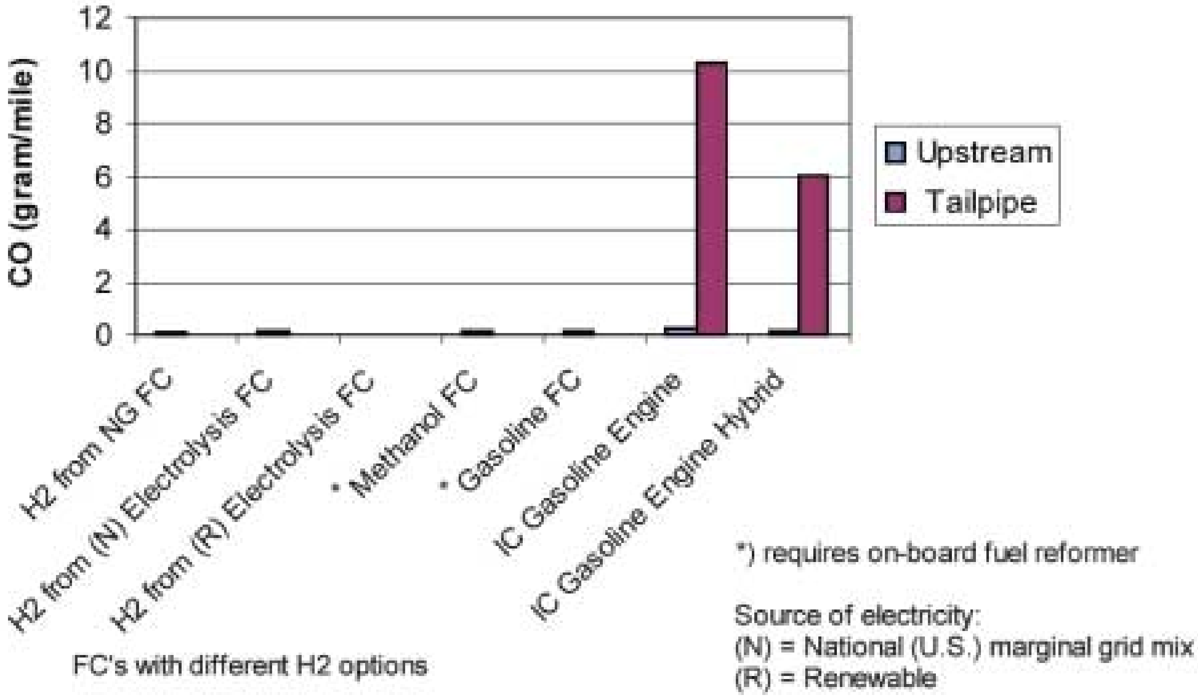


Figure 8.4. Example of CO emission comparison between different fuel/powerplant options /8.12/.

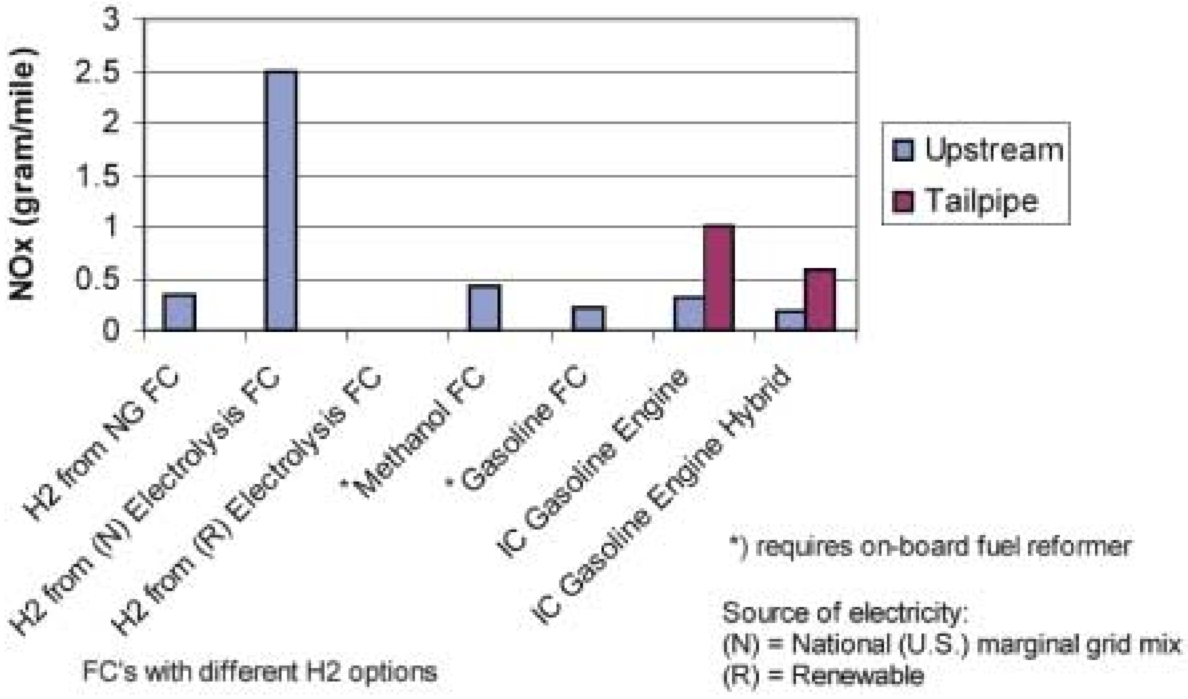


Figure 8.5. Example of NOx emission comparison between different fuel/powerplant options /8.12/.

However, if we take into account the upstream emissions from the hydrogen fuel production cycle, hydrogen based on electrolysis carries a high burden. This is the case because if any fuel-fired boiler is used in a power plant generating the needed electricity, air pollutant emissions are also generated. However, there is no possibility of making a comparative assessment within the context of this study, as the levels of these pollutants depend on the power plant efficiency, fuel mix and eventual flue gas cleaning technology employed, and these items differ strongly from case to case.

8.6 Conclusions on the system efficiencies

Based on the full systems efficiency analysis performed here, no fuel/powertrain combination seems to be clearly overruling the others. Furthermore, the conventional ICEs offer still very respectable target for the new concepts to aim at. This is particularly true, if we take into account the gain in efficiency that the hybrid configurations can offer to the ICEs. This statement is based to the fact that the highest numerical WTW efficiencies were reached with diesel/CI-ICE, without or with hybrid configuration. However, natural gas seem to offer quite a close match, as using CNG with either a hybrid SI-ICE or with an FC gave the next best values. This is the case, even if the FC option requires the use of an on-board fuel reformer to produce hydrogen for the fuel cell.

Compressed natural gas (CNG) has better well-to-tank efficiency than the use of the liquefied storage technology (LNG). Thus the LNG options reach slightly lower total efficiencies than CNG, but are still the runner-up cases and successfully challenge today’s most common option, i.e. gasoline/SI-ICE, or even the FC powertrain, where gasoline is reformed on-board to hydrogen. However, in practice packaging issues and weight penalties associated with the on-board storage of natural gas may render these options unfavorable in case of a FC vehicle, because apart form the fuel, an on-board fuel reformer needs to be accommodated, as well. Therefore, using off-board reforming of natural gas to hydrogen, and storing only gaseous H_2 on board, may prove a more practical, if not that energy efficient alternative. Furthermore, it seems that this combination is even on par with a methanol fuelled FC fitted with an on-board fuel reformer.

Using natural gas as the feedstock for the gas-to-liquid fuel processes yields to lower well-to-tank efficiencies than using straight gas. However, if we consider that this route can offer high-quality, sulphur-free fuel that is compatible with most of the existing CI-ICE stock, it is worth considering, even if it is not the most lucrative pathway energetically. Furthermore, this option may be well-suited to the utilization of remote and stranded gas reserves, as transporting liquid fuel is more efficient than LNG transport. The necessary investments in plant technology are, however, probably higher for the gas-to-liquid process than to LNG production.

Using natural gas in a power plant to produce electricity and then produce hydrogen by water electrolysis is the least efficient option of all the cases considered here. Because combustion in a boiler results also pollutant emissions, this pathway should not be adopted.

Overall, the efficiencies in the reference study seem to be in many cases lower than those associated with other, earlier studies. However, if we consider these somewhat higher values (shown in figure 8.2), FC vehicles using hydrogen that is produced from natural gas offer significant improvement over the diesel/CI-ICE pathway, even if these alternate studies give that case also somewhat higher total efficiency than in the reference study.

Appendix 1 to Chapter 8.

Table 8.1 Well-to-Wheels energy efficiency analysis for all crude oil and natural gas (NG) based fuel pathways; source /8.18/.

Feed-stock	Fuel	Powertrain		Prod	Dist	Reform.	Powertr.	Total	Relative	WTT	TTW
Crude	Petrol	**Otto**	**Conv.**	**0.841**	**0.986**	**1.000**	**0.149**	**0.124**	**1.000**	**83 %**	**15 %**
		Otto	Hybrid	0.841	0.986	1.000	0.185	0.153	1.240	83 %	18 %
	Petrol>H2	FC	Direct	0.841	0.986	0.780	0.226	0.146	1.184	65 %	23 %
		FC	Hybrid	0.841	0.986	0.780	0.235	0.152	1.228	65 %	24 %
	Diesel	**Diesel**	**Conv.**	**0.888**	**0.990**	**1.000**	**0.176**	**0.155**	**1.250**	**88 %**	**18 %**
		Diesel	Hybrid	0.888	0.990	1.000	0.212	0.186	1.507	88 %	21 %
NG	CNG	**Otto**	**Conv.**	**0.957**	**0.909**	**1.000**	**0.149**	**0.129**	**1.045**	**87 %**	**15 %**
		Otto	Hybrid	0.957	0.909	1.000	0.182	0.159	1.281	87 %	18 %
		FC	Direct	0.957	0.909	0.780	0.226	0.154	1.241	68 %	23 %
		FC	Hybrid	0.957	0.909	0.780	0.235	0.159	1.288	68 %	23 %
	LNG	**Otto**	**Conv.**	**0.887**	**0.963**	**1.000**	**0.149**	**0.127**	**1.027**	**85 %**	**15 %**
		Otto	Hybrid	0.887	0.963	1.000	0.182	0.156	1.259	85 %	18 %
		FC	Direct	0.887	0.963	0.780	0.226	0.151	1.220	67 %	23 %
		FC	Hybrid	0.887	0.963	0.780	0.235	0.157	1.266	67 %	24 %
	GH2	Otto	Conv.	0.770	0.794	1.000	0.149	0.091	0.735	61 %	15 %
		Otto	Hybrid	0.770	0.794	1.000	0.182	0.111	0.901	61 %	18 %
		FC	**Direct**	**0.770**	**0.794**	**1.000**	**0.226**	**0.138**	**1.119**	**61 %**	**23 %**
		FC	Hybrid	0.770	0.794	1.000	0.235	0.144	1.161	61 %	24 %
	LH2	Otto	Conv.	0.471	0.916	1.000	0.149	0.064	0.518	43 %	15 %
		Otto	Hybrid	0.471	0.916	1.000	0.182	0.079	0.635	43 %	18 %
		FC	**Direct**	**0.471**	**0.916**	**1.000**	**0.226**	**0.098**	**0.789**	**43 %**	**23 %**
		FC	Hybrid	0.471	0.916	1.000	0.235	0.101	0.819	43 %	23 %
	EL>GH2	Otto	Conv.	0.451	0.820	1.000	0.149	0.055	0.444	37 %	15 %
		Otto	Hybrid	0.451	0.820	1.000	0.182	0.067	0.544	37 %	18 %
		FC	**Direct**	**0.451**	**0.820**	**1.000**	**0.226**	**0.084**	**0.676**	**37 %**	**23 %**
		FC	Hybrid	0.451	0.820	1.000	0.235	0.087	0.702	37 %	24 %
	DME>GH2	Otto	Conv.	0.754	0.641	1.000	0.149	0.072	0.581	48 %	15 %
		Otto	Hybrid	0.754	0.641	1.000	0.182	0.088	0.712	48 %	18 %
		FC	**Direct**	**0.754**	**0.641**	**1.000**	**0.226**	**0.109**	**0.884**	**48 %**	**23 %**
		FC	Hybrid	0.754	0.641	1.000	0.235	0.114	0.917	48 %	24 %
	DME	**Diesel**	**Conv.**	**0.725**	**0.967**	**1.000**	**0.176**	**0.123**	**0.997**	**70 %**	**18 %**
		Diesel	Hybrid	0.725	0.967	1.000	0.212	0.149	1.202	70 %	21 %
		FC	**Direct**	**0.725**	**0.967**	**0.840**	**0.226**	**0.133**	**1.078**	**59 %**	**23 %**
		FC	Hybrid	0.725	0.967	0.840	0.242	0.143	1.153	59 %	24 %
NG	FTD	**Diesel**	**Conv.**	**0.556**	**0.989**	**1.000**	**0.176**	**0.097**	**0.782**	**55 %**	**18 %**
		Diesel	Hybrid	0.556	0.989	1.000	0.212	0.117	0.943	55 %	21 %
		FC	Direct	0.556	0.989	0.780	0.226	0.097	0.785	43 %	23 %
		FC	Hybrid	0.556	0.989	0.780	0.235	0.101	0.815	43 %	24 %
	Methanol	**Otto**	**Conv.**	**0.688**	**0.978**	**1.000**	**0.162**	**0.109**	**0.883**	**67 %**	**16 %**
		Otto	Hybrid	0.688	0.978	1.000	0.201	0.135	1.095	67 %	20 %
		Diesel	**Conv.**	**0.688**	**0.978**	**1.000**	**0.176**	**0.118**	**0.957**	**67 %**	**18 %**
		Diesel	Hybrid	0.688	0.978	1.000	0.212	0.143	1.154	67 %	21 %
		FC	**Direct**	**0.688**	**0.978**	**0.860**	**0.230**	**0.133**	**1.075**	**58 %**	**23 %**
		FC	Hybrid	0.688	0.978	0.860	0.242	0.140	1.132	58 %	24 %
		DMFC	Hybrid	0.688	0.978	1.000	0.172	0.116	0.938	67 %	17 %
	MeOH>GH2	**Otto**	**Conv.**	**0.719**	**0.661**	**1.000**	**0.149**	**0.071**	**0.571**	**48 %**	**15 %**
		Otto	Hybrid	0.719	0.661	1.000	0.182	0.087	0.700	48 %	18 %
		FC	**Direct**	**0.719**	**0.661**	**1.000**	**0.230**	**0.109**	**0.883**	**48 %**	**23 %**
		FC	Hybrid	0.719	0.661	1.000	0.242	0.115	0.930	48 %	24 %

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9. Recommendations for the natural gas vehicle industry

This report provides some indications for the NGV and natural gas industries of what the future might hold for those industries in the medium to longer term. There are some pointers as to what should be done now to keep abreast of what is occurring and to help ensure that natural gas has its place in the future:

- Continue to advocate the growth and benefits of the NGV industry as the here and now means of improving efficiency of transport energy use and reducing local and GHG emissions
- Continue to demonstrate the benefits (economics, performance etc.) of NGVs relative to conventional and FC technology
- Continue to demonstrate emission benefits of NGVs over conventional technology. Emphasise/focus on particulate emissions of heavy duty vehicles, greenhouse gas benefits of light duty vehicles; and on the potential benefits of new and improving heavy duty natural gas engine systems
- Keep track of OEM and environmental requirements regarding fuel quality and develop analytic materials to demonstrate the benefits of natural gas fuel quality compared to liquid fuels.
- Keep track of OBD developments and promote policies and actions that aid the NGV industry to cost effectively meet OBD regulatory requirements
- Encourage the development of high efficiency HD natural gas engines and promote partnerships between government and industry to facilitate this.
- Support hybrid vehicle developments, especially those which have natural gas powertrains in electric/hybrid vehicles.
- Pursue the development of on-board and on-site reforming of natural gas
- Evaluate the prospects for (and develop as necessary) combined natural gas and hydrogen refuelling stations
- For natural gas-to-hydrogen technology, emphasise the need for extending the CNG or LNG refuelling infrastructure, and how to provide advantages of synergies with the growing hydrogen industry.
- Emphasise the importance of the relationship between natural gas and hydrogen, with natural gas and NGVs being a pathway to future technological and fuelling development