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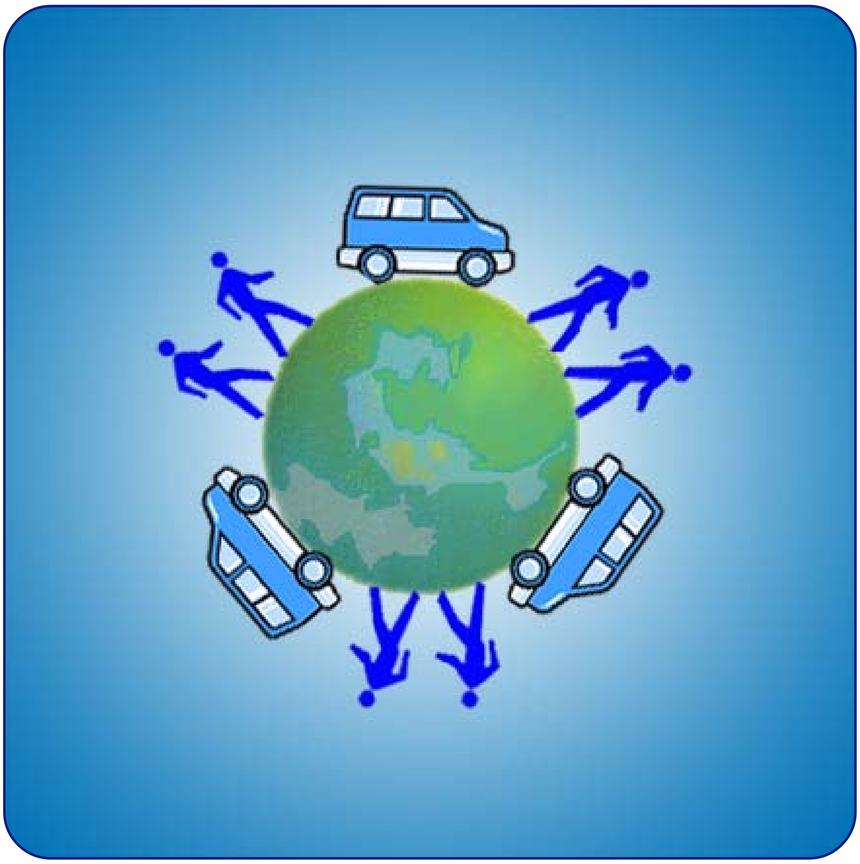

Nils-Olof Nylund, Päivi Aakko-Saksa & Kai Sipilä

Status and outlook for biofuels, other alternative fuels and new vehicles

ADVANCED MOTOR FUELS IEA-AMF

Bioenergy NoE

VTT

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Nils-Olof Nylund, Päivi Aakko-Saksa & Kai Sipilä

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Abstract

The report presents an outlook for alternative motor fuels and new vehicles. The time period covered extends up to 2030. The International Energy Agency and the U.S. Energy Information Administration predict that the world energy demand will increase by over 50% from now to 2030, if policies remain unchanged. Most of the growth in demand for energy in general, as well as for transport fuels, will take place in non-OECD countries. Gasoline and diesel are projected to remain the dominant automotive fuels until 2030. Vehicle technology and high quality fuels will eventually solve the problem of harmful exhaust emissions. However, the problem with CO_2 still remains, and much attention will be given to increase efficiency. Hybrid technology is one option to reduce fuel consumption. Diesel engines are fuel efficient, but have high emissions compared with advanced gasoline engines. New combustion systems combining the best qualities of gasoline and diesel engines promise low emissions as well as high efficiency.

The scenarios for alternative fuels vary a lot. By 2030, alternative fuels could represent a 10–30% share of transport fuels, depending on policies. Ambitious goals for biofuels in transport have been set. As advanced biofuels are still in their infancy, it seems probable that traditional biofuels will also be used in 2030. Ethanol is the fastest growing biofuel. Currently the sustainability of biofuels is discussed extensively. Synthetic fuels promise excellent end-use properties, reduced emissions, and if produced from biomass, also reduced CO_2 emissions. The report presents an analysis of technology options to meet the requirements for energy security, reduced CO_2 emissions, reduced local emissions as well as sustainability in general in the long run. In the short term, energy savings will be the main measure for CO_2 reductions in transport, fuel switches will have a secondary role.

Preface

This outlook report reviews the current situation for energy supply, motor fuels and vehicle technology, and summarizes projections into the future. The focus is on alternative fuels and new vehicle technologies. The time perspective of this report extends to 2030.

The report deals with energy for transportation on many levels: energy resources, policies, fuel technology, vehicle technology, and environmental impacts. Special attention is given to fuel/vehicle interaction. Based on available data, an evaluation of the promises and potential of different fuel and vehicle options under consideration is carried out to estimate future development.

The study was carried out within Annex XXVIII (AMFI Information Service, www.iea-amf.vtt.fi) of the IEA Advanced Motor Fuels Implementing Agreement. The authors would like to acknowledge the IEA Advanced Motor Fuels Implementing Agreement and the Technical Research Centre of Finland VTT for support for this work. Additional biofuels-related information was gathered from the assessment work done within the EU Bioenergy Network of Excellence (NoE).

The report highlights the strong links between alternative fuel production, distribution, and end-use, considering both current and future technology. In order to have new options on the market in large scale by 2020, a strong increase in joint R&DDD activities is essential. IEA's various Implementing Agreements, EU's 7th Framework Programme, as well as many national activities provide efficient platforms in catalyzing international and national innovation management.

The report at hand is a condensed public report based on the full background document, which is restricted for use within the Executive Committee of IEA AMF and EU Bioenergy NoE. The full background document was distributed in February 2007. Most parts of the background report were written in the autumn of year 2006. Some 2007 data has been added to the condensed public version of the report.

The views and opinions of authors expressed herein do not necessarily state or reflect those of the IEA Advanced Motor Fuels Implementing Agreement or EU Bioenergy Network of Excellence.

Espoo, December 31st, 2007.
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Abbreviations and definitions

AFV	Alternative fuel vehicle
bcm	Billion cubic meter
Bpd	barrels per day
BTL	Biomass-to-Liquids
CAI	Controlled auto ignition
CCS	Carbon capture and storage
CCS	Combined Combustion Systems
CH_4	Methane
CTL	Coal-to-Liquids
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DME	Dimethyl ether
EIA	Energy Information Administration
ETBE	Ethyl tertiary butyl ether
EU	European Union
E85	A blend of up to 85% ethanol in gasoline
FAME	Fatty-acid methyl ester
FFV	Flexible Fuel Vehicle
FT	Fischer-Tropsch
GHG	Greenhouse gases
GDP	Gross domestic product
GTL	Gas-to-Liquids
HC	Hydrocarbon
HCHO	Formaldehyde
HCCI	Homogenous charge compression ignition
HFC	Hydrofluorocarbon
HVO	Hydrotreated vegetable oil
IEA	International Energy Agency
IEO	International energy outlook (EIA)
IGCC	Integrated gasification combined cycle
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
mbp	Million barrels per day
MTBE	Methyl tertiary butyl ether
MON	Motor octane number
MY	Model year
NMHC	Non-methane hydrocarbon

NMOG	Non-methane organic gases
NO_x	Nitrogen oxides
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
OBD	On-Board Diagnostics
OECD	Organisation for Economic Co-operation and Development
PAH	Polyaromatic hydrocarbons
PM	Particulate matter
ppmv	part per million (volume)
RME	Rapeseed methyl ester
RON	Research octane number
SF6	Sulfur hexafluoride
SI	Spark Ignition
SME	Soy methyl ester
TAEE	Tertiary amyl ethyl ether
TBA	Tert-butyl alcohol
TFC	Total final consumption (energy)
toe, Mtoe	Tons of oil equivalent, million tons of oil equivalent
TPES	Total primary energy supply
VOC	Volatile organic compound
VOE	Vegetable oil ester
WEO	World energy outlook (IEA)
WWFC	Worldwide Fuel Charter

Biomass: Biobased (renewable) feedstock.

Biofuel: Renewable fuel, either solid, liquid, or gaseous. In this report, however, biofuel means liquid or gaseous biofuels for transport.

Traditional biofuels for vehicles are ethanol from corn, FAME-type biodiesel from vegetable oils, and biogas (biomethane). The usage of traditional liquid biofuels may be restricted due to technical limitations in end-use, and the production of these fuels may compete with food production.

Advanced biofuels for vehicles such as synthetic fuels deliver superior end-use properties. These fuels can be used at high concentrations in existing vehicles. Next generation biofuels do not compete with food production (e.g. cellulosic ethanol or BTL).

Conversion table of energy units with data on energy consumption in the world, the US and Europe (IEA WEO 2006, "Vision 2030" report 2006, EIA).

	Mtoe	**TWh**	**PJ**	**EJ**	**Quadrillion Btu**
Total energy demand					
World energy, 2004	11 204	129 966	467 879	468	443
World energy, 2030	17 095	198 302	713 887	714	677
US total energy 2004	2 324	26 958	97 050	97	92
EU25 total energy, 2004	1 756	20 370	73 331	73	70
EU25 total energy, 2030	1 973	22 887	82 392	82	78
Transport energy demand					
World transport, 2004	1 969	25 993	93 576	94	89
World transport, 2030	3 082	39 660	142 777	143	135
US transport, 2005	707	8 206	29 540	30	28
EU25 transport, 2000	322	3 735	13 447	13	13
EU25 transport, 2010	377	4 373	15 744	16	15
EU25 transport, 2020	416	4 826	17 372	17	16

1. Introduction

The global energy solutions in general are unsustainable, and the situation is the worst in the transport sector, which is almost totally dependent on crude oil. The demand for energy in transportation is growing. A gap between supply and demand of transportation fuels can be foreseen. For sure, in a medium- and long-term perspective our world of transportation will be going through major changes concerning energy sources, energy carriers, and end-use applications.

Some automotive technologies set strict requirements for fuel quality, and some fuels require a dedicated infrastructure. On the other hand, limitations on energy sources (feedstock), production processes, and infrastructure determine the availability of energy carriers (fuels), and all this has to be taken into account by automotive engineers. Furthermore, these factors are not in harmony world-wide; the conditions vary from country to country, and policy actions can have strong impact on the development. In the coming years, we may see a variety of solutions – vehicles running on CNG or LPG, on ethanol or conventional bio-diesel, or on synthetic liquid fuels (based on natural gas, coal and biomass), and, of course, even on oil-based fuels ("the last drop of fossil fuels will be used in transportation"). The complicated fuel mix will be challenging.

This report provides an overview of today's energy situation, and outlines various future transportation energy prospects. Based on the available data, an evaluation of the different engine/fuel options is carried out to summarize possible future solutions. The focus of this report is on advanced fuel and advanced vehicle technologies. Important background documents for this report are, among others, the World Energy Outlook (WEO) reports prepared by IEA, the International Energy Outlook (IEO) reports prepared by the Energy Information Administration (EIA) of U.S. Department of Energy and documents produced by various energy companies. It should be noted that there is some variation in the data, especially in the projections into the future. Within the reports, alternative scenarios are often presented. For example, the 2006 World Energy Outlook presents two scenarios, the Reference Scenario and the Alternative Policy Scenario, in which policies and measures that governments are currently considering that are aimed at enhancing energy security and mitigating carbon dioxide emissions are assumed to be implemented.

In this report biofuels are analyzed mainly from the end-use perspective, and no detailed analysis of the production potential, global logistics, and raw material availability are included. In 2004–2007 energy prices have risen very rapidly, especially in the case of crude oil. This makes cost comparisons for alternative technologies very difficult, as the targets are moving constantly. Higher energy prices should in principle favor alternative solutions, but this has not been the case as the prices of, e.g., grain and vegetable oils have increased as well. Only very recently there was considerable excitement about biofuels. Now a backlash can be seen, with increasing concerns about the sustainability of producing large amounts of conventional biofuels (i.e., ethanol and biodiesel from edible oil). Correspondingly, hydrogen and fuel cells have lost some of their enchantment.

2. Energy figures

IEA predicts that the world energy demand will increase by more than 55% between 2005 and 2030 with current policies. Huge investments will be needed to meet this increase. Transport is the largest energy end-use sector, and today it's nearly 100% dependent on oil. Goals for alternative transportation fuels have been set, but the key issues in the transport sector to reduce oil consumption are ***energy savings and improved energy efficiency.***

Fossil fuels are expected to remain the major energy sources for many decades to come. However, even the most optimistic projections call for urgent actions towards sustainable energy. Sufficiency of supply might become an issue. Oil demand is projected to grow from some 85 mbpd currently to some 120 mbpd by 2030. Oil resources are mainly concentrated in the Middle East, and large importers are increasingly dependent on oil from the Middle East and North Africa. Natural gas resources are more evenly distributed, but utilization of remote natural gas sources means increases in both LNG shipping and fuel prices. For economic and energy supply reasons, coal and nuclear energy may increase within the power sector despite of problems related to both of these energy sources.

IEA expects renewable energy sources, mainly biomass, to account for 14% of total energy in 2030, and biofuels could cover 4–7% of world transport fuel demand. Power and heat production is the most efficient end-use sector for biomass. However, interest in biofuels for transport is enormous today, and biofuels may cover up to even 25–30% of transport fuels in some regions by 2030. Today, global energy demand is some 467 EJ/a, and the maximum bioenergy potential is estimated at some 200–400 EJ/a during this century.

2.1 Reserves and projections for supply

Neither IEA nor EIA predicts a direct shortage of energy by 2030. However, both organizations predict that the price of energy will go up. It should be noted that economically feasible reserves are always a function of cost. The IEA WEO 2006 states: *"The world is facing twin energy-related threats: that of not having adequate and secure supplies of energy at affordable prices and that of environmental harm caused by consuming too much of it."*

Fossil fuels – oil, natural gas and coal – are expected to remain the major energy sources for many decades. The share of oil drops, though oil remains the largest single fuel in the global energy mix in 2030.

Several institutions and organizations report on fossil energy resources. One way to present reserves is the "Reserves-to-Production Ratio" (R/P). Figure 2.1 shows R/P ratios as well as total proven reserves for fossil energy sources. The current global R/P ratio estimates for oil, natural gas and coal are between 41 and 147 years, oil having the lowest R/P ratio. Regional R/P ratios vary significantly. In addition, the R/P ratio is a sensitive parameter: if demand and production increase significantly, R/P expectation shortens, respectively. In the case of oil, R/P ratio of 41 years does not mean that production can be sustained at present levels for some 40 years. A mismatch between supply and demand will lead to turbulence and rapid increase in energy prices. Enhanced oil recovery and non-conventional oil can, on the other hand, extend reserves substantially.

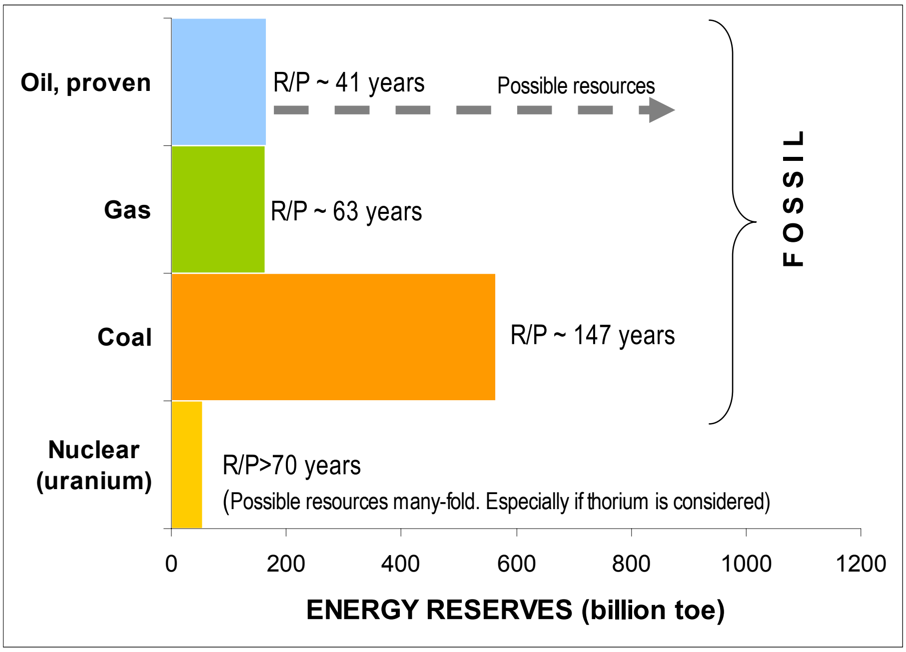

Figure 2.1. Total energy reserves and current R/P ratios (BP 2007, Johansson & Goldemberg 2005).

Oil

One parameter describing sufficiency of oil reserves is called "Peak of oil", which refers to the year of maximum production for conventional oil, after which production decreases. There are different estimations for timing of peak of oil, ranging from today to beyond 2020. Figure 2.2 shows the estimate of The Association for the Study of Peak of Oil and Gas.

Robert L. Hirsch (2006) points out that when oil production is peaking and new technology is not available to cover the increased demand, this results in a rise in prices and development of shortages, maybe long-lasting. The expected economic consequences of the forced energy transition would be inflation, unemployment, recession of economy, and high interest rates. However, if actions would start early enough, some 20 years before the peak, the problems might be even avoided. This means that even in the most optimistic scenario for peak of oil, the actions to move towards sustainable energy should start immediately. (Hirsch 2006)

Analyses have been carried out to evaluate the required new production to cover the demand after the peak of oil. A scenario included in IEA WEO 2004 shows a huge demand of new recoverable oil sources before 2030 (Figure 2.3). The major part of the demand should be covered by new production by 2015, which means that major investments are needed.

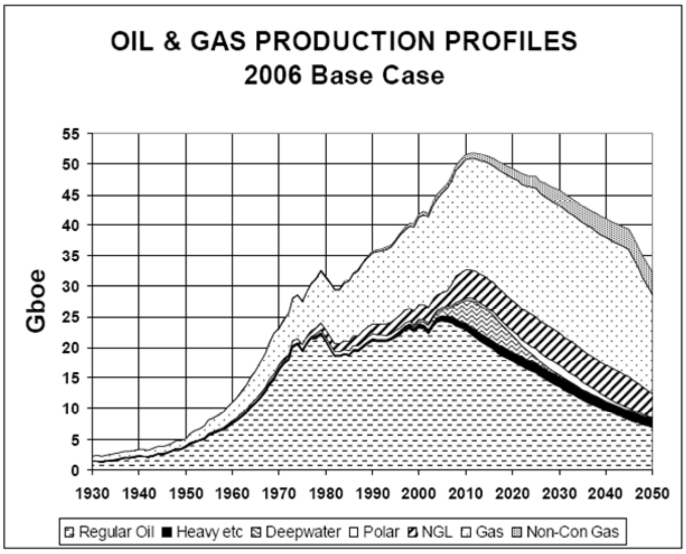

Figure 2.2. Oil and gas depletion (ASPO 2007).

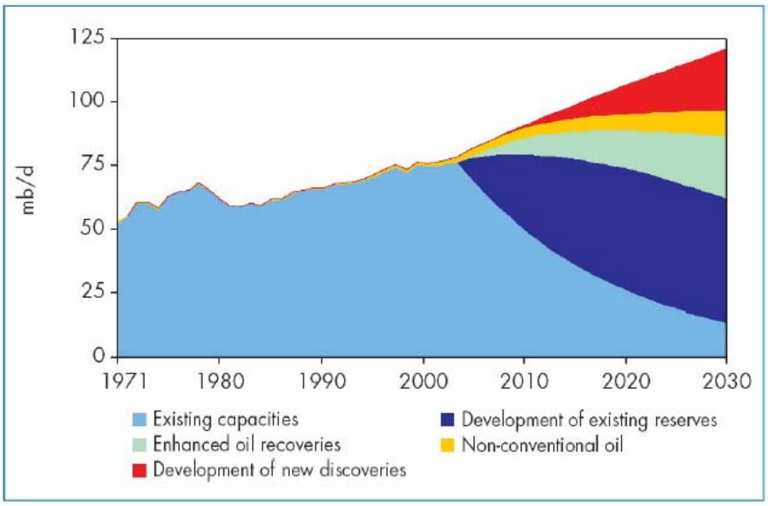

Figure 2.3. Projection of world oil production by source (IEA WEO 2004).

According to EIA IEO 2007 world consumption of petroleum and other liquid fuels grows from 83 million barrels oil equivalent per day (mbpd) in 2004 to 118 million in 2030. IEA WEO 2006 states congruent figures, 84 mbpd in 2005 and 116 mbpd in 2030. OPEC producers are expected to provide more than two thirds of the additional production in 2030. In 2004, world production of unconventional liquids totaled only 2.6 mbpd; in 2030, in the reference case, unconventional liquids production totals 10.5 mbpd and account for nearly 9% of total world liquids production (EIA IEO 2007).

Oil resources are strongly concentrated in the Middle East. IEA countries and large importers like China and India will be increasingly dependent on oil from the Middle East and also North Africa. Non-OPEC oil production starts to decline slowly, but this is partly compensated by increase in unconventional resources. Figure 2.4 shows the distribution of oil reserves and EIA's projection for oil production.

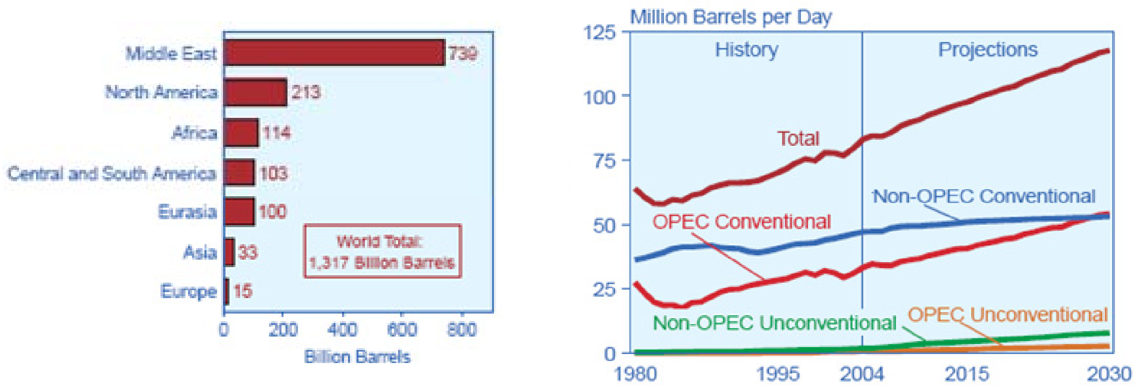

Figure 2.4. Distribution of oil reserves and EIA's projection for oil production (EIA IEO 2007).

The reserves of unconventional oil, e.g., extra-heavy oil, bitumen, and oil shale, are high. Currently, most of these reserves cannot be recovered economically due to the huge investments required. In Canada, where the biggest oil sand resources exist, around 1.1 mbpd day of bitumen and synthetic crude were produced from oil sands in 2005, and the target is 3.5 mbpd in 2020 (Alberta 2005).

In 2005, IEA published the book "Resources to Reserves – Oil and Gas Technologies for the Energy Markets of the Future". It states that there is no shortage of hydrocarbons in the ground, but major technological progress and investments are needed to use them. The report evaluated the oil prices at which the economical feasibility of various resources becomes reasonable (Figure 2.5).

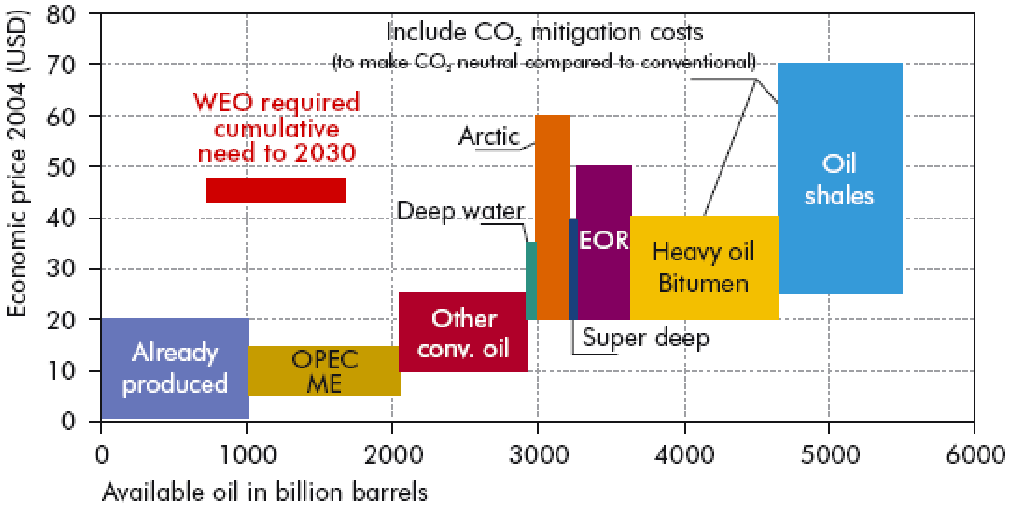

Figure 2.5. Availability of oil resources as a function of economic price (IEA 2005a).

Natural gas

BP estimates the current R/P ratio for natural gas at 63 years (BP 2007). Natural gas resources are more evenly distributed than oil resources. Figure 2.6 presents the distribution of natural gas resources. Over the recent years, the projections for natural gas have varied. Every now and then natural gas has been nominated the fastest growing major energy source. However, IEA WEO 2006 gives this designation to coal and states that the share of natural gas also rises, even though gas use grows less quickly than projected in earlier projections, due to higher prices. (IEA WEO 2006)

Increase in natural gas demand comes mainly from the power sector, but a small growing share will come from gas-to-liquids plants and possibly from the production of hydrogen for fuel cell vehicles. Natural gas derived hydrogen is widely used in the refining industry for ungrading of liquid transportation fuels. Natural gas is seen as a bridge to a future hydrogen society. Biogas and hydrogen can be blended into natural gas, offering a possibility to introduce renewable components into natural gas.

A significant increase in gas usage requires the utilization of remote natural gas sources, which requires liquefaction (LNG or synthetic fuels) and leads to an increase in shipping volumes and in fuel prices. (IEA WEO 2005)

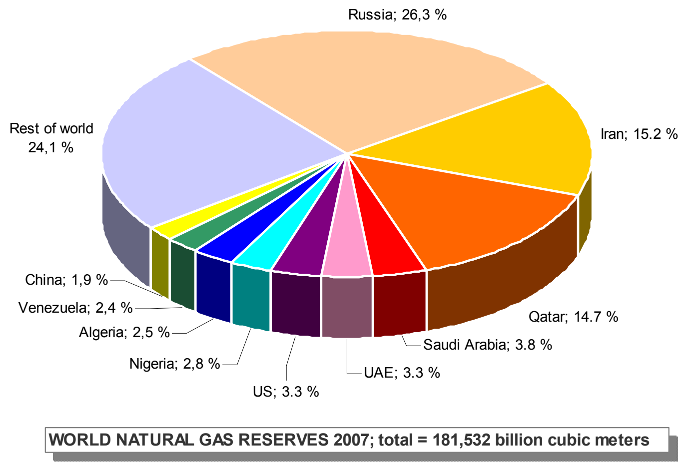

Figure 2.6. World natural gas reserves are located mainly in Russia, Iran and Qatar (Numbers from World Oil and Gas Review 2007).

Coal and nuclear energy

For economic and energy supply safety reasons, use of coal and nuclear energy may increase within large-scale electricity and CHP production despite problems associated with both these energy sources.

Coal is the most abundant fossil energy source in world with reserves of around 1 x 10^{12} tons (1 trillion tons) distributed in many countries. The largest coal reserves are found in the U.S., Russia, China, India and Australia (EIA IEO 2007). Coal resources are estimated to last over 100 years at current demand. However, if utilization of coal strongly increases with increasing demand in electricity and liquid fuels (e.g., in China), the reserve life of coal begins to drop dramatically.

Coal is mainly used for power and industrial sectors. From 2003 to 2030, coal for industrial energy more than triples in China. China and India will account for more than two thirds of the increase in global coal use.

In the EIA IEO 2007 reference case, electricity generation from nuclear power plants worldwide is projected to increase at an average rate of 1.3 percent per year, from 2,619 billion kWh in 2004 to 3,619 billion kWh in 2030. In absolute terms, nuclear power is declining only in Europe.

The role of nuclear power in meeting future electricity demand has been reconsidered more recently, given concerns about rising fossil fuel prices, energy security, and greenhouse gas emissions. On the other hand, issues related to plant safety, radioactive waste disposal, and the proliferation of nuclear weapons, which continue to raise public concerns in many countries, may hinder the development of new nuclear power reactors. (EIA IEO 2007)

Biomass

In principle, the amount of energy adsorbed in biomass is huge. However, only a part of the biomass reserves can be used for energy. Not all biomass is technically feasible, and there are also competitive usages. In addition, if we consume more than the yearly growth, the resource base for future growth will decrease, which is not acceptable. Sustainable biomass usage requires that several problems and challenges are obviated. Major development steps are needed for clean and efficient harvesting and efficient conversion processes.

Typically, studies of biomass potential tend to report "scientific potential" of biomass. From the industrial investors' point of view the techno-economical potential is often significantly lower, typically some 10–30% of the scientific raw material potential. Variations in estimates of biomass potential are typically significant.

Today bioenergy covers some 40–55 EJ/a of the world energy consumption of 467 EJ. IEA Bioenergy (2007) estimates that 200–400 EJ/a of biomass could be harvested annually for energy during this century. World energy demand is projected to increase from 467 EJ to 714 EJ by 2030, and transport energy demand from 94 EJ to 143 EJ. This means that as much as 30% of world energy demand could be covered by biomass by 2030, and if desired, major part of the transport energy. Also the Food and Agriculture Organization of the United Nations (FAO) states that bioenergy could provide 25% of world energy needs over the next 15 to 20 years. (UN-Energy 2007)

IEA WEO 2006 predicts that world production of biofuels for transport will rise from 20 Mtoe in 2005 to 92 Mtoe in 2030 in the reference scenario, and to 147 Mtoe in 2030 in the Alternative Policy Scenario. This would cover 4–7% of the road-transport energy use. IEA WEO 2006 states that yields will be better, and new, next generation production technologies (enzymatic hydrolysis, gasification) could hinder unhealthy competition with other land-usages. Currently, 14 million hectares, 1% of world arable land, are used for biofuel production. This share would be to 2.5–3.8% by 2030, and could rise to 4.2% if the next generation biofuels will become feasible. (IEA WEO 2006).

In the U.S., the biomass potential for 2050 is estimated to be around 1.4 billion dry tons per year, of which around 73% would come from agricultural lands and rest from forestlands. It is estimated that biomass would to be sufficient to cover 30% or more of the petroleum consumption in the U.S. This would require 1,000 Mtons of biomass (dry) annually. (Perlack et al. 2005)

In the EU, current total biomass production for energy purposes is 56 Mtoe. To achieve the 2010 European target of 12% renewable energy (RES), 130 Mtoe of biomass energy is needed annually by 2010 (EU Biomass Action Plan). The 2006 EU vision report on biofuels estimates that biofuels could account for 25% of transport fuel in Europe by 2030, and environmentally-compatible indigenous biomass potential could cover as much as 27–48% of the road transport fuel needs in the case that all biomass is dedicated to biofuels production (A vision for 2030 and beyond 2006).

The European Environment Agency (EEA) has conducted studies on the biomass potential in Europe. EEA concludes that the technically available biomass potential is significant, even when tight environmental considerations are taken into account. According to EEA, biomass potential represents 15–16% of the projected energy demand of the EU-25 in 2030 (EEA 2006). A recent study by the EEA reports on the biomass resources in the European forests, taking environmental constraints and cost analysis into account. The effect of price on potential is significant, which is demonstrated in Figure 2.7. The higher the cost that can be accepted is, the higher is the potential, see also Figure 2.5. (EEA 2007)

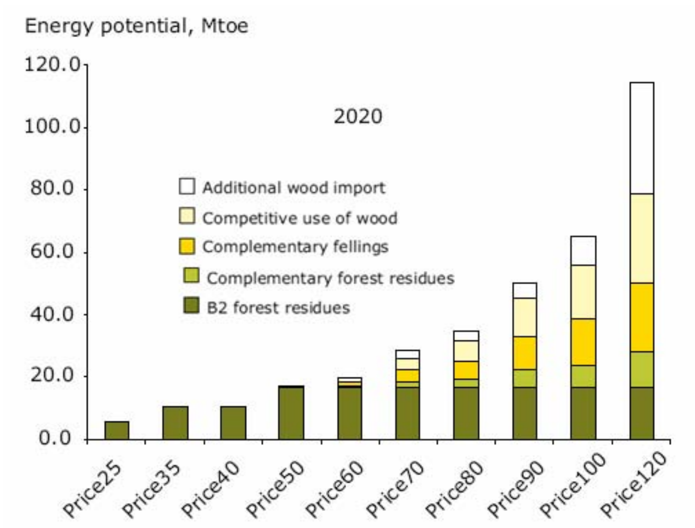

Figure 2.7. The costs and supply of forest biomass from different sources in EU-25. The cost for forest residues (EUR per m^3 at the mill gate) is calculated from extraction costs. 50 EUR per m^3 is equivalent to 240 EUR per toe or 35 USD/barrel energy equivalent. (EEA 2007)

Table 2.1 shows various estimates of biomass potential.

Table 2.1. Estimates of biomass potential.

	Bioenergy potential	Time frame	Reference
Global bioenergy potential	200–400 EJ/a	During this century	IEA Bioenergy (2007)
Global transport biofuel potential	92 Mtoe/a (transport)	2030	IEA WEO (2006), reference scenario
Global transport biofuel potential	147 Mtoe/a (transport)	2030	IEA WEO (2006), alternative policy scenario
U.S. biomass potential	~530 Mtoe/a (1,400 million dry tons/a)	2050	Perlack 2005
European biomass potential	190 Mtoe	2010	"A Vision for 2030" (2006)
European biomass potential	215–239 Mtoe/a	2020	"A Vision for 2030" (2006)
European biomass potential	243–316 Mtoe/a	2030	"A Vision for 2030" (2006)

The use of palm oil for renewable electricity and biofuels is increasing rapidly. However, if the biofuel targets for transport were to be realized with vegetable oils, enormous quantities of additional production and plantations would be needed. This could lead to serious sustainability problems, e.g., regarding rain forest devastation, herbicide use, and working conditions, if production is not controlled properly. Figure 2.8 shows world vegetable oil consumption and EU's total biofuel target for transport sector by 2020 (green bar). The situation is even more drastic when increasing usage of vegetable oils in power production is taken into account.

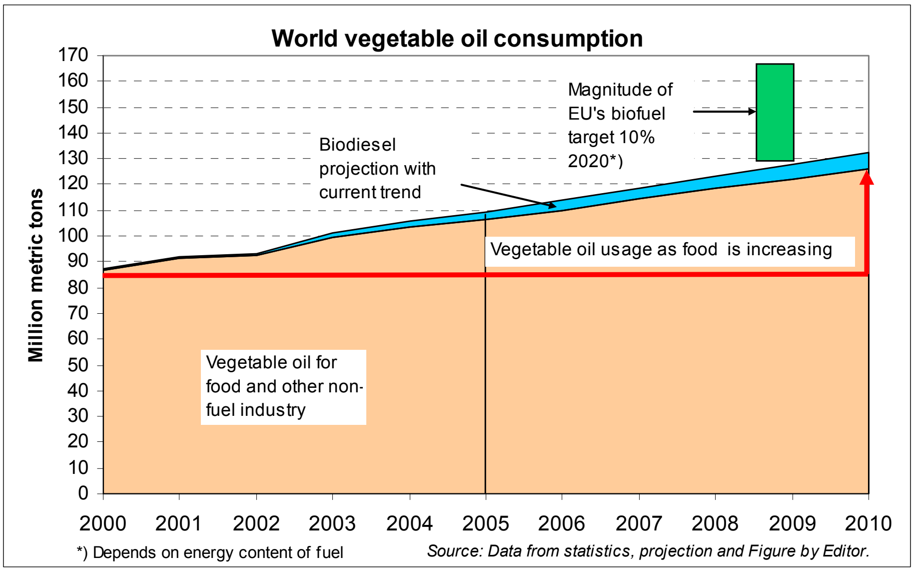

Figure 2.8. World vegetable oil consumption and EU's total biofuel target for transport sector by 2020 (green bar).

There are also new candidates for non-food biofuel feedstocks, such as Jatropha and algae. Jatropha curcas, relative to castor, grows well in marginal and poor soils, and even in the crevices of rocks. It grows relatively quickly and produces seeds for some 50 years. Jatropha is suitable for preventing soil erosion and shifting of sand dunes. However, Jatropha is toxic with the exception of a non-toxic Mexican variety. There are substantial plans to establish Jatropha plantations. China plans to devote 13 million hectares (the size of England) to Jatropha trees, producing some 6 million tons of biodiesel yearly and fuel for a 12 MW power plant by 2010. Currently, 2 million hectares is devoted to Jatropha in China. Jatropha is already planted in India, the Philippines, Thailand, and African countries. (DieselNet 2007)

Algae contain lipid oils, which can be used to produce biofuels. Fabulous characteristics are claimed for algae:

- Production yield of some 4.5 million liters of oil per hectare yearly, which is about 100 times more than for e.g., soybean
- Costs around 50 cents per gallon in the demonstration plant in the Netherlands. Costs depend on many factors, e.g. climatic conditions. (www.algaelink.com).

A number of algae-to-biodiesel projects are going on, but research of utilization is still in the starting phase. Most articles on algae seem to give over-optimistic figures. Carlsson et al. (2007) analyzed studies on algae and concluded that many statements on algae are, to some extent, in conflict with each other. There is general agreement that the production is not economically feasible for biomass production alone. Costs of infrastructure, harvesting, and drying are high, and there are also contamination problems. However, it is pointed out that the future carbon sequestration requirements can support economy for algae production (captured CO_2 is fed to algae).

2.2 Energy demand

Significant rise in prices of crude oil, natural gas and coal was seen in 2005. Growth of global economies slowed as well as growth of consumption for all energy sources. World energy use increased by 2.7% in 2005, whereas in 2004 the increase was 4.4%. Now projection for growth of global primary energy is 1.8% annually between 2005 and 2030 (IEA WEO 2007).

Despite of the slowdown in the growth of the energy consumption, the projection of the total increase of global energy demand over the next 25 years is striking. IEA WEO 2007 projects that the world energy demand will increase some 55% between 2005 and 2030, from 11,400 Mtoe in 2004 to some 17,700 Mtoe in 2030, if policies remain unchanged.

IEA WEO 2006 presents two energy scenarios, the "Reference Scenario" and the "Alternative Policy Scenario". In the latter scenario the world energy demand in 2030 would be about 10% lower than in the reference scenario (Figure 2.9). Investments of $20 trillion will be needed to supply the increase in energy demand by 2030. This is an enormous figure when considering that global GDP was $45 trillion in 2005. Oil investment – three-quarters of which goes to the upstream – amounts to over $4 trillion in total over 2005–2030. Upstream investment needs are more sensitive to changes in decline rates at producing fields than to the rate of growth of demand for oil.

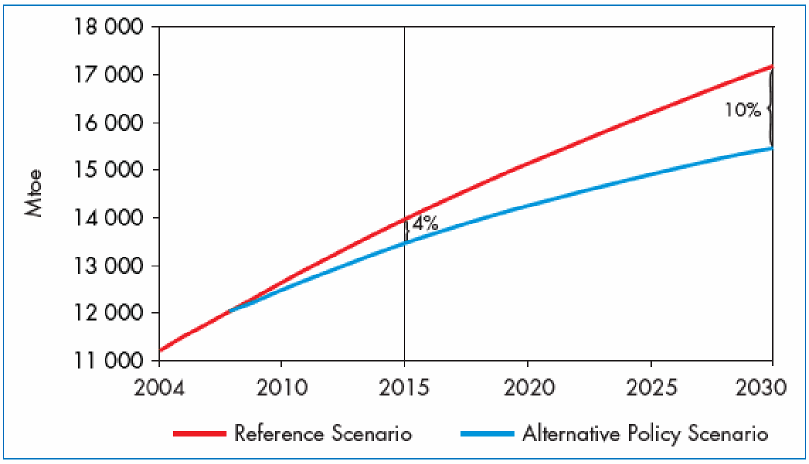

Figure 2.9. World primary energy demand in the "Reference Scenario" and the "Alternative Policy Scenario" of IEA WEO 2006.

About two thirds of the increase in energy demand is expected to take place in developing countries, mostly in China and India. Developing countries would consume more than half of the global energy in 2030, whereas today's share is 41% (IEA WEO 2006 and 2007). Within OECD, the energy consumption is moving from energy-intensive industries toward services (EIA IEO 2007).

The energy demand in China is projected to about double from 2004 to 2030. China is expected to take the place of US as the biggest energy consumer. China is rich in coal reserves and increasingly uses coal as an energy source. Thus, China is catching the US as the world's biggest contributor to GHG emissions. China's growing CO_2 emissions could even nullify achievements of climate agreements over the next 20 years. When developing countries are considered, there are also new options available. Totally new solutions can be applied, e.g. regarding infrastructure, in systems yet to be built. A hydrogen society could be built up in China, if technology and economy for that would be feasible (McCarthy 2005).

Energy intensity (in Figure 2.10) means energy required to generate a fixed amount of gross domestic product (GDP). Dramatic improvement is expected in the energy efficiency in the non-OEDC countries by 2030, but also OEDC countries can improve efficiency. Reductions in energy intensity alone will not reduce energy consumption, if energy consumption per capita increases.

Figure 2.11 shows energy consumption per capita in different regions of the world. Note that energy consumption per capita is twice as high in North America compared to Western Europe. Individual choices can annul achievements of improved technological energy efficiency.

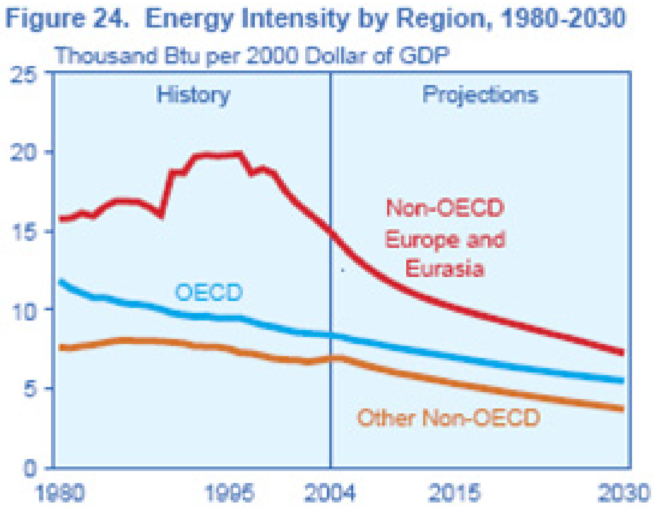

Figure 2.10. Energy intensity per GDP (EIA 2007).

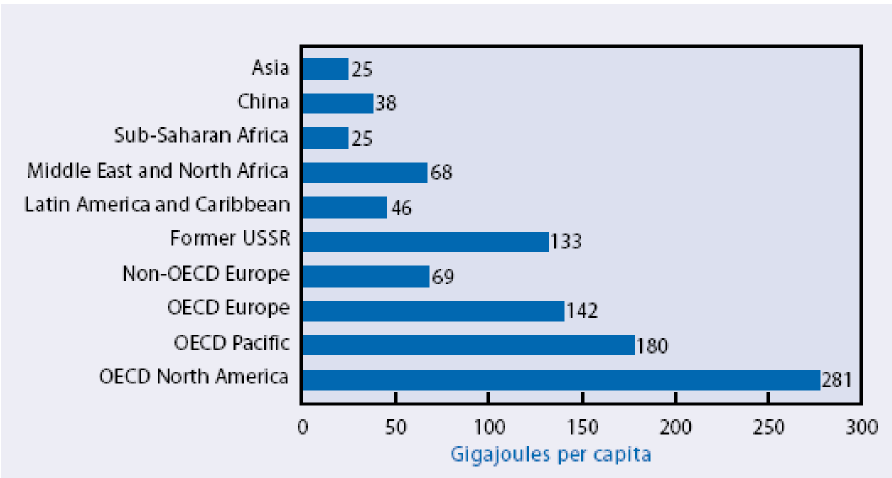

Figure 2.11. Energy consumption per capita (Johansson & Goldemberg 2005).

Energy pool

According to energy prospects from IEA and EIA, no dramatic changes in the energy pool are foreseen over the following decades (Figure 2.12). This is based on the assumption that the new reserves of fossil energy meet the projected energy demand. Energy and transportation systems are rigid so that huge investments are needed to change energy sources. However, the recent price development of crude oil combined with the Kyoto process and emissions trading might speed up the introduction of other, less carbon intensive, energy systems.

IEA WEO 2006 and 2007 predict that until 2030 fossil fuels (oil, gas, coal), with a share of around 80%, will dominate world energy consumption (Figure 2.12). Oil's share of world energy is projected to decrease to 32%, but the demand in absolute terms will grow from 4,100 Mtoe (84 mbpd) in 2005 to 5,700 Mtoe (116 mbpd) in 2030. The highest increase in absolute terms is projected for coal, originating mainly from growth of power-sector in China and India.

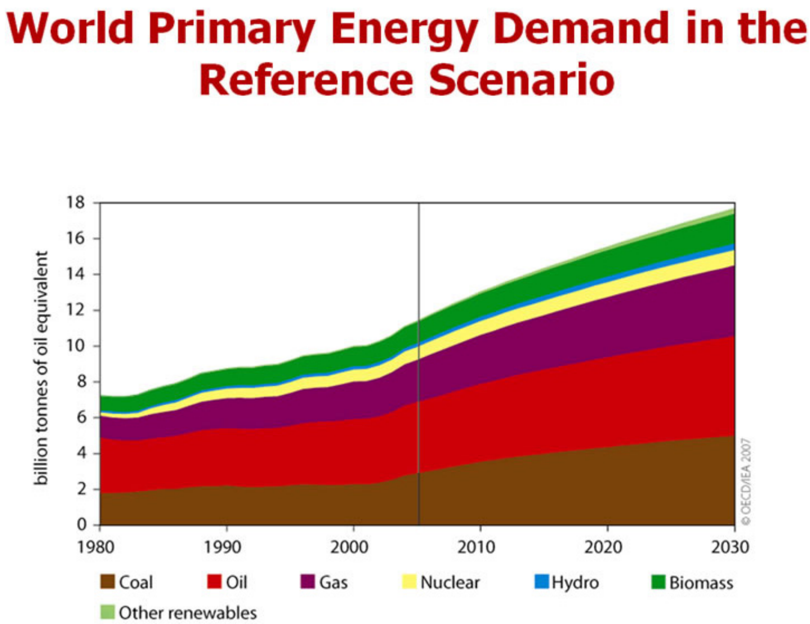

Figure 2.12. Projections for primary energy demand. Reference scenario (IEA WEO 2007).

According to IEA WEO 2006 hydropower's share of primary energy use rises slightly, while that of nuclear power falls. The share of biomass falls marginally, as developing countries increasingly switch to using modern commercial energy, offsetting the growing use of biomass as feedstock for biofuels production and for power and heat generation. Non-hydro renewables – including wind, solar and geothermal – grow quickest, but from a small base. (IEA WEO 2006)

Renewables represented 6% of energy in US in 2005, and almost half of this was biomass. Wood, wood waste, and black liquor from pulp mills were the largest biomass sources. Waste (municipal solid waste, landfill gas, sludge waste, tires, agricultural by-products) accounts for about 20% of total biomass consumption in US. (EERE 2006)

High fossil fuel prices, emission trading schemes and mandates for renewable electricity should in principle, improve competitiveness of biomass in power production. Ambitious goals for biofuels in transport could also increase the demand for biomass.

Figure 2.13 shows ExxonMobil's estimations of relative contributions and expectations for the growth of various energy sources. ExxonMobil predicts that the annual growth in primary energy from 2005 to 2030 will be 1.3%, with nuclear energy, natural gas and renewable energy growing more than average. ExxonMobil treats biomass for stationary applications and biofuels for transport separately. According to ExxonMobil, the strongest relative growth within renewable energy can be expected for wind energy, solar energy and biofuels in transport (close to 10% annually).

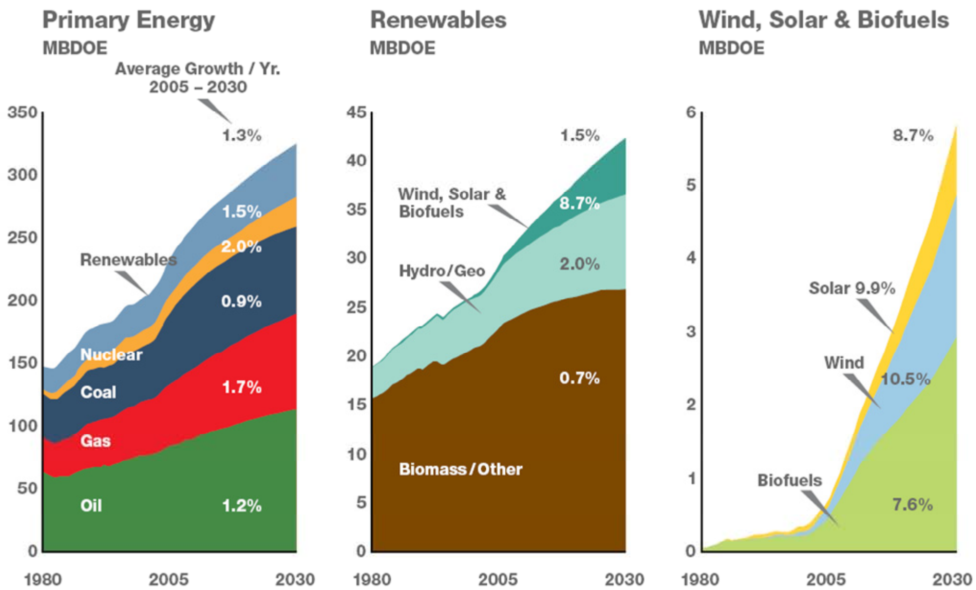

Figure 2.13. Estimations of relative contributions and expectations for the growth of various energy sources (ExxonMobil 2007).

Oil markets

Energy markets have been turbulent over the past years. The rise in crude oil price has been dramatic, with an oil price approaching $100 per barrel (Figure 2.14). Several factors have affected oil prices, such as the crisis in the Middle-East and Nigeria, and natural disasters. These events, combined with the increased demand for energy, have led to decreased excess oil production capacity.

Both IEA and EIA prepare projections on future oil price development. These prospects have traditionally been considered rather conservative and optimistic by many external experts. Now the projections of international energy prices have been moved upwards, but the estimates are still moderate when the forecasted rise in primary energy consumption is taken into account. The price development of oil in 2007 was not in line with the prospects.

The 2006 IEA WEO assumes that the crude oil price would ease to around $55 per barrel in 2030. The corresponding prospects were $39 per barrel in IEA WEO 2005 and $29 per barrel in IEA WEO 2004.

In the EIA IEO 2007 reference case world oil price is projected to decline from $68 per barrel in 2006 to $49 per barrel in 2014, then to rise to $59 per barrel in 2030. This means that the IEA WEO 2006 and EIA IEO 2007 projections for 2030 are rather coherent. However, EIA IEO also contains a high oil price scenario with a steadily increasing oil price. Figure 2.15 shows a comparison of EIA IEO 2005 and 2006 oil price projections, as well as the three price projections presented in EIA IEO 2007.

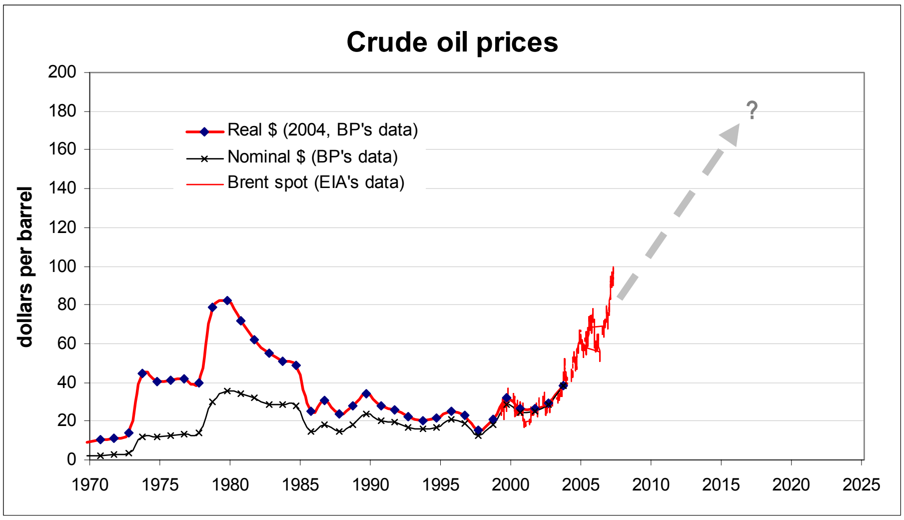

Figure 2.14. Realized crude oil price and possible future development in the case that current trend continues.

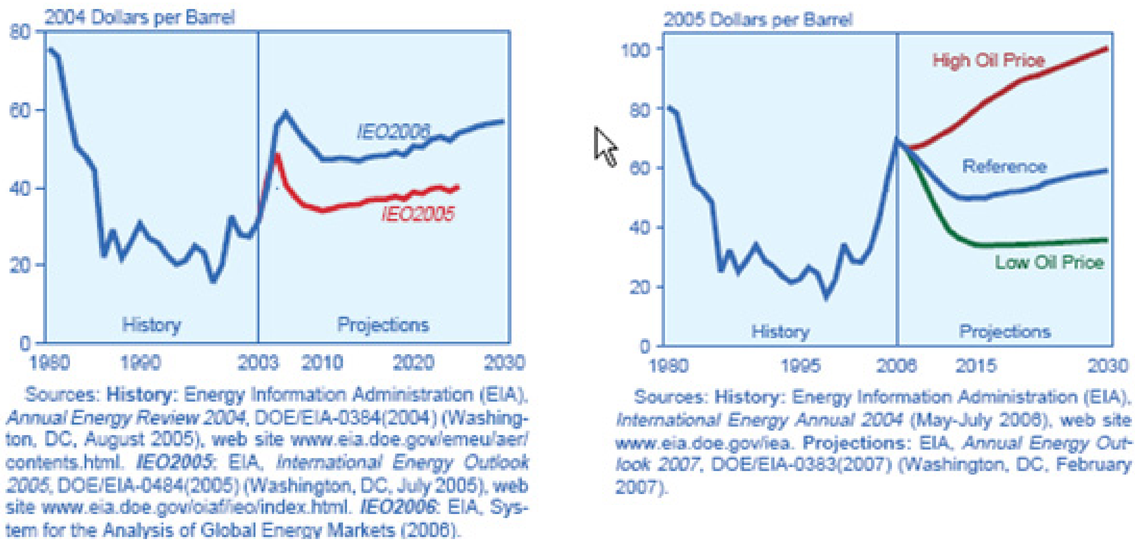

Figure 2.15. Prospects of the crude oil price according to EIA IEO 2006 (left) and 2007 (right).

At the end of 2007 IEA made a statement on high oil prices:

"Prices have been rising and stocks falling over most of the second half of 2007, recently falling below the five-year average. $100/bbl may be just a symbolic figure but it is a strong reminder that consumers and governments have to implement measures that improve energy efficiency. Such measures are available now and provide the most effective short-term response. In the longer term, greater investment in the upstream and downstream sectors is needed. The resources are there, but access to resources, aging infrastructure and chronic new project delays and cost inflation mean it will take time to also increase investment in alternative energy sources." (www.iea.org)

Energy end-use and transport

Total primary energy supplied (TPES) was 11,400 Mtoe and total final consumption (TFC) 7,900 Mtoe in 2005. The difference in energy supply and consumption figures are due to losses in conversion processes and energy transfer. Figure 2.16 shows energy consumption by sector. Transport is the single largest energy end-use sector with a share of 28%, equivalent to 2, 200 Mtoe. The industrial sector is nearly as large, with a share of 26%. (IEA 2007)

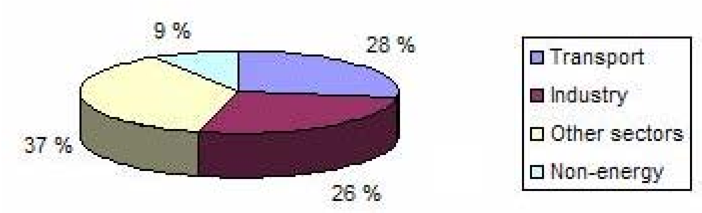

Figure 2.16. Energy end-use by sector. Numbers from IEA Key Word Energy Statistics 2007. "Other sectors" includes, e.g., residential and commercial sectors.

Transport is also the largest oil end-use sector. Transport represents some 60% of the world's oil consumption compared to 45% in 1973. Road transport is almost completely dependent on oil, and oil will be increasingly used in the transportation (Figure 2.17).

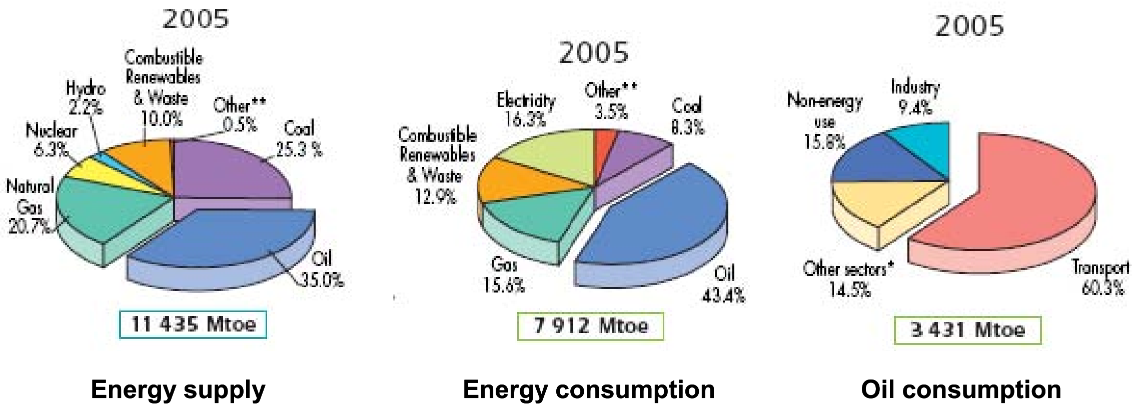

Figure 2.17. Energy supply and consumption by fuel and oil consumption by sector (IEA 2007).

ExxonMobil predicts that the total demand for energy in transport starts to even out in the OECD countries, with a decline in the light-duty vehicle sector. Average growth rate is estimated at 0.6% annually for 2005–2030, whereas the growth rate for non-OECD countries is estimated at 3.1% annually. This means that transport energy demand will be equal in OECD and non-OECD countries by 2030 (Figure 2.18). ExxonMobil predicts that unconventional oil and biofuels will contribute in total some 6% to the liquids supply in 2030.

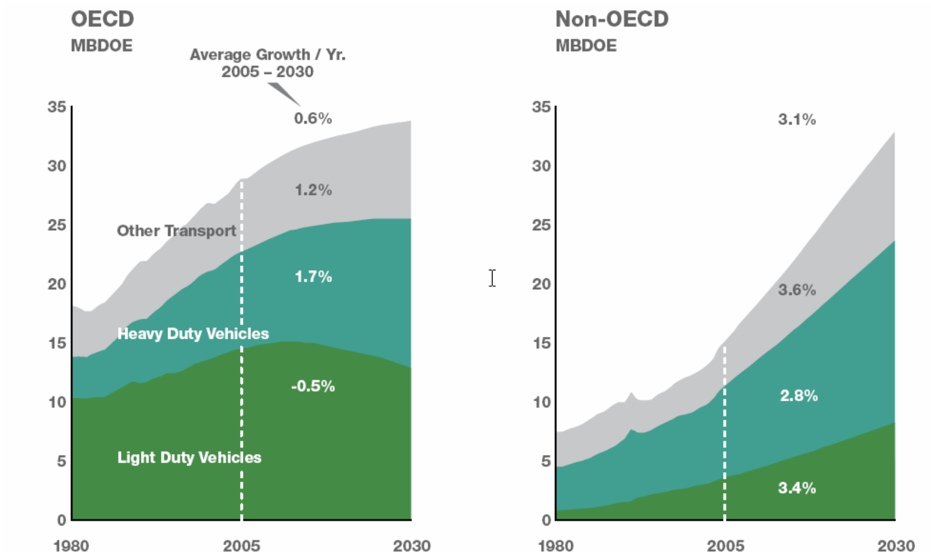

Figure 2.18. Projections for energy demand in the transport sector (ExxonMobil 2007).

According to IEA WEO 2006, the share of biofuels in transport on a world basis was 1% in 2004. In the reference scenario, this share grows to 4% in 2030, and to 7% in the alternative policy scenario. Europe has set a preliminary target of 20% alternative fuels in transport in 2020. This would be equivalent to some 60–70 Mtoe annually.

3. Policy

Driving forces behind alternative fuels have shifted from energy security and air pollution towards climate change, and again, now moving towards energy security. Energy savings is one of the key elements in coping with sufficiency of energy and to reduce greenhouse gases. IEA predicts that energy-related CO_2 emissions will almost double between 2004 and 2030, if no actions are taken. The Kyoto Protocol and other agreements and policies have been put in place to mitigate climate change. Bioenergy is one option to reduce greenhouse gases. Considerations of biofuels are calling for sustainable policies, taking into account, e.g., competition with food production, threat to rain forests, and impact on social issues. In this respect, the next generation biofuels might provide a sustainable solution, if processed from lingo-cellulosic crops grown in poor soils without chemicals or processed from waste materials. Reduction of GHG emissions with CO_2 capturing and storage (CCS) is suitable for large stationary sources, but not for transport applications.

Generally, new energy policies e.g. in the US, Europe and Japan encourage energy efficiency, conservation, alternative and renewable energy sources. It is obvious, taking into account the time needed to bring large quantities of sustainable CO_2 efficient biofuels on the market, that improving fuel efficiency of vehicles has a greater potential for CO_2 reductions than biofuels. Traditional biofuels might not be helpful in combating local pollution, whereas next generation biofuels can provide advantages for both CO_2 and local pollution. Recently the ambitious goals for biofuels have been strongly criticized due to the fact that in the short-term, only traditional biofuels are available, and production of these in large-scale present a risk to food supplies, food prices, the environment and biodiversity.

3.1 General

In the past, alternative fuels were considered for air pollution reasons, and promotion of biofuels was more agricultural policy. Today, however, climate change and energy security are the main driving forces in the development (Figure 3.1). In the short term the effects of fuel switches will be limited, and thus energy savings is one of the key elements to reduce greenhouse gases and to cope with possible shortages of liquid fuels, especially in the transportation sector.

Road transportation is by far the biggest consumer of energy in the transport sector, with a share of around 85% in developed countries. There are about 900 million road vehicles today, by 2030 possibly over 2 billion (IEA WEO 2007). CO_2 emissions from road transport are increasing with increasing energy consumption, whereas regulated emissions have been dramatically reduced in markets such as the US, Europe and Japan. However, only industrialized countries can afford low-emission, modern transportation technologies, and thus, increased mobility in developing countries will pose serious environmental problems.

Vehicle efficiency is one of the focal points among IEA's tasks in support of the G8 Plan of Action on climate change, clean energy and sustainable development (IEA OPEN Bulletin, 12 December 2006, www.iea.org).

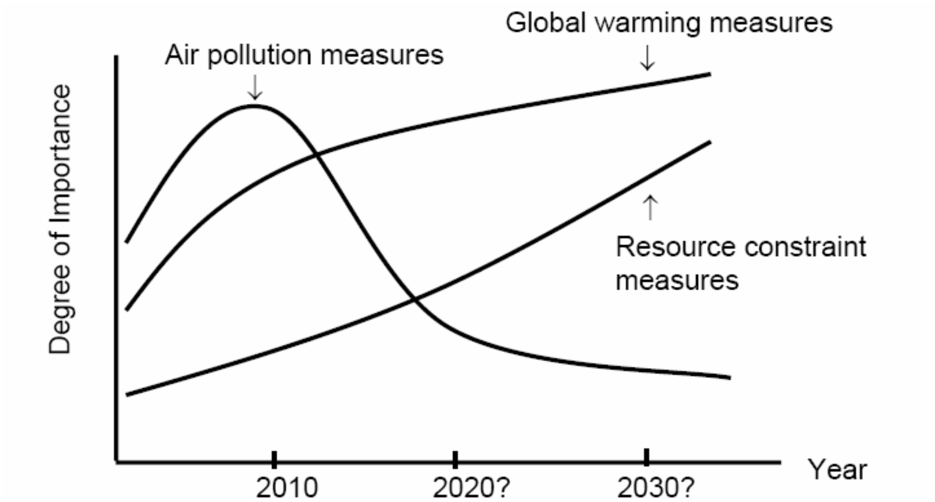

Figure 3.1. Priorities in environmental and energy issues in transportation (Tabata 2005).

3.2 Agreements to mitigate Climate Change

The Kyoto Protocol

The Kyoto Protocol entered into force on February 16, 2005, after ratification by Russia. The protocol is ratified by 128 countries, together responsible of 61.6% of global GHG emissions. According to the protocol, GHG emissions must be reduced on average 5% by 2012 compared to 1990 levels by the so called "Annex I" countries. Different countries have individual targets, developing countries including Brazil, China, India and Indonesia are parties but do not have emission reduction targets. Four industrialized countries have not yet ratified Kyoto Protocol. These are the United States, Australia, Lichtenstein and Monaco. Some 75% of the projected CO_2 increase will come from non-OECD countries.

IEA WEO 2006 suggests that Annex I countries will not meet the targets, if greenhouse gas emissions follow the rise of energy consumption. It is also stated that even if new policies and measures were to be adopted, this would not help the situation significantly before 2010. There is a need for a continuation of the Kyoto Agreement to engage high-emitting countries to a long-term plan of reducing greenhouse gas emissions. (IEA WEO 2006)

In December 2007, the UN Climate Change Conference took place in Bali. The agreement calls for negotiation of a new international climate change treaty by 2009 in Copenhagen to succeed the Kyoto Protocol when it expires in 2012. The EU proposed that developed countries would commit to cut their emissions by 25–40% of 1990 levels by 2020. The United States, Japan and Canada opposed those targets. Thus, no specific figures were included in the Agreement. (UNFCC Press release 2007, CNN News 2007)

Asia-Pacific Pact

Six countries, U.S., China, India, Australia, Japan, and South Korea, signed a joint energy and climate pact, the Asia-Pacific Partnership on Clean Development (AP6) in July 28, 2005. The member countries account for around 50% of the world's greenhouse gas emissions, energy consumption, GDP, and population. The new Asia-Pacific pact is a non-binding agreement targeting to reduce greenhouse gas emissions by developing energy technologies.

The Asia-Pacific Pact partners have approved eight public-private sector task forces covering cleaner use of fossil energy, renewable energy and distributed generation, power generation and transmission, steel, aluminum, cement, coal mining, buildings, and appliances. With the exception of the US and Australia, the other countries within new agreement have also signed the Kyoto Protocol. However, only Japan has a reduction obligation of carbon dioxide. The initiatives of pact are stated to be complementary to the Kyoto Protocol, not to replace it. (EurActiv 2005)

3.3 European, U.S. and Japanese policies

European policy

Battling against climate change and competitiveness are the major driving forces behind the European transport policy. European policy is promoting new technologies and fuels with increasingly stringent limits for emissions, requirements to use alternative fuels, and requirements to improve fuel economy. This development also dampens the increase in oil demand.

The EU is very active regarding policies on climate change and is strongly committed to the Kyoto Protocol. However, climate change is not included in EU's Lisbon top priorities which are competitiveness, jobs and economic growth. European industry is

Proposed EU Energy Policy Strategy 2020

- *Cutting GHG emissions and improving energy efficiency by 20% by 2020*
- *Share of renewable energy to 20% by 2020*
- *Alternative fuels in transport 20% by 2020*
- *Biofuels in transport 10% by 2020*
- *Focus on 2nd generation biofuels*

worried that the EU's strong climate change strategy is a risk for competitiveness, but green non- governmental organizations (NGOs) think that EU is not doing enough. The European Commission has set also a post-2012, post Kyoto, strategy for climate change. (EurActiv 2006)

The European Union has ambitious goals for renewable energy and bioenergy. The 2001 RES-E directive (2001/77/EC) sets a target of 22.1% of "renewable electricity" by 2010. The 2000 Green Paper "Towards a European Strategy for the Security of Energy Supply" sets a preliminary target for 20% alternative fuels in the road transport sector by 2020 (Green Paper 2000). Directive 2003/30/EC sets indicative targets for biofuel usage in transport, the reference value being 5.75% by 2010 (energy content).

In January 2007, a new climate change strategy to cut EU's GHG emissions by at least 20% by 2020 was proposed. The Commission also proposed a binding target of 20% for renewable energy by 2020, which will be supplemented by a binding minimum target for biofuels of 10% (Europa 2007a). In March 2007, EU leaders committed to the proposed policy. For the 10% biofuels target a reservation was made. It was stated that the binding character of the biofuel target is appropriate subject to production being sustainable and second-generation biofuels becoming commercially available.

Following up on the strategy, the Commission will present a new directive on renewable energy in January 2008. The new directive will cover both the current RES-E directive and the Biofuels directive, and reassert the statements of the strategy. In addition, the new directive will contain individual renewable energy targets for the member countries.

In 2005, the European Commission presented the Green Paper on Energy Efficiency, which calls for reduction of energy consumption by 20% from its present level by 2020 (Green Paper 2005). In 2006, a directive (2006/32/EC) on energy end-use efficiency and energy services came into force. The directive requires member states to draw up national action plans to achieve 1% yearly energy savings in the retail, supply, and distribution of electricity, natural gas, urban heating, and other energy products including transport fuels. The 1% target is only indicative but the national action plans will need approval from the Commission and will be reviewed every three years. The process will be spread over nine years, starting in January 2008.

In addition, an Action Plan for energy efficiency was launched. This calls for legislation to limit CO_2 emissions from cars, fuel-efficiency labeling, regulations for public vehicle procurement, improving energy efficiency in urban areas and international agreements to foster energy efficiency worldwide. The Action Plan states that the transport sector has the highest potential for energy savings. In parallel, a proposal to include aviation in the EU CO_2 trading scheme is expected. (COM(2006)545, SEC(2006)1173)

The Commission's strategy to cut CO_2 emissions from cars has been based on the voluntary commitments by European, Japanese and Korean manufacturers. These agreements, with a target of average CO_2 emissions of 140 g/km for 2008–2009, seem to fail, and thus mandatory limits were proposed in February 2007. The proposal is that average CO_2 emissions from new cars sold in the EU-27 would be required to reach a target of 120 g CO_2/km by 2012. Improvements in vehicle technology would have to reduce average emissions to no more than 130 g/km, while complementary measures would contribute a further emissions cut of up to 10 g/km, thus reducing overall emissions to 120 g/km[1]. These complementary measures include efficiency improvements for car components with the highest impact on fuel consumption, such as tires and air conditioning systems, and a gradual reduction in the carbon content of road fuels, notably through greater use of biofuels. (Europa 2007b)

In 2007, a target for greenhouse gas reduction was proposed to be included into the European directive on the quality of gasoline and diesel fuels (98/70/EC). This proposal calls for an obligation for fuel suppliers to reduce GHG emissions of their fuels by 1% annually from 2011 (base year) to 2020. This proposal has been criticized by e.g., Stans et al. (2007). For instance, the procedure to determine the CO_2 reductions and the traceability requirements are not clearly defined. Sustainability, biodiversity, nature conservation or social aspects are not taken into account. In addition, this punishes companies that have taken early actions against climate change.

U.S. Policy

In August 2005, President Bush signed the first law covering energy policy in more than a decade. The energy plan will encourage energy efficiency and conservation, promote alternative and renewable energy sources, reduce dependence on foreign sources of energy, increase domestic production, modernize the electricity grid, and encourage the expansion of nuclear energy. (The White House 2005, EPAct 2005)

For climate change, the United States has a goal to reduce domestic greenhouse gas (GHG) emissions by cutting its GHG intensity[2] by 18% from 2002 to 2012. This would be achieved by technology improvements, improving the energy-efficiency, voluntary programs with industry, and shifts to cleaner fuels. (DOE 2005) The U.S. is committed to the Asia-Pacific Partnership on Clean Development and agreed with the Bali Agreement (Chapter 3.2).

The Energy Policy Act of 2005 basically promotes biofuels as well as non-petroleum fuels such as alcohols, biodiesel, natural gas, LPG, hydrogen and domestically produced

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[1] 120 g/km corresponds to 4.5 l diesel or 5.0 l gasoline/100 km.
[2] GHG intensity is the ratio of greenhouse gas emissions to economic output.

natural gas and coal derived liquids. The Renewable Fuels Standard (RFS) requires 7.5 billion gallons of renewable fuel required to be blended into gasoline to by 2012. (EPAct 2005)

In the transport sector, the biomass-to-fuels policy has aggressive goals. The share of transportation fuels from biomass is estimated to grow from 0.5% in 2001 to 4% in 2010, 10% in 2020 and 20% in 2030. (Kaempf 2005, Perlack et al. 2005)

In 2006, the U.S. President announced the Advanced Energy Initiative (AEI), with a main goal to replace 75% of imported oil from the Middle East by the year 2025. This will be accomplished by utilizing more domestic resources for energy. As part of the AEI the Biofuels Initiative will be a major contributor to reaching the goals. The short-term goal of the Biofuels Initiative is to make cellulosic ethanol competitive with conventional ethanol processes by the year 2012. The target is set in the form of an ethanol-from-cellulose price of $1.07 by 2012. The longer-term goal is to replace 30% of 2004-level U.S. energy needs with biofuels by the year 2030, the so-called "30-by-30" goal. (The White House 2006)

The Biomass R&D Technical Advisory Committee conducted a study commonly referred to as "The Billion Ton Study". This report concluded that over 1.3 billion dry tons of biomass per year could be harvested from just agricultural and forest lands in U.S. and this would be sufficient to support the goal of replacing 30% of petroleum by biofuels while still continuing to meet food, feed, and export demands (Perlack 2005). An implementation plan for accomplishing this goal is presently being developed by multiple government agencies working together, and the President's proposed 2007 budget includes large increases in funding to the departments and programs that will be involved in implementing the program.

The U.S. Targets

- *Cutting greenhouse gas intensity by 18% from 2002 to 2012*
- *Replace 30% of 2004-level energy needs with biofuels by 2030 ("30-by-30" goal)*
- *Reduce gasoline consumption by 20% during 10 years by 2017 ("20-in-10" goal)*
- *36 billion gallons of renewable fuels by 2022*

"The 2007 State of the Union Policy Initiatives" pointed out the importance of diversification of America's energy supply by greater use of clean coal, solar, wind and nuclear power. In addition, emphasis is given to battery research for plug-in and hybrid vehicles, promotion of clean diesel vehicles and biodiesel plus developing new methods to produce ethanol. A target was set for reducing gasoline consumption in the U.S. by 20% during the next 10 years (twenty-in-ten). The following actions were listed to reach this goal (The White House 2007):

- Increasing the supply of renewable and alternative fuels by a mandatory requirement of 35 billion gallons (132 million metric tons) by 2017 – represents 15% of projected annual gasoline use in 2017.
- Revising the Corporate Average Fuel Economy (CAFE) Standards for cars and the Light Truck Rule. In 2017, this will reduce projected annual gasoline use by a further 5%.

The Energy Independence and Security Act of 2007 expands the Renewable Fuels Standard (RFS) by requiring 36 billion gallons of renewable fuel be used annually by 2022. Of particular note, the legislation specifically states that 21 billion gallons of that goal must come from advanced biofuels, i.e., renewable fuel other than ethanol derived from corn starch and achieving minimum 50% GHG emissions reduction. More ambitious alternative fuel goals were proposed in the State of the Union Address, but the new RFS bill still represents a nearly five-fold increase over current levels.

Ethanol, which is currently very dependent on subsidies, is the major biofuel in the U.S. Ethanol is under a vivid discussion, especially due to the high price of corn leading to unfavorable economy for ethanol production. The ethanol producers are asking for more support from the Government, but the food industry is strongly against this.

In 2007, “The low carbon fuel standard”, the world’s first standard of greenhouse gases (GHG) for transportation fuels, was established in California. By 2020, the standard will reduce the carbon intensity of California’s passenger vehicle fuels by at least 10%. Fuel providers are required to ensure that the fuels they sell meet a declining standard. This is expected to replace 20% of gasoline with lower-carbon fuels, and place more than 7 million alternative fuel or hybrid vehicles on roads. (AMFI Newsletter 1/2007).

Japanese policy

Japan has committed to both the Kyoto Protocol and the Asia-Pacific Pact. The Kyoto Target Achievement Plan was approved in Japan by the Cabinet in April, 2005 with a target of 6% reduction (Mizuno 2005).

In its government’s long-term energy policy outlines, Japan has been internationally active with initiatives such as a proposal of a massive reduction in CO_2 emissions in advanced nations to levels one-fourth of those in 2002 by 2050. According to the outlines, oil consumption in areas other than transportation will be almost zero by 2050. By 2100, natural gas will remain as an energy source for industry and transport, but most other energy needs will be met by renewable energy sources such as nuclear power, hydrogen energy, and solar energy. In the transport sector the targets for climate change, toxic emissions, and energy security are addressed by the following measures (Minato 2005, Takada 2007):

- improving fuel-efficiency of gasoline and diesel vehicles
- advanced powertrains
- penetration of CNG vehicles etc.
- promotion of "Eco-driving" etc.
- utilization of public transportation and promotion of ITS etc.
- improvement of freight distribution efficiency.

3.4 Biofuel policy and sustainability criteria

Recently, an increasing number of actions have been taken to promote alternative fuels and biofuels. Bioenergy is of major interest as it can contribute to energy security, boost economy, and reduce environmental impacts including global warming. Generally, biomass is more efficiently used in power and heat production than in transport, but the interest in biofuels for transport is enormous with today's high oil prices.

Product yield as diesel equivalent

- *Rapeseed methyl ester:* *1,300 l/ha/y*
- *Ethanol (cereals):* *2,500 l/ha/y*
- *Ethanol (sugar cane):* *3,800 l/ha/y*
- *Palm oil:* *3,500–6,000 l/ha*
- *BTL (energy crops)* *4,046 l/ha/y*

(Seyfried 2005, Carioca et al. 2006)

Only traditional motor biofuels, some of which are associated with sustainability problems, are available today. Thus, many organizations have presented objections to biofuel policies. In most cases traditional biofuels require high-quality farm land plus fertilizers and pesticides. Via land usage these fuels compete with food production. In tropical countries biofuel production may pose a threat to rain forests. In addition, even well-to-wheel greenhouse gas emissions are not necessarily favorable, since these vary significantly depending on, e.g., type of feedstock, growing conditions, fuel processing technology and utilization of by-products. For example, the product yield from different types of crops varies significantly.

One important requirements for biofuels and biocomponents is that they should provide at least equivalent end-use properties compared with conventional fuels. Increases in vehicle emissions are not acceptable. Traditional biofuels tend to fail also in this respect.

Next generation advanced biofuels are considered a promise for the future, on condition that they can be processed from lingo-cellulosic crops that can be grown in poor soil without chemicals. However, sustainable methods in biomass cultivation, harvesting, transportation as well as technological breakthrough in refining processes are needed before commercialization of these next generation biofuels from non-food feedstocks can take place. Waste materials could also be used as feedstock.

One of the most significant warnings against biofuel policies was given by OECD's roundtable on sustainable development in the report "Biofuels: Is the cure worse than the disease". OECD's report concluded that large-scale production of traditional biofuels (corn ethanol and vegetable oil esters) presents a risk to food supplies, food prices, the environment and biodiversity. The OECD report asks national governments to phase out current mandates for biofuels by replacing them with technology-neutral policies, such as carbon taxes. The OECD report states that biomass production will likely put increased environmental pressure on tropical regions, but that liberalizing trade in biofuels is essential for global objectives, as the biofuels produced in tropical regions have an economical advantage. The OECD report points out that only worldwide certification of biofuels makes a difference. Selective certification creates the appearance of sustainable production for some, while others may continue the unsustainable production. (Doornbosch & Steenblik 2007)

An example of vivid discussion on sustainability of feedstock for biofuels relates to palm oil. According to the statistics from Fediol, the world production of palm and soy oil has about doubled since 1993. Palm oil plantations, located mainly in Malaysia and Indonesia, are a threat to rain forests and endangered animal species such as orangutans. Currently, 80% of all palm oil is used by the food industry. Now palm oil is increasingly used for power generation and biodiesel production in Europe, and with current biofuel policies these volumes will grow (Umwelt Magazin 2006, Fediol). The Roundtable on Sustainable Palm Oil (RSPO), in which organizations around the entire supply chain for palm oil are represented, are aiming to define criteria for the sustainable production and use of palm oil, and to promote best practices and solutions. (RSPO)

Sustainability criteria

Recently, a number of new political actions have been taken to promote bioenergy and wide-scale market penetration of biofuels in transport sector. In this situation sustainability of biofuels is a critical topic. The whole chain from biomass production to biofuels processing, and also local effects, should be considered.

The Netherlands has been one of the active countries in discussions of sustainability criteria for biofuels. Also in UK efforts have been put in developing sustainability criteria on national level. European level sustainability criteria are in progress, and expected in 2008. Harmonized criteria should be used in evaluations of feedstocks and fuel options. Criteria will include requirements regarding information on the fuel life cycle and the origin of feedstock as well as suppliers (i.a. social aspects). Audits or other type of screening of performance of the supply chain will be required. In the Netherlands, generic sustainability criteria for the production and processing of biomass for energy, fuels, and chemistry was divided into six themes (Cramer et al. 2006):

- Greenhouse gas balance
- Competition with food, local energy supply, medicines and building materials
- Biodiversity
- Economic prosperity
- Social well-being
- Environment.

In 2005 the European Environmental Bureau (EEB) listed seven key points related to sustainability. EEB states that the objective of a policy for bioenergy should be to combat climate change; incentives should be based on real environmental benefits; the crops for bioenergy should meet sustainability criteria; and biomass should be used in sectors where it achieves the highest benefits. (EEB 2005)

The IEA Implementing Agreement on Bioenergy has conducted a study on developments in sustainable biomass certification. The study states that the need to secure the sustainability of biomass production and trade in a fast growing market is widely acknowledged by various stakeholder groups. Setting standards and establishing certification schemes are recognized as possible strategies that help ensure sustainable biomass production and trade. The study lists the following urgent actions to be taken (van Dam et al. 2006):

a) Better international coordination between initiatives is required to improve coherence and efficiency in the development of biomass certification systems.

b) A negotiation process on the development of a biomass certification system between WTO members to reach further agreements and more insight.

c) An open vision for (a combination with) alternative policy tools should be maintained to look for the best suitable options to secure sustainable biomass production and trade. Certification is not a goal on itself.

d) A gradual development of a certification system with learning (through pilot studies and research) and expansion over time, linked to the development of advanced methodologies can provide valuable experience, and further improve the feasibility and reliability of biomass certification systems. This stepwise approach gives the possibility for coherence of activities, monitoring and adjustment if needed.

4. Fuel alternatives

Alternative fuels and technologies are considered based on fuel security, economy, local pollution, and global warming. However, in the transport sector, end-use issues and fuel properties are more critical than in the other energy sectors. The infrastructure for transport fuels is rigid and requirements for fuel quality are tight. Fuel production processes, fuel quality, engines, and infrastructure set a number of obligations and limitations to each other. The solid biomass is more efficiently used for power and heat than for liquid transportation fuels. Overall, energy savings should be given high priority in transport sector.

Gasoline and diesel are projected to continue as the dominant automotive fuels by 2030. Natural gas is a quite common fuel alternative. Cleaned biogas can substitute natural gas. Biogas is already used in many countries.

Generally, advanced (synthetic) fuels show better performance than traditional fuels, and are expected to gain importance in the long run. Traditional biofuels, such as corn ethanol and vegetable oil esters, are typically attached with sustainability and end-use problems. These fuels might gradually be replaced by advanced synthetic biofuels.

In addition to synthetic Fischer-Tropsch diesel, dimethyl ether (DME), methanol, hydrogen, and methane can be produced from synthesis gas. DME is the least energy-intensive synfuel option. However, it is a gaseous fuel resembling LPG, and it requires pressurized fuel storage and a high-pressure injection system.

Hydrogen will, at the most, be a niche fuel in transport sector in the medium-term. Estimates for the longer term depend on development of sustainable hydrogen production technology.

By 2030, alternative fuels could represent a 10–30% share of transport fuels, depending on policies. As advanced biofuels are still in their infancy, it seems probable that traditional biofuels will also be used in 2030. There are three main drivers for the development of alternative fuels, exponential increase in transport fuel demand in the developing countries, the risk of oil peaking sooner than predicted and the need to reduce greenhouse gas emissions some 50% by 2050.

4.1 General

Alternative fuels and technologies should be considered within the framework of fuel security, economy, local pollution, global warming and end-use performance (Figure 4.1). In the transport sector, end-use issues, fuel properties and energy density are more critical than in other energy sectors. This should be taken into account when evaluating future options and setting up targets. Foresight is especially needed when evaluating how rapid movements can be achieved by setting indicative targets, obligations for usage, or incentives to promote market introduction of alternative fuels. The domination of hydrocarbon fuels in transport is partly based superior energy density (Figure 4.2).

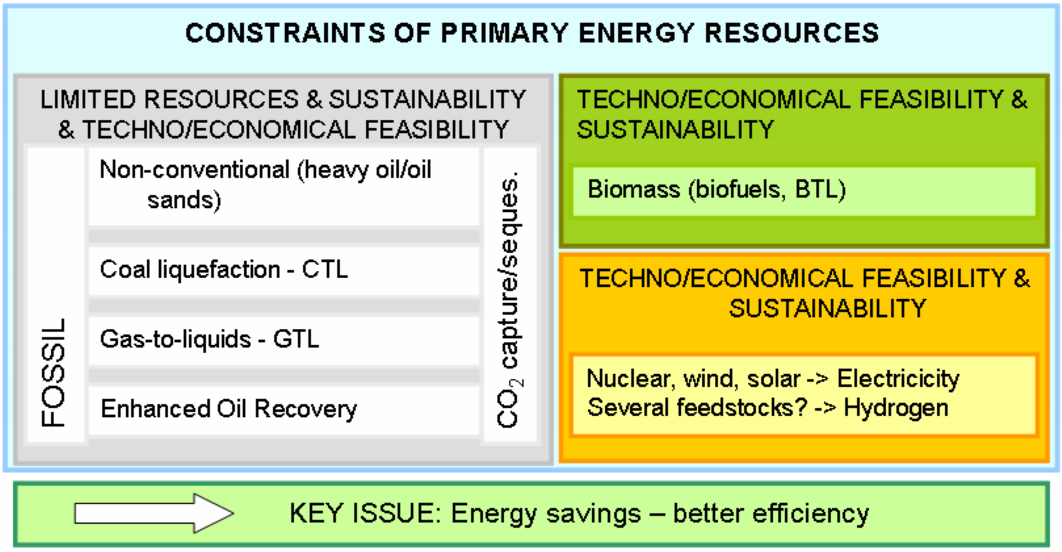


Figure 4.1. Energy sources and the main constraints in transport sector.

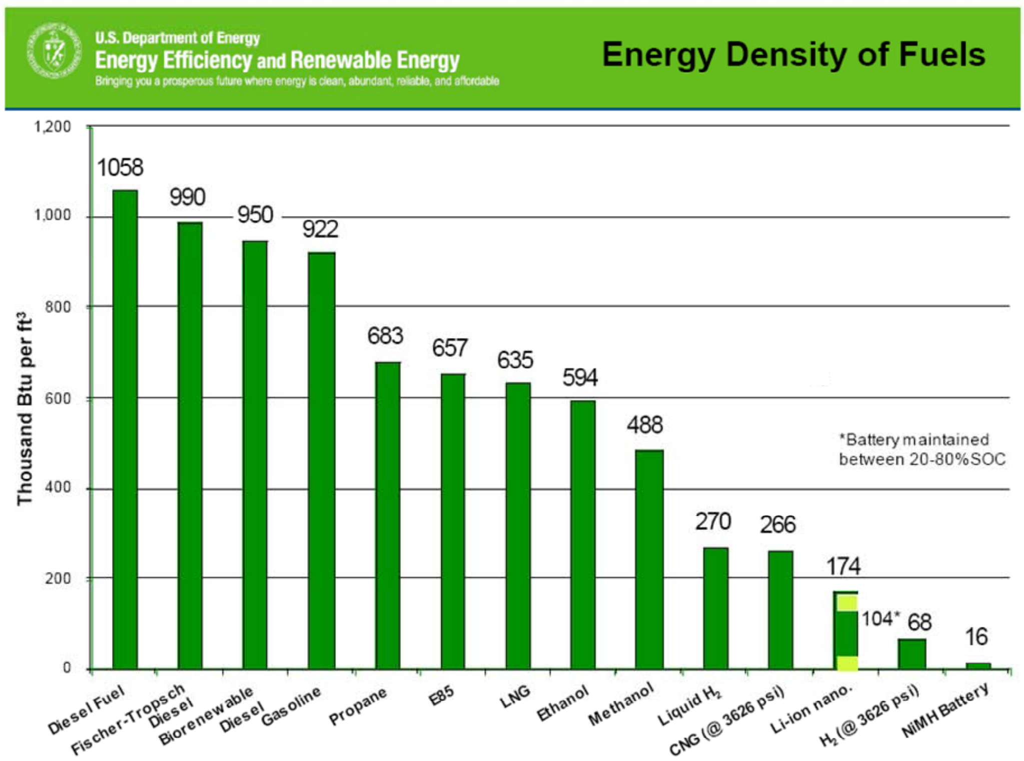


Figure 4.2. Energy density of various energy carriers (Goguen 2006).

New engine and exhaust after-treatment technologies set strict requirements for the quality of fuels. Thus, the transport sector is challenging for alternative energy options, and for this reason it is said that "the last drop of oil will be used in transportation." When considering this, and the fact that the energy-efficiency in transport sector is rather poor, it is evident that the energy savings should be emphasized in the transport sector. A number of alternative motor fuel options based on various feedstocks are available (Figure 4.3). Economical feasibility of alternative fuels should be improving with rising oil prices. However, the production processes, fuel quality, engines, and infrastructure are "married" to each other, and this marriage sets limitations on combinations. For example, gaseous fuels can only be used in special vehicles and requires dedicated infrastructure, and thus, usage of gaseous fuels is typically limited to centrally-fueled fleets.

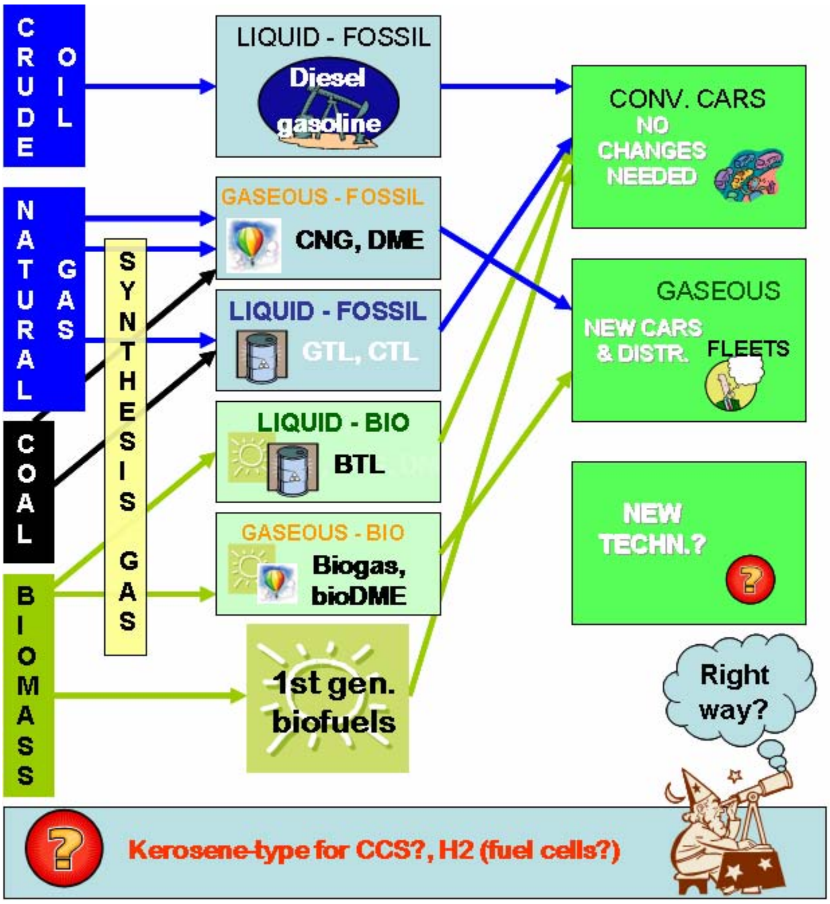


Figure 4.3. Links between feedstocks, fuels, and end-use in transportation.

Liquid fuels, such as synthetic liquid fuels processed from natural gas (GTL), biomass (BTL), or coal (CTL) are easier in this respect, as they are compatible with the existing infrastructure. Overall, selections for new technology typically lead to long-term commitments, either on the production or the end-use side. Thus political promotion actions should be long-sighted and thoroughly evaluated for local suitability and sustainability in general to avoid bad investments. Competition and lobbying by different organizations may lead to unwanted development.

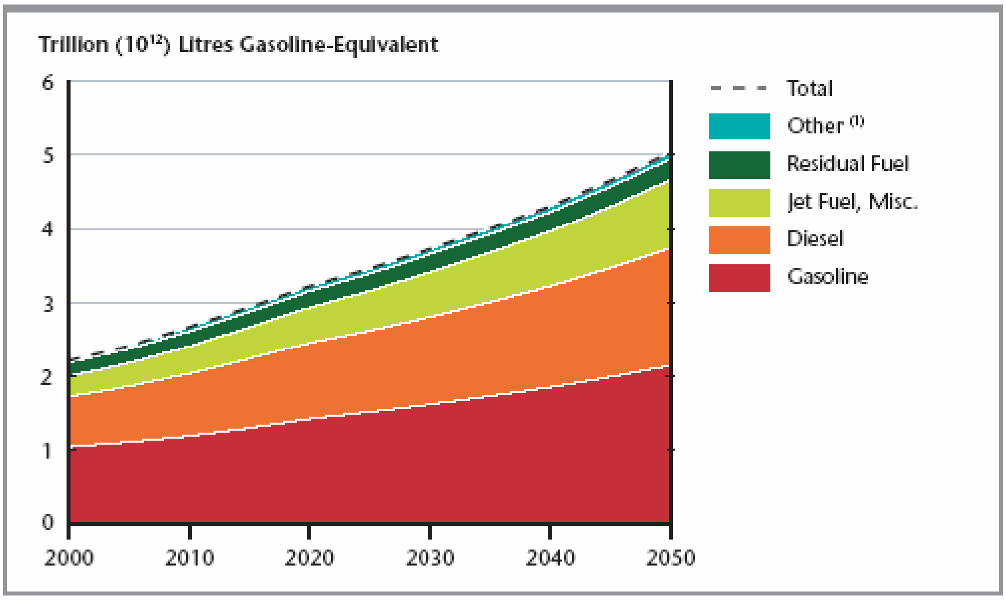
4.2 Gasoline, diesel

Fossil fuels are expected to be the leading energy source, especially in transport sector, for many decades despite the environmental concerns linked to them. The type of crude oil and the oil refining technology available limit the relative shares of oil products that can be produced from a barrel of crude oil. Gradually the crude oil pool is turning heavier, and sulfur content of crude oil will rise. Combined with increasing demand of gasoline and diesel plus tightening of the fuel quality requirements, this means that the refineries should increase performance and thus, complexity. Modern refineries with sufficient cracking and hydrotreatment capacity will be essential to meet the market demand for high-quality transport fuels, especially in developed countries. Upgrading of refineries, or building up new ones will require substantial investments (IEA WEO 2006).

Gasoline and diesel are expected to dominate in transport sector still in 2050 (Figure 4.4, WBCSD 2004). Figure 4.5 shows the dominance of gasoline in the light-duty sector. In Europe the volumes of diesel fuel increase rapidly, both as a consequence of increased goods traffic and dieselization of the passenger car fleet. It will be interesting to see how the changing balance between gasoline and middle distillates is handled, and what the consequences are for the world trading. The situation is challenging especially when low refining excess capacity and increased quality requirements of fuels are taken into account.

General trends by 2030

- *Low or zero sulfur fuels will be required*
- *Synthetic fuels, GTL etc., will grow*
- *Biomass based fuels will grow*
- *CNG usage increases regionally*
- *"The last drop of oil will be used in transportation"*



(1) CNG\LPG, Ethanol, Biodiesel, and Hydrogen Source: Sustainable Mobility Project calculations.

Figure 4.4. Projection of worldwide usage of transport fuels (WBCSD 2004).

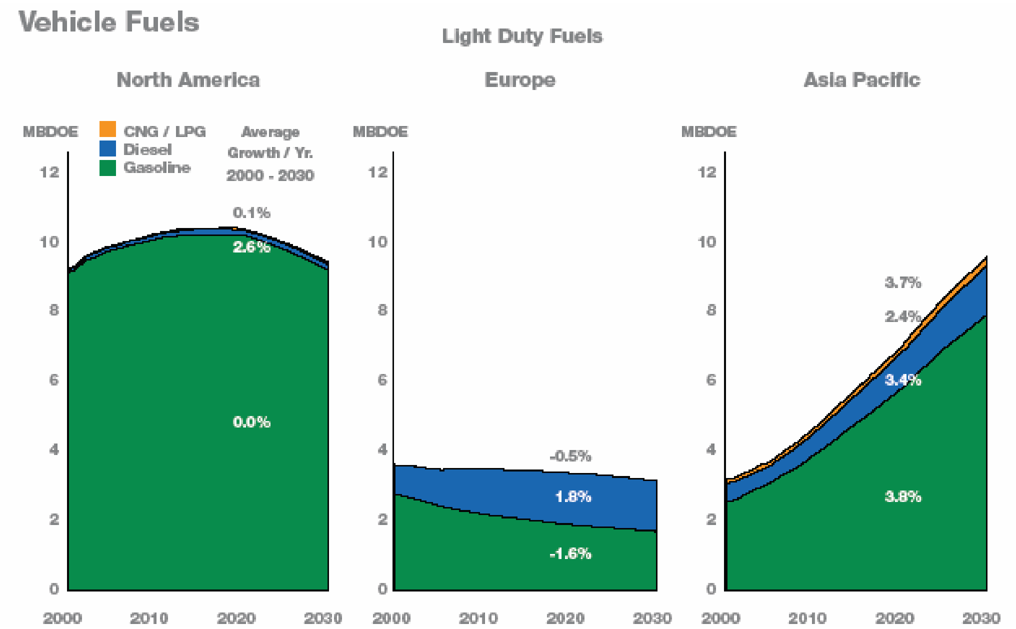


Figure 4.5. Prospects for gasoline, diesel, and gaseous fuels in the light-duty vehicle market in different regions from 2000 to 2030 (ExxonMobil 2005).

4.3 Biofuels – general discussion

4.3.1 Definitions

Today biofuels, especially in the case of biodiesel, is an imprecise word meaning various products with different origin and different end-use properties. Biofuels can, in principle, be used as such or as blending components in conventional fuels. In most cases the use of biofuels as blending components is the most cost-effective approach. Biofuels can be divided into two main categories:

a) traditional classic biofuels and
b) next generation or second generation advanced biofuels.

However, the terminology is still not fully established. Reality is such that it is not just "black and white," there are also shades of grey. The criteria could be looked upon from two different angles, from a feedstock and process point of view and from an end-use point of view. From a feedstock and process point of view advanced biofuels should fulfill at least the following criteria, with a focus on sustainability:

- feedstock production should not compete with food production
- feedstock production should not harm the environment (e.g. cause deforestation, ground water pollution etc.)
- feedstock production and fuel processing should be efficient from a GHG point of view.

The criteria from an end-use point of view could be:

- at least equivalent end-use quality compared with traditional mineral oil based fuels
- compatibility with existing refueling infrastructure
- compatibility with existing vehicles
- fuel components that do not only provide heating value but also a possibility for reduced harmful exhaust emissions.

Ethanol can be produced both from sugar-rich crops using conventional technology (first generation) and from cellulosic materials using more advanced technologies (next generation). First generation ethanol can be efficient, as well as for yields and CO_2, as demonstrated by the Brazilian case. On the other hand, some experts claim that production of cellulosic ethanol can be energy intensive.

Regardless of the process, the quality of the end product is the same. Ethanol is not a trouble-free fuel. Used as a blending component in gasoline it increases evaporative emissions, may cause corrosion, and may lead to troubles with phase separation in cold conditions. Ethers give better end-use properties than plain ethanol. When used at high concentrations, e.g. E85, ethanol creates problems with corrosion, aldehyde emissions and startability. Therefore, at least at the current level of engine technology, ethanol is not the preferred biofuel regarding end-use properties.

Biogas is often classified as a first generation biofuel, based on the rather simple production process. However, biogas is a high quality clean fuel. Cleaned biogas can, unlike other first generation biofuels, substitute natural gas up to 100% in vehicle applications. In addition, the well-to-wheel GHG balance of biogas is very favorable.

There are a number of alternative routes to diesel-type biofuels. The abbreviations are not commonly harmonized, but the following are those used in this report:

- SVO = straight vegetable oil (authors' comment: not recommended for high speed diesel applications)
- VOE = vegetable oil esters, traditional "biodiesel" (typically methyl esters, FAME)
- HVO = hydrotreated vegetable oils and fats (NExBTL, H-BIO)
- BTL = Biomass-to-Liquids, gasification of any hydrocarbon biomass (e.g. biowaste) followed by Fischer-Tropsch liquefaction.

From an end-use point of view traditional esterified biodiesel VOE or FAME resembles ethanol in the sense that both using FAME as a diesel component and especially using FAME by itself presents some problems. Most current fuel specifications limit ethanol concentration in gasoline as well as FAME concentration in diesel to 5–10%. Maximum permissible concentrations are set so that no problems will occur in normal service.

Both hydrotreatment of vegetable oils and animal fats and gasification of biomass combined with a Fischer-Tropsch process render high quality paraffinic diesel fuel. The Fischer-Tropsch synthesis can be used for any hydrocarbon-containing feedstock. When the feedstock is natural gas, the product is called GTL (Gas-to-Liquid); in the case of coal, CTL (Coal-to-Liquid); and in the case of biomass, BTL. Even low-quality heavy oils can be gasified and used as feedstock. Syngas technology can also be used to produce gasoline, methanol, and DME.

Traditional biofuels:

- *Ethanol from sugar-rich crops*
- *Biodiesel by esterification of oils or fats*
- *Biogas*

Next generation biofuels and synthetic fuels:

- *Ethanol from cellulosic feedstock, bio-methanol, higher alcohols e.g. biobutanol*
- *Ethers, such as ETBE, bio-MTBE*
- *Synthetic biodiesel, e.g. BTL diesel*
- *Hydrotreated oils and fats (NExBTL, H-BIO)*
- *GTL from natural gas and CTL from coal*
- *Synthetic natural gas (biogas)*
- *Bio-DME*
- *Biohydrogen*

Note: Vegetable oils as such are not suitable for today's transport applications.

Paraffinic diesel has very high cetane number and good combustion properties in general. It is miscible with conventional diesel fuel at any ratio, and if used as such, it can reduce harmful exhaust emissions significantly. As there are no quality or end-use related limitations, synthetic type biofuels can easily contribute to increased use of biofuels in transport.

If hydrotreated vegetable oil is produced for edible oil, then the fuel is a first generation biofuel from a feedstock point of view but a second generation biofuel from an end-use point of view. If produced from waste oils, then HVO could be considered a second generation biofuel. BTL from cellulosic material or waste is considered an actual second generation biofuel, both regarding feedstock and end-use properties. Figure 4.6 shows alternative routes to biodiesel fuels. The end-use properties of FAME biodiesel differ radically from hydrotreated or BTL-type biodiesel and thus, it is important to use more exact definitions for these fuels.

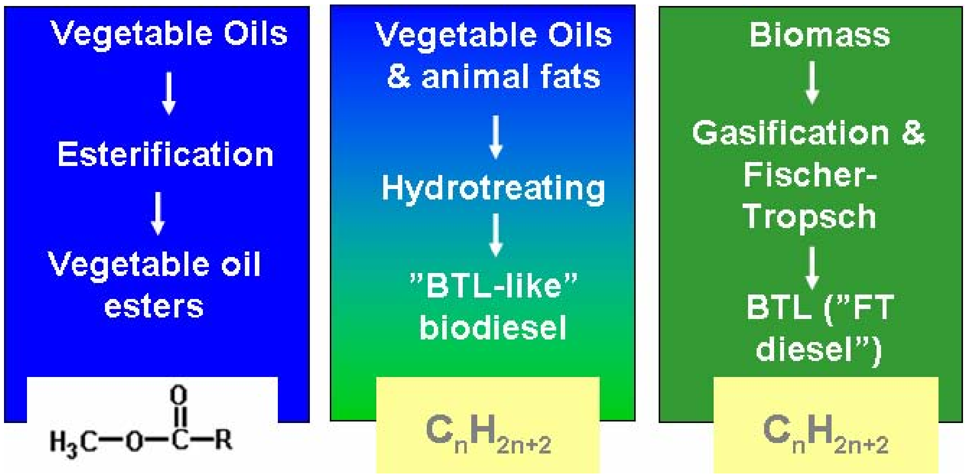


Figure 4.6. A schematic figure of the main biodiesel processes and end products.

One advantage of traditional ethanol and FAME is that these fuels can be processed in large or small scale. The costs for the processing facilities are relatively low. Hydrotreatment and especially the combination of gasification and Fischer-Tropsch are only feasible for large refinery-type units. Capital costs for these types of plants are high.

Traditional production of ethanol and FAME results in side products, some of which are used as animal feed. Overall economics, GHG, and energy balances are highly dependent on how these byproducts are appraised.

Taking into account that the traditional biofuels have a long history and production is in place, that HVO is just entering the commercial phase, and that actual BTL is in the pre-commercial stage, it is easy to foresee that even traditional biofuels will play a role in the future. However, the requirements on efficiency, sustainability, and compatibility with current and future vehicles are probably best met with next generation biofuels.

4.3.2 Trends

When discussing the potential of biofuels for transport it should be noted that when solid biomass is transformed into liquid fuels, the conversion losses are significant. Biomass potential is discussed in Chapter 2. IEA WEO 2006 predicts that usage of biofuels in transport will rise, depending on scenario model used, to supply 4–7% of world transport fuel demand in 2030 (Figure 4.7). The highest absolute increase in biofuel usage is expected in the U.S., which is the biggest biofuel consumer in absolute terms already today. Europe will take the second place from Brazil, whereas other regions will show only modest increases in biofuel usage.

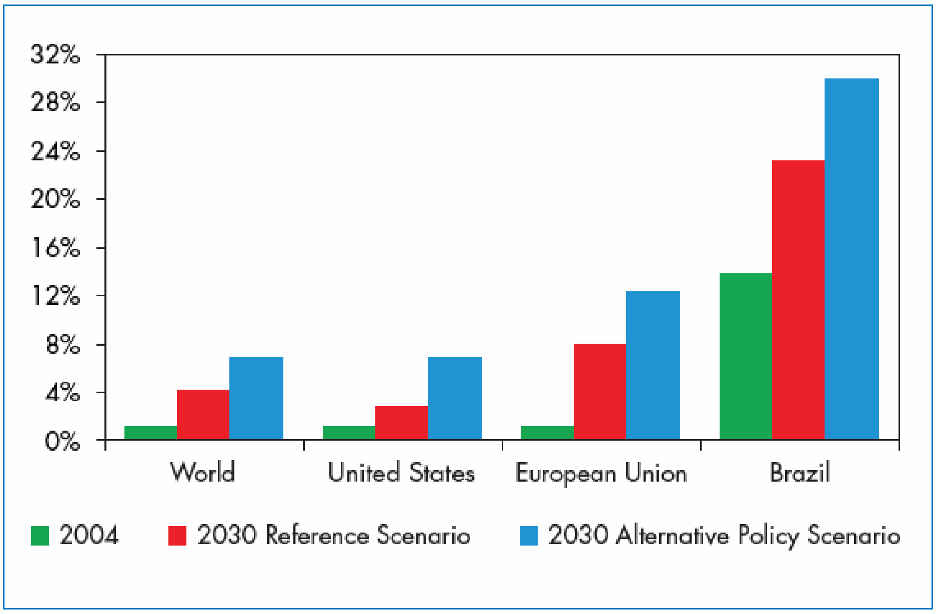


Figure 4.7. Prospect for the share of biofuels in road-transport in energy terms (IEA WEO 2006).

In 2005, world transport biofuel production was some 21 Mtoe, 85% of which is ethanol and 15% biodiesel. Europe is the only region where biodiesel is dominating over ethanol. Some 80% of all biofuels are produced in US and Brazil. The highest shares of biofuel in transport can be found in Brazil (almost 14%) and Cuba (over 6%). The consumption of biofuels in Europe was around 5.4 million toe in 2006, which represents a share below 2% of road transport fuels in Europe. (System Solaires 2007)

Figure 4.8 shows a projection for biofuel volumes. Mandates in both Europe and the U.S. will increase biofuel volumes. On a world-wide basis ethanol will maintain its position as the leading biofuel due to lower production costs compared with biodiesel. In the long run, next generation biofuels are expected to take shares from traditional biofuels.

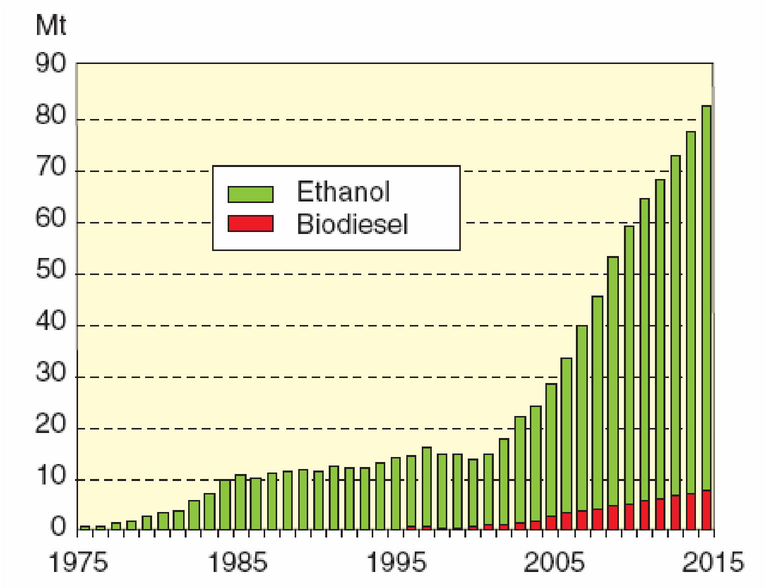


Figure 4.8. Projection of global biofuels production in million tons (not corrected for energy content) (IFP 2007).

The costs for biofuels vary significantly. Figure 4.9 shows cost estimates for biofuels from various regions. In 2007, the refinery cost for conventional fuels (gasoline, diesel) was some 0.40–0.50 €/l. According to Figure 4.9, Brazilian sugarcane ethanol and ethanol from cassava are competitive, with cost corrected for energy content at some 0.30 €/l. Currently European biofuels are not cost competitive.

4.4 Alcohols and ethers

4.4.1 Processes and properties

Ethanol has a long history as an automotive fuel. Henry Ford's Model T from 1908 and other early automobiles ran on alcohol, gasoline, or any combination of these. World War I increased the ethanol demand to around 0.2 million t/a. In the 1920's ethanol became a major blending component in gasoline. World War II and the oil crisis in the 1970's also increased the ethanol demand (EIA).

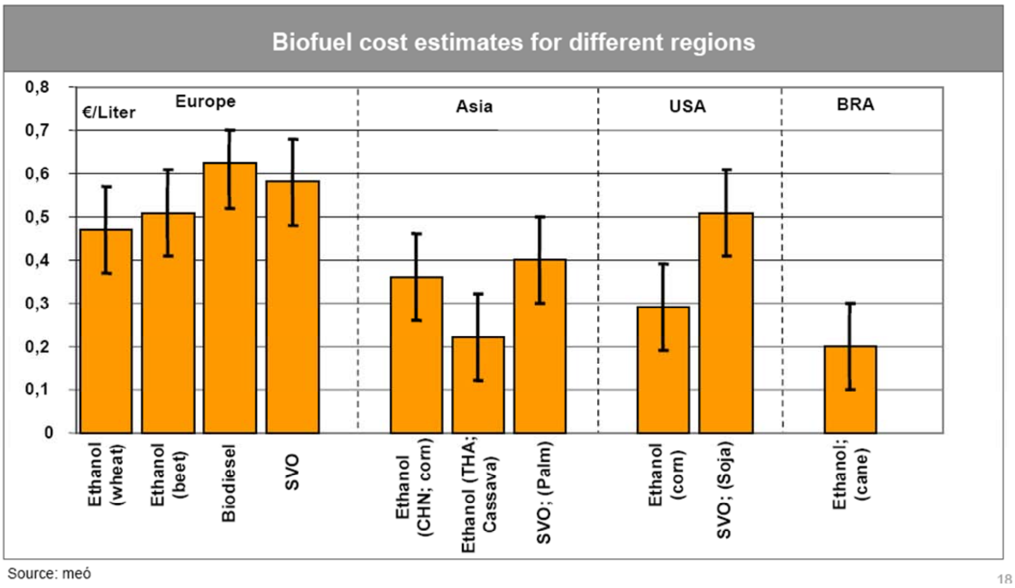


Figure 4.9. Biofuel cost estimates (Schmitz 2007).

Both methanol and ethanol can be used as transportation fuels, as blends with gasoline, additives in the form of ethers, or as neat fuels in modified engines (Chapter 5.4.2). Both these alcohols have a high octane rating. Hydrated ethanol contains 95% ethanol and some 5% water after distillation. Dehydration produces an anhydrous grade with an ethanol content of 99.5%. Hydrated ethanol can be used for E85, whereas anhydrous ethanol is required for low-level gasoline-ethanol blends.

Methanol was the primary alternative fuel considered for transport in 70's and 80's when the focus was on energy security. In the 90's the focus moved towards climate change issues, and bioethanol took a leading position, mainly due to the rather simple production technology (Grahn 2004). Also Flexible Fuel Vehicles (FFVs) were first developed for methanol use, but they were later optimized for ethanol. Methanol is technically more challenging than ethanol. Methanol is toxic, corrosive, and less soluble with gasoline than ethanol. Serious material problems with vehicles using M85 were experienced in the 80's.

Ethanol, methanol

- *Liquid fuels (easy re-fuelling and storage)*
- *High octane numbers enable blending with gasoline and usage in spark-ignition engines. Even neat alcohols can be used in modified engines (FFV)*
- *Ignition properties of alcohols are not suitable for diesel engines, but they can be used if engine or fuel is modified.*
- *Phase separation problems with blends*
- *Several fuel properties cause end-use problems (low energy content, high heat of vaporization, vapour pressure).*
- *Methanol burns with an invisible flame, ethanol with a slightly luminous flame.*

Other alcohol-based options

Conversion of alcohols to ethers (e.g. MTBE, ETBE) improves end-use properties of alcohols. In addition, some heavier alcohols, such as butanol, provide better end-use performance than ethanol or methanol as gasoline components.

Conversion of alcohols to ethers, e.g. methanol to MTBE and ethanol to ETBE, provides a pathway to improve properties of alcohols. Other possible components are methanol-based TAME and ethanol-based TAEE. Both MTBE and TAME could be biocomponents, if the methanol part were to be processed from biomass. Ethers are produced from alcohols and light olefins. The latter are unwanted components in gasoline. Thus ethers can help out in making better use of the total oil barrel, as undesirable fractions are combined into desirable components.

From an end-use point of view ethers are preferred over alcohols. However, water-solubility of ethers is generally higher than for hydrocarbon fuels. This is the case especially for MTBE. Leaking storage tanks and other spills may lead to ground water problems. This led to the ban of MTBE in the U.S. Existing MTBE plants could easily be switched to produce ETBE.

4.4.2 Development

Some 17 Mtoe of fuel ethanol was produced in 2005, which is about double when compared with production in 2000. The production of fuel ethanol has been rising, and this trend is projected to continue (Figure 4.8). In the U.S., the driving forces behind ethanol have been agricultural policies and the MTBE ban. New production centers could be Thailand, with a planned production of 0.65 million t/a, and China, with an announced production of 1.6 million t/a. India has started to produce anhydrous fuel ethanol for blending into gasoline (below 5% alcohol). (Distillery Network)

The major part of fuel ethanol is used as low level blends for spark-ignition engines. In the U.S., some 3.9 billion gallons (12.7 million m^3) of corn-ethanol were produced in 2005, and sold as a blend with gasoline. This accounted for 2.8% of total gasoline sales by volume (1.9% by energy content due to the lower energy content). The U.S. ethanol production capacity is expected to be 4.8 billion gallons (15.6 million m^3) in 2006 and to increase to 7.5 billion gallons by 2012 (24.4 million m^3, below 5% of projected consumption). A further goal is to displace 60 billion gallons of the U.S. gasoline by ethanol by 2030. (Harvard Magazine 2006)

In Europe, fuel ethanol is not as widely used as biodiesel. Only some countries in Europe, e.g., Sweden, blend ethanol in gasoline and use neat ethanol in buses. In Europe, ethanol is mainly converted to ETBE, which is used as gasoline blending component. Leading producers of ETBE are France and Spain. It is estimated that 2 million tons of ETBE was produced in Europe in 2005. This consumes almost 1 million tons of ethanol. Ethanol production in Europe was around 0.7 million tons in 2005 and 1.2 million tons in 2006. (Systemes Solaires 2007)

Japan also uses ethanol mainly in the form of ETBE in gasoline. Japan aims to replace about 20% of the gasoline demand with gasoline containing 7% of ETBE. To bring ETBE-blended gasoline into market, new refueling equipment and improved underground tanks will be installed (Takada 2006a).

In the U.S., MTBE was widely used gasoline component, however, now banned due to ground water problems. ETBE is likely to be used besides ethanol to replace MTBE in California and in other states as the MTBE ban widens.

When considering the production efficiency of alcohols, it seems that methanol from wood would be one of the best options (Grahn 2004). However, methanol as such is technically difficult.

A lot of effort is invested in the development of processes for cellulosic ethanol. In this case variable and abundant feedstocks that do not compete with food production could be used for ethanol production. However, the process technology still needs development. In addition, agricultural fibers have low density. Thus, shipping and storing as well as harvesting are costly.

In Canada, Iogen Corporation is developing a process that will convert wood, hay, straw and other agricultural residues to ethanol. Similar development is going on in Denmark. Sweden has carried out extensive programs on ethanol, focusing on new, cost-effective production technologies based on hydrolysis of woodchips and fermentation of free sugars, both hexoses and pentoses. Process concepts based on enzymatic and dilute acid hydrolysis are studied. The work includes studies both in laboratory and pilot scale.

Several pilot plants for cellulosic ethanol are operational in the U.S. (NREL/ABRD), Canada (Iogen, SunOpta), Sweden (SEKAB E-technology), Denmark (Elsam), and China. Commercial plants are being built in Spain (by Abengoa, wheat straw), the U.S., Canada, the Netherlands, and China. (Burke 2006)

The estimated costs of ethanol from lignocellulosic feedstocks is around $28/GJ, which means slightly less than $1 per liter of gasoline equivalent, and this is expected to decrease to $0.5 per liter of gasoline equivalent. (IEA Energy Technology Essentials 2007)

Another development path is research on heavier alcohols. In 2006, BP and DuPont joined forces to develop, produce and market 2nd generation biocomponents for gasoline. They announced that the first product will be biobutanol. Existing ethanol capacity can be retrofitted to biobutanol production which can utilize a variety of feedstocks such as sugar cane, sugar beet, corn, wheat, cassava and sorghum. In the future, feedstocks such as lignocellulosics from energy crops (e.g. grasses) or agricultural byproducts could be used. Biobutanol was expected on the market in 2007 (~41,000 m^3 per year). (BP-DuPont 2006)

Biobutanol has many advantages over ethanol: e.g., low vapor pressure with less evaporative emissions, better energy content and biobutanol can use the industry's existing distribution infrastructure. According to DuPont and BP, up to 30% biobutanol could be used in gasoline in future. Biobutanol is well suited to current vehicle and engine technologies and does not require automakers to compromise on performance to meet environmental regulations. (BP-DuPont 2006).

4.5 Biodiesel – FAME

4.5.1 Processes and properties

Straight (raw) vegetable oils are not suitable for high-speed diesel engines used in light- and heavy-duty vehicles, even though some technologies, such as the fuel system from Elsbett, enable usage in special applications. Esterification with methanol or ethanol brings down viscosity so that preheating of the fuel or major modifications on the engine are not needed.

Various feedstocks are feasible for transesterification, such as palm oil, soybean oil, rapeseed oil (also called canola), animal fats like tallow, and waste materials such as cooking and trap greases. Vegetable oils are the most commonly used feedstock. There are significant differences in the properties of possible feedstocks, e.g., the free fatty acid content is below 1.5% for rapeseed oil, but can be over 50% for animal fats. Feedstock properties affect the properties of the end product (Kinast 2003).

FAME-type esters:

- *Esters can be used as neat or as blends with diesel.*
- *Cetane numbers are reasonable. Low sulfur content and no aromatics. Lubricity is excellent.*
- *Impurities may lead to deposits in engine and exhaust after-treatment devices. May dissolve impurities from distribution system and tank. Material problems. Stability problems.*
- *Heat content of esters is low – volumetric fuel consumption higher than with diesel, but compensated by higher density.*
- *Distillation range is narrow and boiling point high -> dilution of engine oil, difficulties in the cold start. Natural cold properties of vegetable oil esters are poor (additives can help).*
- *Biodegradable – leaks to ground or water less harmful than with diesel.*

Generally, the feedstock needs to fulfill certain requirements, and pretreatment may be needed (filtering, removal of water and contaminants). The catalyst is usually sodium or potassium hydroxide. Methanol is the most commonly used alcohol in transesterification (Preseco). Other alcohols could be used as well, but this may mean more complicated process, slower reaction times and lower yields.

Glycerol is formed as a by-product in transesterification. Glycerol can be used e.g., in pharmaceuticals and cosmetics (Kinast 2003). Possible free fatty acids are converted into soaps, which can be used for other products (agricultural) or composted.

The basic fuel properties of FAME, such as density and cetane number, are suitable for diesel engines. Quite like ethanol in the case of gasoline, FAME can be used as a blending component in diesel or as a neat fuel. However, there are critical end-use problems associated with FAME. The views of automobile and engine manufacturers on fuels are summarized in the Worldwide Fuel Charter, WWFC, which points out the concerns of engine manufacturers regarding usage of FAME especially at higher levels (WWFC 2006):

- possible instability
- fuel injection equipment problems
- possible rise in viscosity at low temperatures (need for additives)
- hygroscopic -> affinity to water and risk of corrosion and microbial growth
- deposits in the fuel injection system (detergent additives)
- problems with natural and nitrile rubber seals or some metals
- increase in tank sediments
- dissolve the paint coatings
- an increase in NO_x emissions.

Due to challenges in end-use, the concentration of FAME in diesel fuel is limited by fuel regulations in Europe. Currently up to 5% FAME may be added to conventional diesel fuel, and for higher concentrations the fuel supplier is required to declare the fuel's composition (Directive 98/70/EC and 2003/17/EC). In the 2006 edition of WWFC, FAME level should be "non-detectable" for Category 4 diesel, which applies in areas where sophisticated after-treatment devices are used. (WWFC 2006)

Despite the shortcomings of FAME-type biodiesel, many individual engine manufacturers have announced approvals for using neat or blended FAME in their engines, especially in non-road engines.

4.5.2 Development

Biodiesel (vegetable oil ester) has been mainly used in Europe, but now it is increasingly used also in the U.S. Figure 4.8 shows global biofuels consumption and Figure 4.10 projections for vegetable of based biodiesel. Vegetable oil esters are part of the fuel selection today, but probably better quality/efficiency next generation fuels will gradually replace them at least in developed markets where fuel quality requirements are high.

In Europe, rapeseed oil (canola) is the major feedstock for biodiesel, whereas soybean oil is used in the U.S. Soy oil production is increasing strongly in South America. Animal fats and waste greases are also an option to be used as fuel, but variation of the quality is more problematic than for vegetable oils. Asian countries produce increasing amounts of palm oil for transportation fuels and power generation.

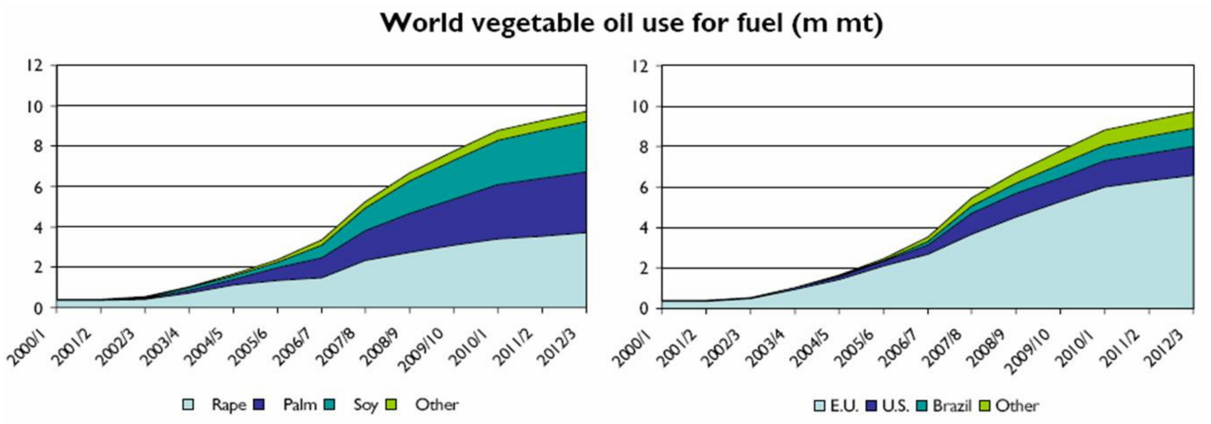


Figure 4.10. World vegetable oil use for fuel to 2012/13 (Promar 2005).

In Europe, actions have been taken against non-sustainable biofuels. For instance, biodiesel trials in UK were suspended due to concerns over the sustainability of food crop as biodiesel feedstock. The Swedish distribution chain, OKQ8, withdraw from delivering of palm oil based biodiesel to the market. (AMFI Newsletter 4/2007)

In Germany, the government introduced taxes on traditional biofuels and thus only about one half of the five million ton biodiesel production capacity will be used in 2007. Table 4.1 shows the new German taxation scheme for biofuels, providing tax exemptions for 2nd generation biofuels (and E85) until 2015. B100 (FAME) will be fully taxed starting 2012. (Schmitz 2007)

Table 4.1. Taxation of biofuels in Germany (Schmitz 2007).

Taxation of biofuels in €/l
(according to Energiesteuergesetz and Biokraftstoffquotengesetz)

	8-12/06	2007	2008	2009	2010	2011	2012	2013	2014	2015
E85	0	Tax exemption								
E5	0	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65	0,65
Lig. E.	0	Tax exemption								
B100	0,09	0,09	0,15	0,21	0,27	0,33	0,45	0,45	0,45	0,45
B5	0,15	0,47	0,47	0,47	0,47	0,47	0,47	0,47	0,47	0,47
SVO	0	0*	0,1	0,18	0,26	0,33	0,45	0,45	0,45	0,45
BtL	0	Tax exemption								
Biogas	0	Tax exemption								

(Red shading) Overcompensation reporting; adaption possible

4.6 Biodiesel by hydrotreatment and synthetic fuels (GTL, CTL, BTL)

4.6.1 Biodiesel by hydrotreatment (HVO)

A process that has recently gained a lot of interest by several refiners is based on hydrotreatment of triglycerides such as vegetable oils and animal fats. The end product is clean paraffinic diesel fuel. The process combines the feedstock of conventional biodiesel production and the high quality end product of synthetic diesel (see Figure 4.5). In a way it also decouples feedstock and end product properties. Properties of hydrotreated biodiesel (HVO) and synthetic fuels are covered in the next section.

Neste Oil in Finland developed the refinery-based NExBTL process, which benefits from refinery's infrastructure including energy, blending facilities, logistics and laboratories. The first NExBTL plant with a capacity of 170,000 tons/year started production in May 2007 in Finland, and a second plant with equivalent capacity will come on stream at the end of 2008. A memorandum of understanding on a joint venture with the Austrian oil company OMV has been signed as well. In November 2007, Neste Oil announced of building a NExBTL plant with capacity of 800,000 t/a in Singapore by 2010. (Neste Oil)

Petrobras of Brazil has developed the H-Bio biodiesel process, which hydrogenates mixtures of vegetable oil and petroleum (co-hydrogenation). The output is a mixture of diesel and hydrogenated vegetable oil, not a separate biodiesel component as in the case of NExBTL. The oil used in development was soy oil, but oil from other oleaginous plants may be used. Brazil already produces 5.6 million m^3 of soy oil per year. Petrobras planned to start production in 2007 in one refinery, and to introduce production in two more refineries in 2008. However, Petrobras postponed production due to high soy prices, but is maintaining production target of 425 million liters of H-Bio in 2008, and 1.6 billion liters in 2012. (Green Car Congress 2006a, 2007)

A number of other projects on the hydrotreatment of vegetable oils and fats were announced in 2007, such as (AMFI Newsletter 3/2007):

- Galp Energia together with Petrobras in Portugal
- UOP/Eni in Italy
- Dynamic Fuels LLC (a venture of Tyson Foods and Syntroleum) in the U.S.

In the U.S., the renewable diesel fuel processed by hydrotreatment of vegetable oils or animal fats will get similar credits as traditional ester-type biodiesel. The U.S. Internal Revenue Service has defined hydrotreated renewable diesel eligible for a tax credit, which is granted for fuels produced by “thermal depolymerization” of biofeedstock. The credit takes into account the heating value of the fuel, and is thus 1.7 times the credit of ethanol due to higher energy content. Credit for conventional biodiesel (ester) is 1.5 times the credit of ethanol. (DieselNet Update 2007)

4.6.2 Properties of HVO, GTL, CTL, BTL

Regarding end-use properties, hydrotreated oils and synthetic FT diesel show superior quality compared with conventional diesel fuel and conventional biodiesel. Almost no sulfur, high cetane number, and low aromatic content result in significant emission reductions compared with conventional diesels. Appendix 1 shows properties of standard diesel fuel, conventional biodiesel (FAME), synthetic GTL diesel, and HVO (NExBTL). Regardless of the feedstock, all paraffinic diesel fuels or components have the following benefits:

- can be used as is or as blends in existing diesel engines and infrastructure
- enables the development of engines with improved engine efficiency
- sulfur-free, low aromatic, no oxygen
- no problems with materials compatibility or storage life
- almost odorless, colorless liquids

- more biodegradable, more non-toxic, not as harmful to aquatic organisms as conventional diesel
- significant reductions in regulated and unregulated exhaust emissions
- increases energy-security and diversification
- FT technology makes it possible to tailor fuels for future advanced combustion systems.

Hydrated oils, HVO:
New refinery-based technologies: hydrotreatment of oils and fats. Traditional feedstock, vegetable oils and animal fats converted into high-quality biodiesel, end-use properties resemble FT diesel.

Fischer-Tropsch diesel, GTL, CTL, BTL:
- *Synthetic fuels: gasification or steam reforming to synthesis gas (H2, CO), Fischer-Tropsch liquefaction*
- *From natural gas GTL (Gas-to-Liquid), from coal CTL (Coal-to-Liquid) and from biomass BTL (Bio-to-Liquid).*
- *GTL and CTL are commercial technologies. The first commercial BTL plant is built in Germany*

Properties of paraffinic fuels:
- *Clean, high-quality fuels. Can be used as neat or blends with diesel.*
- *Very high cetane number, high hydrogen to carbon ratio, no aromatics or sulfur, no oxygen, low density.*

4.6.3 Processes and development for synthetic fuels, GTL, CTL, BTL

Production of synthetic fuels is based on synthesis gas (H_2, CO) and a liquefaction step. Synthesis gas can be produced by reforming (methane or light oil) or gasification (e.g., coal, biomass, and heavy oils). Basically any hydrocarbon-containing material can be used as feedstock. There are several types of fuels that can be made from synthesis gas. The Fischer-Tropsch synthesis renders synthetic crude than can be refined into diesel and gasoline. Alternative liquefaction steps are synthesis into methanol or DME, both of which are more selective than the Fischer-Tropsch process.

The output of the Fischer-Tropsch process is typically 50% high-quality, sulfur-free high cetane synthetic diesel, 30% naphta and 20% other products (Rehnlund 2007). The Fischer-Tropsch process was originally developed by German coal researchers in the 20's, and it was used during World War II in Germany and later on in South Africa by Sasol to produce liquid fuels.

Fischer-Tropsch plants (major ones)
- *Sasol/South Africa 156,000 bpd, mainly coal*
- *Shell/Malaysia 15,000 bpd, natural gas*
- *Planned or under construction:*
  - *Sasol Chevron, Nigeria, Qatar – 2 x 34,000 bpd, natural gas*
  - *Sasol Shell, USA – 5,000 bpd, waste coal*
  - *Shell, Qatar – 140,000 bpd*

Source: Rehnlund (2007)

The biomass-to-liquid processes (BTL) are still under development. It is more difficult to apply gasification and liquefaction to biomass than to coal. Gas cleaning in the gasification step is difficult with biomass, which contains a lot of impurities. (Blades 2005, AMFI Newsletter 3/2006)

Today Sasol produces synthetic fuels and chemicals from both coal and natural gas. Shell operates a GTL plant in Malaysia, and new plants are under construction in the Middle East, e.g., in Qatar. Shell is marketing GTL as a diesel component in Thailand, Germany, Austria, Italy, the Netherlands, Greece and Switzerland (Shell).

The production cost of synthetic FT diesel is slightly higher than costs for e.g., DME, but the overall costs might be lower, because no changes in infrastructure are needed. GTL from stranded natural gas becomes increasingly competitive with soaring crude oil prices. Increased requirements on fuel quality may also drive the development towards synthetic fuels.

The Alliance for Synthetic Fuels in Europe (ASFE) has estimated production of GTL fuel to approach one mbpd day by 2020 (10 large-scale plants). This is still a modest quantity compared with some 50 mbpd of oil consumed by transport today. The addition of a single 140,000 bpd GTL plant (equivalent to some 6 Mtoe/a) would consume 0.5 trillion cubic feet of natural gas per year (Sasol Chevron 2006).

CTL production could well be competitive with current and anticipated crude and natural gas prices, and promising figures have been given also for DME from coal. CTL production is most favorable in cogeneration of electricity (Gielen & Unander 2005). There is a rapid increase in the number of proposals on CTL projects in the U.S., Australia, and China (Sasol is in the phase of selling its CTL technology to China). However, certain limitations, e.g., high capital costs of plants as well as environmental concerns may retard CTL development. CTL will increase well-to-wheel GHG emissions significantly compared with oil based transportation fuels. Even if carbon capture and storage (CCS) were used for the flue gases of the processing plant, the fuel itself would still contain carbon.

The world’s first commercial BTL plant is being built in Freiberg, Germany by CHOREN, supported by Volkswagen and DaimlerChrysler and Shell. The pilot plant (Beta) with a capacity of 15,000 tons/year is expected to come on stream in the second half of 2008. Large-scale production in a full-scale plant (Sigma) in Schwedt, Germany, is expected to start in 2012 (output 200,000 tons/year). (Peters 2007)

Finnish companies are interested in developing BTL technology. The oil company Neste Oil and the pulp and paper company Stora Enso have teamed up for a demonstration plant at Stora Enso's Varkaus Mill. Expected start-up is in 2008. Full-scale commercial production is expected around 2012–2014 with a 250 MW plant, which would produce around 120 million liters of diesel fuel annually. (Neste Oil 2007)

The Finnish forestry company UPM and the international technology group Andritz with its associated company Carbona intend to co-operate to develop technology for biomass gasification and syngas purification for BTL production. The joint testing project will start with tests using Carbona's gasification technology at the Gas Technology Institute's pilot plant in Chicago, U.S. (UPM 2007)

Table 4.2. Summary of the GTL, BTL and CTL technologies (ASFE).

	Gas to Liquids (GTL)	**Biomass to Liquids (BTL)**	**Coal to Liquids (CTL)**
Feedstock:	Natural gas	Biomass (agricultural and forestry biomass)	Coal
Likely plant location:	Countries with abundant remotely located gas reserves and/or where natural gas is flared	In proximity to large biomass production centres (e.g. France, Germany)	In countries with abundant coal reserves (e.g. South Africa, China, U.S.)
Greenhouse gas emissions:	Comparable to crude oil refining, potential for reduction via technology improvement.	Most promising potential for substantial reduction of greenhouse gas emissions.	Carries carbon penalty, significant reductions possible with CCS.
Supply potential:	Announced global capacity equivalent to 10% of EU diesel demand by 2015.	Biomass feedstock potential in the EU for up to 50% of EU diesel demand.	CTL plants under discussion (U.S., China) ~2% of world diesel demand by 2020.
Industrial status:	Operating units already available (South Africa, Malaysia) Further commercial-scale plants under construction or designed	Pilot plant scale only. Prototype plant planned.	Large scale plant, high-temperature FT process operational for decades in South Africa. Large plants under discussion in the U.S. and China
State of technology:	Proven and well-known	Further R&D and scale-up required	Proven and well-known

ASFE has collected a summary on synthetic liquid fuels shown in Table 4.2. ASFE estimates the potential of synthetic fuels as follows (ASFE):

- GTL: global capacity 10% of European diesel demand by 2015. (Authors' comment: roughly equivalent to 1% of global demand of transport fuels in 2020)
- CTL: ~2% of world diesel demand by 2020. (Authors' comment: roughly equivalent to 1% of global demand of transport fuels in 2020)
- Biomass feedstock theoretically available in the EU for up to 50% of EU diesel demand.

Putting together all initiatives it is easy to foresee that the contribution of synfuels will still be rather limited in 2020. IEA estimates that the cost of BTL diesel from ligno-cellulose is currently more than $0.9 per liter of diesel equivalent, with a potential reduction to $0.7–$0.8 per liter of diesel equivalent. (IEA Energy Technology Essentials 2007)

In the long run, synthetic fuels compatible with existing vehicles are predicted to take the lead as alternative fuels for transport. The quality of FT diesel fuels is high and thus FT diesel might also be used to upgrade lower quality diesel fuels on some markets.

4.6.4 Fuels for advanced combustion systems

Engine development for the future is focused on advanced combustion systems such as CCS (low-temperature combined combustion system) promising both improved efficiency and reduced emissions (Chapter 5). New combustion processes may require totally different fuels than conventional spark-ignition and compression ignition engines.

Seyfried (2005) stated that CCS technology could favor low cetane number (about 40–45) and kerosene-like distillation range 150–210 °C (Appendix 1). Consequently, there are a number of studies with CCS technologies using a variety of fuels, including hydrocarbon fuels, oxygenates, and even diesel/ethanol blends. This development would require a new direction of development of production processes of liquid fuels, and possibly also a new supplementary distribution infrastructure. Production of synthetic fuels provides a possibility to tailor and adjust fuel properties, i.e., to produce fuels optimized for new combustion schemes.

4.7 Natural gas, biogas, DME

Properties, processes

The properties of natural gas are shown in Appendix 1. Natural gas typically consists of over 80% of methane (CH_4), and some other hydrocarbons (mainly ethane and propane), and other gases such as nitrogen, helium, carbon dioxide, hydrogen sulfide, and water vapor as impurities. Natural gas does not need any chemical processing, only drying and some clean-up steps (EERE). Methane is the simplest hydrocarbon molecule, and is characterized, e.g., by clean soot-free combustion. The specific CO_2 emission of methane expressed in g CO_2/MJ is some 25% lower compared with gasoline and diesel.

Most natural gas engines operate on spark-ignition. Natural gas has a high octane number, which allows high compression ratios and improved efficiency when compared to a corresponding gasoline engine, but efficiency is still lower than that of diesel engines. Natural gas is lighter than air, and ignition temperature is high. However, a risk of explosion exists in closed spaces. Due to the high storage pressure level safety precautions are stricter than e.g., for LPG. (van Walwijk 1999). On the other hand, LPG is heavier than air, and this poses a safety risk. Normally compressed natural gas (CNG) vehicles can be parked in indoor and underground garages, whereas LPG vehicles are banned from indoor parking.

Gaseous natural gas has low volumetric energy density, but in liquid form this figure improves. Natural gas is stored on-board under high pressure, as CNG (200–240 bar), and sometimes also at low temperatures, as liquefied natural gas (LNG). In both cases these tanks are heavier and bigger than those of conventional liquid-fuel vehicles to reach the same driving range.

LNG is stored on-board at a pressure of 2–6 bar and at –161 °C. The insulated tank can hold the liquid for at least a week without any boil-off losses. (van Walwijk 1999)

From an end-use point of view cleaned biogas is equivalent to high quality natural gas. Biogas used in compressed systems has to cleaned for CO_2, moisture and corrosive impurities. Normally the methane concentration on cleaned biogas is >97%. CO_2 can be removed e.g., using water scrubbing.

Synthesis gas technology turns out an array of products, not only synthetic liquid hydrocarbons. Included on the list are, e.g., methanol, ammonia, dimethyl ether (DME), and even synthetic methane. Fuel DME is one option to utilize remote natural gas. DME is the least energy-intensive synfuel option. Natural gas based DME is, except for conventional diesel fuel, the most efficient fossil fuel on a well-to-well basis. (Jobson 2007)

Appendix 1 shows the properties of DME. It is a gaseous fuel, heavier than air. DME can be liquefied at a moderate pressure (5 bar at +20 ^{o}C). For its physical properties DME resembles LPG. However, DME has, unlike LPG, good ignition properties (high cetane), and is therefore suitable for the diesel process (Haldor-Topsøe 2007). However, DME is a difficult motor fuel because of the extremely low viscosity, low lubricity, and high volatility. Engine technology for DME is discussed in Chapter 6.

DME is not toxic, but it irritates the eyes and the respiratory system. Flammability limits for DME are wider than for CNG or LPG, thus stricter safety measures may be needed. Energy content of liquid DME is only about half of diesel oil, and thus DME needs bigger storage tanks to obtain equivalent driving distances.

Bio-DME is mainly developed by a Swedish Volvo–led consortium using spent cooking liquors from the pulp and paper industry as feedstock. (Landälv 2005)

Trends

Demand for natural gas is projected to increase in oncoming decades (Figure 4.11). This increase will come mainly from power and petrochemical sectors. Gas-to-liquid (GTL) plants will also influence the gas demand (IEA WEO 2006). In addition to piped natural gas, increased amounts of LNG will also be needed to meet the increased demand. The use of LNG from remote natural gas fields will increase shipping volumes.

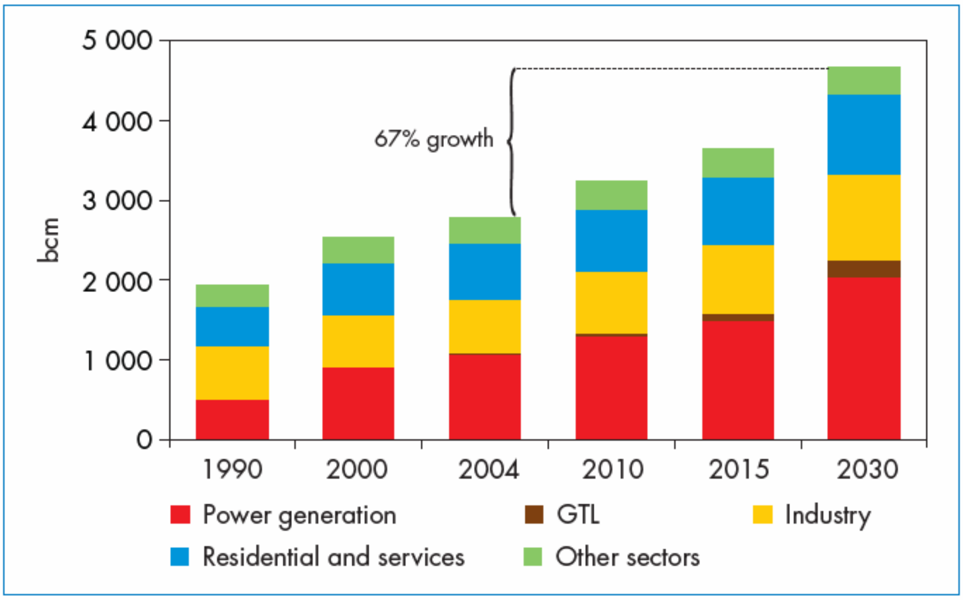


Figure 4.11. Global natural gas demand and future prospects (IEA WEO 2006).

The European Union has set a preliminary target for 10% natural gas usage in road transport by 2020 (Green Paper 2000). This would represent about 5% of the EU's total gas demand at that time. The European Natural Gas Vehicle Association has calculated that some 25 million CNG vehicles would be needed to fulfill the target, if the target is met with compressed natural gas only. (Seisler 2005)

Currently, fossil natural gas dominates in methane fuelled vehicles, but biogas could be used as well after proper purification. Feedstock for biogas can be waste (animal manure, waste water treatment sludge, etc.) or energy crops converted into methane. Production cost of biogas is normally higher than that of natural gas. Biogas can help meet biofuel targets and waste requirements (AFCG 2003).

The leading countries for biogas utilization in Europe are Germany, Sweden, Switzerland and UK (Jönsson 2004). Sweden and Switzerland have been leading a development where the biogas is upgraded to a quality at least on par with natural gas and suitable for direct use as a vehicle fuel, or allowing injection of pure bio-methane into the natural gas grid. In the latter case the natural gas refuelling network can be used to dispense biogas or "green gas". There are more than 10,000 methane vehicles in Sweden, and more than 50% of the methane used in vehicles is biogas. (Boisen 2006, 2007).

Boisen sees a great potential for biogas in general. According to Boisen, biogas potentials from 18 to 90 Mtoe/a have been reported for Europe for 2020. The latter figure, presented by the Altener BIOCOMM, equals 20% of the total EU-15 use of natural gas, or 29% of all fuel used in road transports. The two most important feed stocks are energy crops and manure. (Boisen 2006)

Originally DME was used as a propellant for aerosols. New production capacity for DME is being built. In Kushiro City, Japan, a pilot plant (100 tons/day) using direct synthesis technology has been in operation since 2003 (Oikawa et al. 2005). The Japanese company, Toyo, has been awarded several DME projects in China. The first was a 10,000 t/a plant which started in 2003, the second a 110,000 t/a plant which started in 2005. In late 2005, Toyo announced the contract for the Ningxia DME plant, which will have an initial production capacity of 210,000 tons of DME annually and is to be completed at the end of 2007. The facility will be part of a larger petrochemical complex (Green Car Congress 2005).

The main objective for DME production is to replace LPG in heating and cooking applications.

4.8 Hydrogen

Hydrogen, in parallel with electricity, is seen as the energy carrier for future society by some researchers. Hydrogen is the most abundant element in the world, and in principle, it can be processed from various sources (Figure 4.12). If hydrogen were to be processed from renewable sources, it would enable a carbon-free society. Zero tailpipe emissions could be obtained with fuel cells vehicles, as they emit only water. Hydrogen is non-toxic, but it raises many other safety issues.

Extensive programs and investments are directed to development of hydrogen technologies in the U.S., Japan as well as Europe. International co-operation on hydrogen is carried out within the IEA Implementing Agreements (www.iea.org, Hydrogen, Advanced Fuel Cells), International Partnership for the Hydrogen Economy

IPHE (http://www.iphe.net/) and The European Hydrogen and Fuel Cell Technology Platform (http://ec.europa.eu/research/energy/index_en.htm).

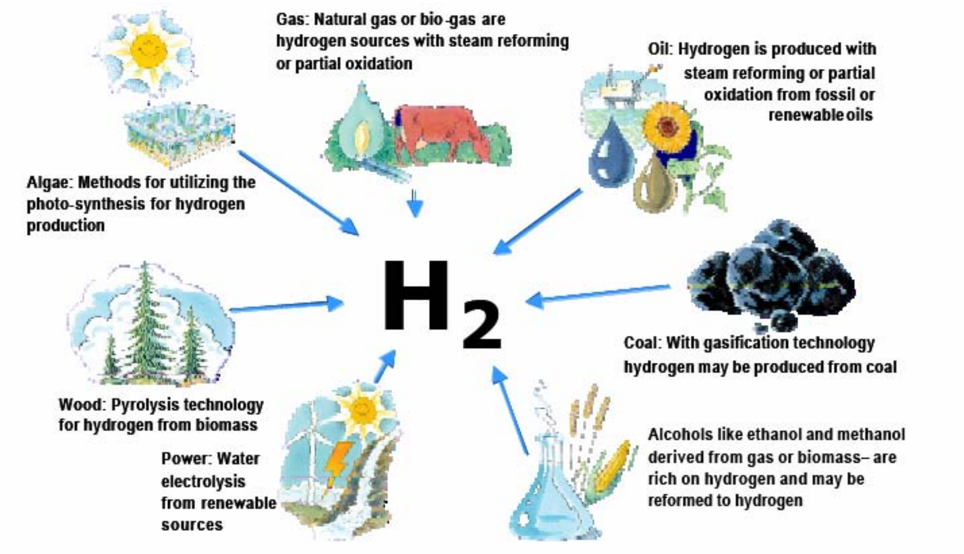


Figure 4.12. Examples of feedstock and process alternatives for hydrogen production (Riis et al. 2005).

Iceland is a special case targeting to become the world's first hydrogen-powered society within 40 years. Hydrogen in Iceland is based on geothermal energy.

> *Hydrogen*
>
> - *Various feedstocks can be used: energy-security*
> - *Carbon-free society possible*
> - *Zero-emission transportation possible*
> - *Problems with fundamental feasibility and costs of production*
> - *Challenges and high costs with distribution, storage, safety, and applications*

Currently industrial hydrogen comes mainly from natural gas (50% globally), oil, and coal. Industrial hydrogen production covers only about 1% of the world's total energy use. Electrolysis only accounts for some 4% of hydrogen production, and is very inefficient. Also packaging, storage, transfer, and delivery of hydrogen are energy-consuming when compared to liquid fuels. One analysis showed that with today's technology hydrogen from water electrolysis using non-renewable electricity would double greenhouse gas emissions compared with conventional gasoline. (Morris 2003).

The major barriers for large-scale market introduction of hydrogen are economical feasibility in general and sustainability of hydrogen production. Hydrogen can, in principle, be processed from various primary energy sources. Capability to use different indigenous primary energy sources would lead to increased global energy security. However, most of the advanced sustainable process technologies, including chemical, biological, electrolytic, photolytic, and thermo-chemical, are in different stages of development, and none of them is currently economically feasible or sustainable.

The IEA Hydrogen Co-ordination Group (HCG) prepared several analyses regarding hydrogen; one of those was reported as "Prospects for Hydrogen and Fuel Cells" (IEA 2005 b). Various technologies promise hydrogen production at costs of 10–15 USD/GJ, e.g., natural gas reforming below 15 USD/GJ and coal gasification (IGCC) with CCS at below 10 USD/GJ. Current hydrogen cost in decentralized production is over 50 USD/GJ. (Gielen & Simbolotti 2006)

One question is, whether hydrogen should be produced in large centralized facilities and distributed to service plants, or produced in decentralized facilities (or using reformers onboard a vehicle). MIT reports that decentralized gas reforming plants can provide hydrogen at lower cost than other options within the 2020 time frame (MacLean & Lave 2003). However, for fossil feedstock, centralized production might be essential to enable CO_2 capture and sequestration.

Natural gas is seen as a pathway to hydrogen society providing infrastructure for distribution of hydrogen in the future. One example is the "NaturalHy" program, organized by the Netherlands. They are testing distribution of hydrogen mixed with natural gas in existing natural gas pipelines. IEA (2005 b) reported that pipelines are practical options for hydrogen distribution, but using the natural gas pipelines is questionable. Mixes of methane and hydrogen are also known under the name of Hythane. Tests with Hythane for vehicles have been carried out in, e.g., Canada and Sweden.

Morris' study (2003) was a critical analysis of the reasonability of hydrogen, stating that too little attention is given to weaknesses of hydrogen. Putting all efforts into one basket may hinder the rise of better technologies. For instance, in the transport sector, flow of the investments to hydrogen infrastructure might prevent or slow-down development of mid-term solutions, such as hybrid electric vehicles. This dual energy solution would enable the use of another universal energy carrier, electricity, combined with liquid fuels that could be increasingly from renewable sources.

4.9 Legislation and standardization

National and regional legislation and standards set requirements for fuel quality. Many fuel properties are critical for the operation of engines and motor vehicles, and the properties also affect the emissions. Selected requirements for diesel fuel and gasoline for Europe, U.S., and Japan are presented in Appendix 2. The World Wide Fuel Charter

(WWFC 2006) of the vehicle and engine manufacturers is also an important document regarding fuel quality. The most stringent fuel quality category (Category 4) of WWFC is also shown in Appendix 2.

In Europe, the Directive 98/70/EC and its amendment 2003/17/EC include fuel requirements to ensure that gasoline and diesel fuel are suitable for vehicles as regards to exhaust emission control. These Directives only cover fuels containing a mineral oil portion of more than 70%.

In Europe, standards are not legally binding, but manufacturers of vehicles may require in their warranty statements that the fuel shall meet a specific standard. The European standards on transport fuels, EN 228 for gasoline and EN 590 for diesel, set a wider scale of fuel requirements to ensure many aspects of operability, safety, durability and performance (Appendix 2). For diesel fuel, the European Directive 2003/17/EC currently sets limit values only on a few properties: cetane number, density, 95% point of distillation, content of polycyclic aromatic hydrocarbons, and sulfur. The EN 590 standard for diesel fuel covers a wide scale of fuel properties like flash point, water content, copper strip corrosion, oxidation stability, lubricity, viscosity, and cold properties. In the U.S. and Japan, lower cetane numbers are permitted for diesel fuel than in Europe.

The gasoline quality requirements in the European Directive 2003/17/EC and in the European standard, in this case EN228, are more coherent than in the case of diesel fuel. Both include similar requirements for e.g., octane numbers and composition of gasoline.

Currently, both the fuels directive and EN 228 limits ethanol concentration in gasoline to 5% (volume). In the case of diesel fuel the fuels directive contains no direct limitations for biocomponents, but the EN 590 limits FAME concentration in ordinary diesel to 5% (volume). In 2006, 5% RME was allowed in the Swedish Environmental Class 1 diesel, which is known as the world's cleanest diesel fuel. This required modification of the Swedish specification for diesel fuel (Privata Affärer, 2006).

On January 31st 2007, the Commission proposed changes to the fuels Directive. Increasing the use of biofuels is included in the proposal. The proposal includes an obligation for fuel suppliers to reduce greenhouse gas emissions over the life-cycle of their fuels by 1% annually from 2011 onwards (on energy basis, compared to 2010 level). This will result in a 10% cut by 2020. A separate "high biofuel gasoline quality" will be established. This blend allows higher content of oxygenates, e.g. up to 10% ethanol. This blend will be clearly marked. To compensate for an increase in evaporative emissions due to greater use of ethanol, the Commission will put forward a proposal for the mandatory introduction of vapor recovery equipment at filling stations later in 2007. (Europa 2007c)

From January 2009, sulfur content of diesel fuel shall be maximum 10 ppm. This will cut primarily particulate matter emission, but also enables introduction of sophisticated emission-control devices. In addition, the maximum content of polyaromatic hydrocarbons (PAHs), will be reduced by one-third. The permitted sulfur content of diesel fuel for use by non-road machinery and inland waterway barges will also be substantially cut. (Europa 2007c)

In January 2001 and in June 2004, EPA finalized the highway diesel and non-road diesel rules, respectively, which will implement more stringent standards for new diesel engines and fuels. The rules mandate the use of lower sulfur fuels, meaning 15 ppm S for on-road diesel fuel starting 2006 and 500 ppm S for non-road diesel fuel starting 2007. These fuels will enable the use of after-treatment technologies for new diesel engines, which can reduce harmful emissions by 90% or more. After-treatment technologies will start phasing into the diesel sector beginning in 2007 for highway and 2011 for non-road. These programs will yield significant, long-term benefits for public health and the environment. (EPA 2006)

Thus 15 ppm sulphur automotive diesel called ultra-low sulfur diesel (ULSD) was introduced in 2006. The phase-in period ends in 2009. ULSD will be mandatory for use in model year 2007 and later on-road vehicles. Fuels with 500 ppm sulphur (low sulfur fuel) can still be used in older vehicles during the phase-in period.

4.9.1 Ethanol

In the U.S., there are three specifications related to fuel ethanol. ASTM D 5798, Standard Specification for Fuel Ethanol (Ed75-Ed85) for Automotive Spark-Ignition Engines, is the key specification used in the production of E85 fuel for flexible fuel ground vehicles with automotive spark-ignition engines. ASTM D 4814, Standard Specification for Automotive Spark-Ignition Engine Fuel, is the specification for automotive gasoline and its blends with up to 10 volume % ethanol. ASTM D 4806, Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel, is the specification for the ethanol intended to be blended with gasoline at 1 to 10 volume %. (ASTM 2007)

In Europe, the European Committee for Standardization CEN is working on standards for fuel ethanol. For ethanol used as blending component up to 5% in gasoline a draft standard prEN15376 is available. In CEN's system, a so-called CEN Workshop Agreement (CWA) is the lowest level of standards. A CWA is the first step towards a CEN standard. A CWA for E85, "Automotive fuels. Ethanol E85. Requirements and test methods, CWA 15293:2005", has been developed. (CEN 2007)

4.9.2 Fatty acid esters – traditional biodiesel

In Europe, e.g. in Austria, Germany and Italy, national specifications for rapeseed methyl ester (RME) have been available for a long time. In addition, the European specification, EN 14214, has been available since 2003 (Appendix 2). The specification applies only to fatty acid methyl esters, FAME (processed with methanol), used as neat in engines designed for FAME or as diesel fuel component. The EN 14214 standard specifies a minimum ester content of 96.5%.

Standards for biodiesel also exist in the U.S., Japan, Canada and Australia. The U.S. specification, ASTM D6751, has been available from 2002. This standard defines the use of fatty acid esters as blend components with middle distillate fuels, up to 10% in diesel fuel as accepted in the diesel specification (D975). Vegetable oils and animal fats can be used as feedstock, and any type of alcohol can be used in the production. An ASTM standard for a blend of 20% biodiesel and 80% diesel (B20) is planned. The U.S. military has developed own specification for B20 blends, CID-A-A-59693A (DieselNet).

In Japan, FAME is covered in two standards: "Law on the Quality Control of Gasoline and Other Fuels" and a voluntary Japanese Industrial Standard (JIS). The Quality Assurance Law allows up to 5% Fatty Acid Methyl Esters (FAME). The requirements cover sulfur content, cetane index, T90 distillation temperature, and upper limits on FAME and triglycerides, methanol, total acid number (TAN), low molecular weight acids, and oxidation stability.

In Canada, the biodiesel standard (CAN/CGSB-3.520) sets specification for blends of diesel fuel containing up to 5% of fatty acid esters. The biodiesel component shall meet ASTM D6751 or EN 14214 specifications. A specification for blends from B6 to B20 is being developed. Australia has published a fuel standard for biodiesel in 2003, a standard which is a combination of the ASTM D6751 and EN 14214 standards (DieselNet). The Engine Manufacturers Association, EMA, has defined a specification for B20 fuel, a blend of diesel and 20% of bioester. (EMA 2006)

4.9.3 Synthetic fuels

ASFE, the Alliance of Synthetic Fuels in Europe, has proposed to develop a specification for XTL fuels (synthetic biomass-, coal- and gas-to-liquids fuels) as a CEN Workshop Agreement. The CWA specification would be used on a voluntary basis supporting local regulations and international trade. In the longer term, a more formal standard could be developed depending on future volumes of XTL as automotive fuel. (XTL plan 2007)

4.9.4 Biofuel standards – global harmonization

Biofuels are becoming global trading commodities and there is a need for global harmonization of the quality standards. Thus Task Forces with experts from Brazil, the U.S. and Europe have been established. Their aim is to review existing documentary standards and identify areas where greater compatibility can be achieved in the short and long term.

As for biodiesel, there are many differences in biodiesel feedstock, use of fuels, vehicle fleet and regular diesel quality between Europe and the U.S. Consequently, the biodiesel specifications show many differences. Iodine value was chosen as an indicator for product stability in Europe. In addition, there are problems with some test methods in terms of precision, application and availability.

The goal of the task forces for on the harmonization of biofuel standardization is to submit a White Paper to the Brazilian, EC and U.S. authorities by the end of 2007. This document will be used as basis for the work at the ISO level to form global biofuel standards. (Biofuel Cities 2007)

4.9.5 Gaseous fuels

LPG is widely covered in standards in Europe, Japan as well as the U.S. In Europe, automotive LPG is specified by EN 589, Automotive fuels – LPG – Requirements and test methods (http://www.cen.eu/cenorm/homepage.htm).

The situation is more difficult for natural gas, as it is technically, as well as economically impossible, to specify a dedicated automotive gas quality. Therefore the vehicle manufacturers have to cope with the fact that natural gas composition varies from site to site.

5. Engine and vehicle technology

The internal combustion will be the prime mover for decades to come. Over the last 20 years focus has been on reducing emissions, in the future, fuel efficiency will become increasingly important. Electronic controls are crucial in improving engine performance. The complexity of engines and exhaust after-treatment system will increase, and high quality fuels will be needed. New combustion processes promising both improved fuel efficiency and reduced emissions are investigated.

Electrification will increase, both in auxiliaries and the powertrain itself. Hybridization helps to cut fuel consumption and well as emissions. The hydrogen fuelled fuel cell vehicle is often presented as the ultimate goal in vehicle development.

The internal combustion engine can be operated on a variety of fuels and fuel components. Some fuels require engine modifications whereas synthetic fuels resemble current fuel qualities and can be used in existing vehicles without modifications. Alcohols and gaseous fuels are suitable for spark-ignited engines, whereas vegetable oil and animal fat derivatives are suitable for diesel engines. In reality the options are rather limited. Over the years, engines, fuels and exhaust after-treatment systems have been tuned together for optimum performance. Changing one component, e.g. the fuel, dramatically, necessitates a recalibration of the other components. Compromising reliability, performance, efficiency, exhaust emissions, or safety is not acceptable when introducing a new fuel quality.

The current alternative vehicle numbers are LPG 10 million, FFV 10 million, CNG 7 million, hybrids 1.5 million, FCV less than 1,000 and DME less than 100. In 2030, hybrid penetration could be some 30% and the share of alternative fuels in transport 10–30%.

5.1 General

The development of internal combustion engines has been significant over the past 20 years. The role of electronic controls in performance enhancement has been crucial. The main emphasis has been given to the reduction of exhaust emissions. As for new gasoline passenger cars, exhaust emission levels are now well below 5% of the levels 20 years back. In the case of heavy-duty vehicles the progress has been somewhat slower.

The progress in fuel efficiency has not been as dramatic as in exhaust emissions. In the case of heavy-duty vehicles, the direct-injected diesel engine has been the predominant power source for many years. Direct-injection has also taken over diesel passenger cars and light-duty commercial vehicles. The share of diesel passenger cars in new car registrations in Europe is high, in the order of 50% (Schindler 2006). In Japan and the U.S. diesel passenger cars are practically non-existent. Direct fuel injection is making progress also into gasoline engines. In the coming years, more focus will be given to reducing fuel consumption. For example, the European Union will tighten its limits on passenger car CO_2 emissions. Figure 5.1 shows a projection for passenger car CO_2 emissions for different markets. For CO_2 emissions and fuel efficiency, Europe and Japan are way ahead the rest of the world.

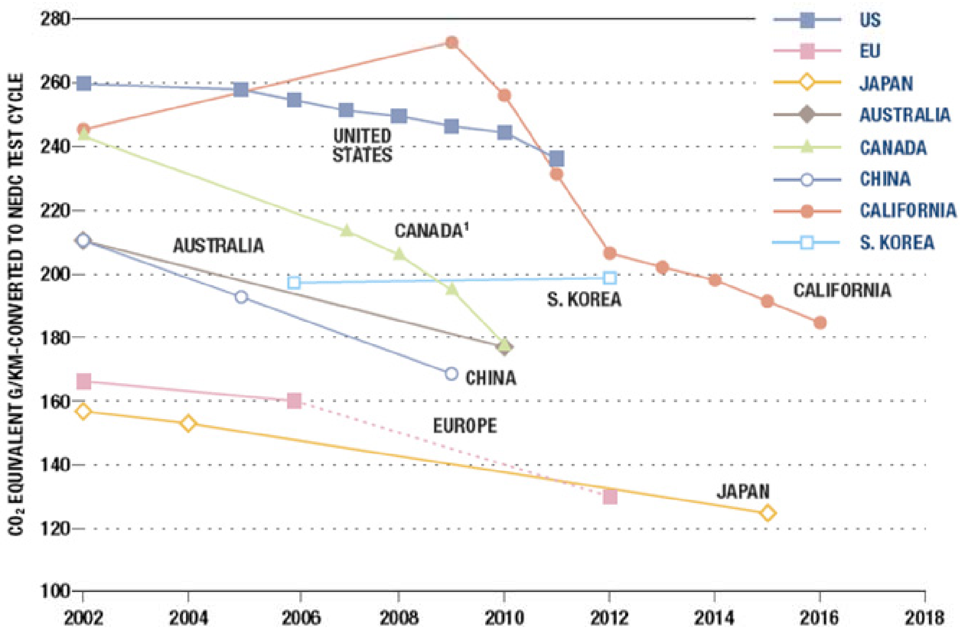


Figure 5.1. Actual and projected GHG emissions for new passenger vehicles by country, 2002–2018 (ICCT 2007).

Engine and fuel technology go hand in hand into the future. Exhaust after-treatment technologies are also a part of the solutions. Fuel properties always have to be in balance with the fuel requirements of the engines. A key question for the future is how engines and the fuel requirements of new types of engines will develop. Some technical improvements might increase fuel flexibility, while other new solutions, such as combined combustion systems, might require tailored or "boutique-type" fuels (Figure 5.2). Fuel cell vehicles fueled by hydrogen from renewable sources are often seen as the ultimate goal in transportation (Figure 5.3).

A multitude of fuel options presents a problem to the vehicle industry. It is very costly to develop and certify engines for a large number of fuels. Therefore, many auto manufactures favor synthetic fuels which provide fuel flexibility on the feedstock side rather than on the end-use side.

Hybrid technology makes it possible to save fuel by recovering braking energy. Lately, plug-in hybrids, charged over night and capable of traveling some distance in pure electric mode, have received a lot of attention. In general, hybrid vehicles are often seen a step towards fuel cell vehicles and full electric propulsion (see Figure 5.3).

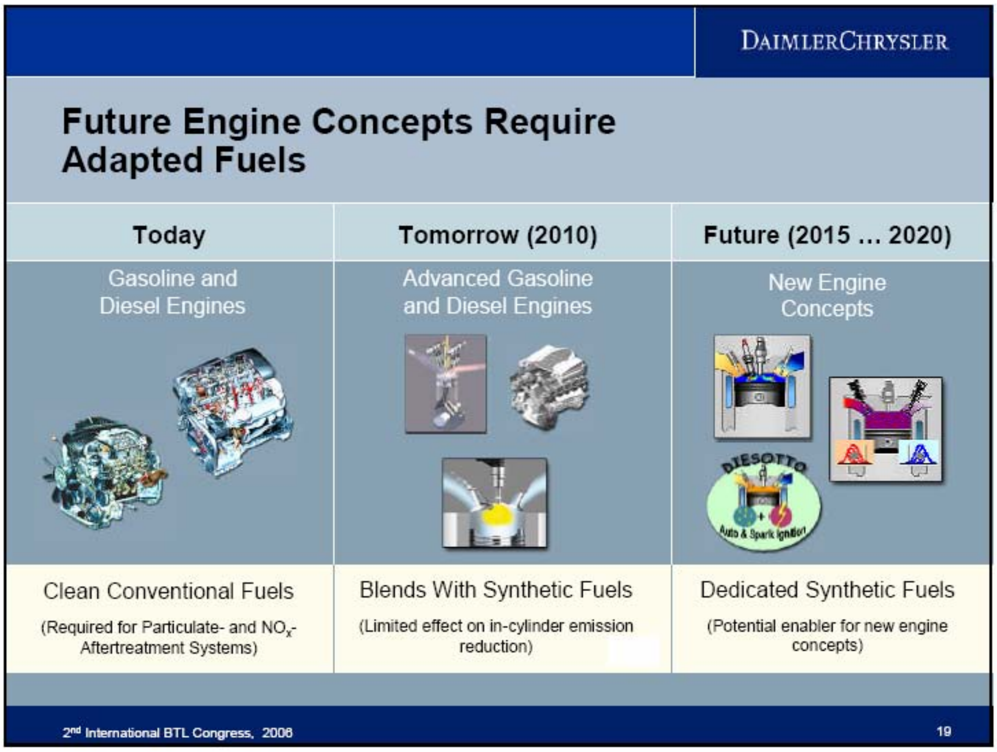


Figure 5.2. Changing fuel requirements (Keppeler 2006).

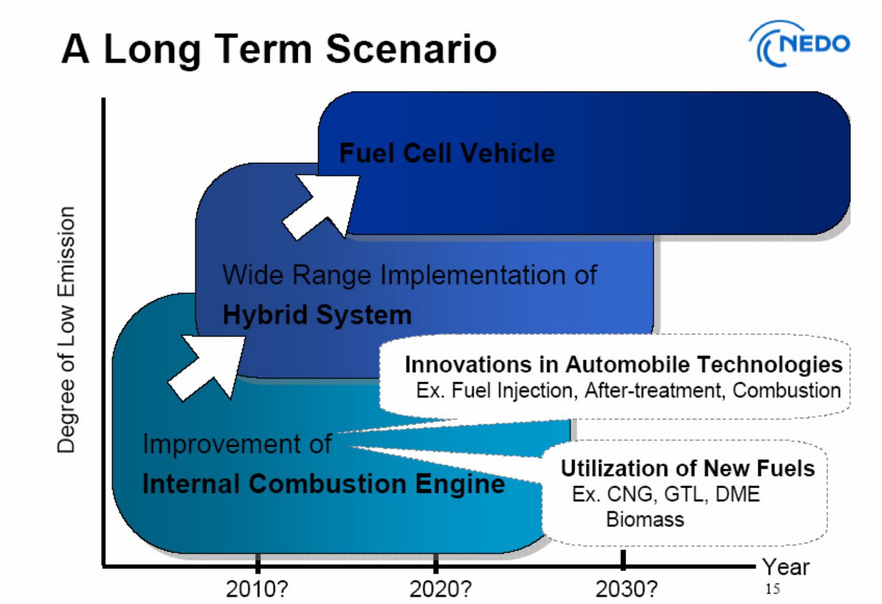


Figure 5.3. A road map for power train development (Tabata 2005).

5.2 Development trends for gasoline engines

Currently the dominating technology option for gasoline engines is stoichiometric combustion ($\lambda = 1$) in combination with indirect port fuel injection and a three-way catalyst, which reduces regulated emissions very efficiently. Conventional gasoline engines deliver lower fuel efficiency on part loads compared to diesel engines. This is mainly due to pumping losses induced by intake air throttling. Today many sophisticated gasoline engines feature variable valve timing or variable valve actuation to optimize engine characteristics and to increase part load efficiency. Gasoline direct injection improves performance in two ways. Power output increases as volumetric efficiency is improved and the risk for knock is reduced. Fuel efficiency, on the other hand, is improved as direct injection enables stratified charge and lean mixture operation on partial load.

Another current trend is turbocharging or supercharging. The newest development is two-stage charging using a combination of mechanical charger and turbocharger. Charging increases power output from a given engine displacement, but charging can also increase efficiency. In the latter case the swept volume of the engine is reduced to minimize losses in friction and auxiliaries and to reduce engine weight, while power output is retained through charging. This is often called engine downsizing. Downsizing is also used in current diesel engines.

5.3 Development trends for diesel engines

The diesel engine is the prime mover for heavy-duty vehicles all around the world. It has reached this position thanks to its good fuel efficiency and high reliability. In Europe, the diesel engine has a strong position also in light-duty vehicles. The downside of the conventional diesel engine is high emissions of both particles and nitrogen oxides. Thus, it can be said that the diesel engine faces greater challenges in meeting the emission regulations of 2010 and beyond than the gasoline engine. The diesel engine is becoming increasingly complex, with several exhaust after-treatment devices added to the engine. Many diesel manufacturers are, therefore, looking for alternative ways such as homogenous low-temperature combustion and special synthetic fuels like DME to meet the future challenges. Also, natural gas in fleets such as city buses will become increasingly competitive.

Looking at the engine itself, the diesel engine also has gained a lot from electronic controls. Increased injection pressures and accurate injection control have improved performance significantly. Ignition pressures on the order of 2000 bar are now common. The predominant technology in fuel injection today is the common rail system comprising a separate high-pressure pump, a hydraulic accumulator, and a rail connecting the electrically actuated injection nozzles. Very fast piezo-electric actuation makes it possible to divide the injection into 5–6 separate phases for optimized engine performance and minimum emissions (Figure 5.4). Almost all current automotive diesel engines are turbocharged and inter-cooled for enhanced performance. The number of control variables and actuators (variable geometry turbochargers, valve timing, exhaust control devices etc.) is increasing all the time. (Allain et al. 2007)

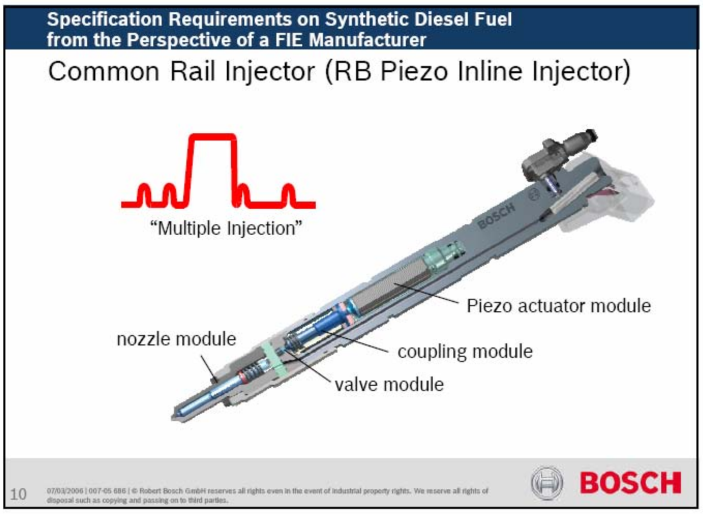


Figure 5.4. A Common Rail injector with piezo-electric actuation and phased injection (Stutzenberger 2006).

For conventional diesel engines, the basic problem is simultaneous reduction of nitrogen oxides and particles, as there is a well-known trade-off effect between NO_x and particles (as well as fuel consumption). The only way to really break this trade-off effect is to implement exhaust after-treatment technology. Figure 5.5 shows NO_x and PM control strategies for HD on-road vehicles. Emission regulations will tighten significantly from 2004/2005 to 2010.

Exhaust gas recirculation (EGR) is commonly used to lower combustion temperatures and thus suppress NO_x formation. However, the drawbacks of high EGR ratios are increased particle emissions and increased need for cooling. New combustion schemes, especially in combination with new types of fuels, might provide opportunities for performance enhancement.

An alternative technology for NO_x reduction is selective catalytic reduction (SCR). Urea is the most commonly used reducing agent. SCR technology makes it possible to reduce NO_x emissions by more than 80%. The great advantage of SCR technology is that engines can be tuned for high engine-out NO_x and low fuel consumption.

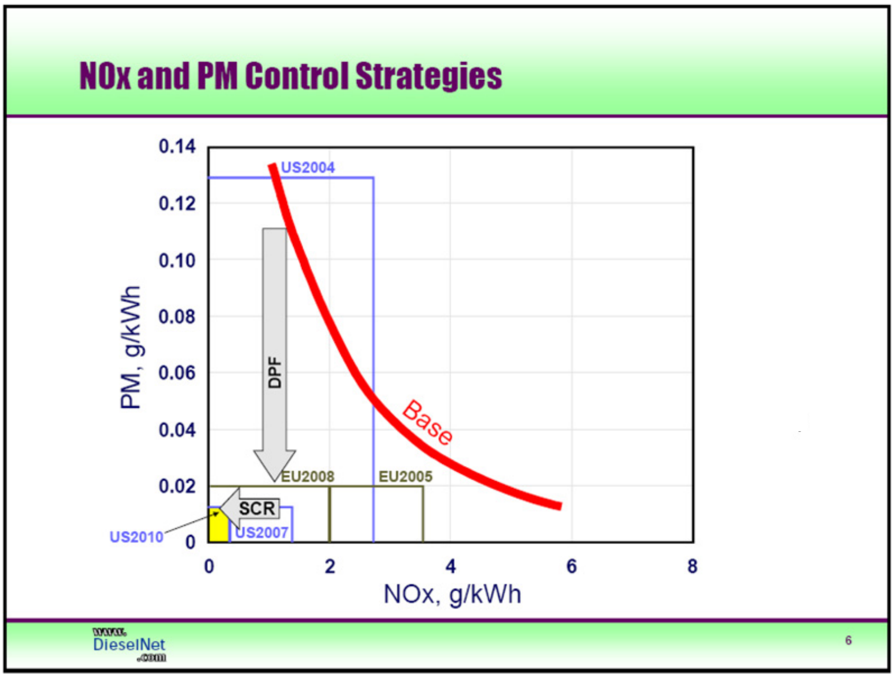


Figure 5.5. Emission reduction strategies for HD on-road vehicles. Base shows the trade-off between NO_x and PM for conventional diesel engines. (Majewski 2006)

For light-duty diesel vehicles, the combination of EGR and oxidation catalyst has been the predominant technology. (Peugeot/Citroen) has been the forerunner in introducing particle filters (DPF) for light-duty diesel vehicles. PSA uses a cerium-based additive to facilitate filter regeneration (PSA 2007). The light-duty Euro 5 emission regulations, entering into force in 2009, will in practice require particle filters on all diesel passenger cars.

Similar technology is also used in heavy-duty vehicles as all U.S. manufacturers use the combination of cooled EGR and particulate filter to meet the 2007 on-road heavy-duty emission requirements. The manufacturers have diverging views on technology to meet the 2010 on-road emission regulations. Detroit Diesel, a part of the Daimler group, is in favor of SCR technology, whereas Caterpillar, Cummins and International are trying to meet the 2010 emission regulations with improved combustion systems and without NO_x after-treatment (Aneja et al. 2007, Gehrke et al. 2007, Stanton 2007, International 2007).

Most of the European HD manufacturers have opted for SCR technology for Euro IV and Euro V and the voluntary EEV certification class. For Europe, SCR currently delivers better fuel efficiency than EGR. For the oncoming Euro VI regulation, roughly equivalent to U.S. 2010 and scheduled for 2013–2014, the Commission has predicted that fuel consumption will increase 2–3% (Enterprise and Industry 2007). In a presentation from 2005, Puetz (2005) predicts that all engines will eventually use a combination EGR, SCR and DPF.

PM emissions from diesel engines can, to a certain extent, be controlled by improving air handling, injection system performance, and fuel quality. However, exhaust after-treatment devices are needed to achieve significant PM reductions. Capturing the particles is not a big problem, the problem is rather how to burn the particles (soot) to prevent clogging of the filter. Both active (engine management, fuel injection, actual burners) and passive (catalyzed filters, NO_2, fuel borne catalysts) and combined systems can be used for regeneration. Overflow" or "slip" of NO_2 can be a problem with effective oxidation catalysts and catalyzed filters. Slip can occur when production of carbon and NO_2 is not in balance. Direct NO_2 emissions are detrimental for urban air quality.

Advanced combustion systems

The conventional combustion processes of spark and compression ignition engines can be replaced by a special low-temperature, combined auto-ignition combustion method where spontaneous auto-ignition occurs at several locations within the air-fuel mixture. In principle, there is no diffusion-controlled combustion phase and no development of a flame front in this auto-ignition burning method. Physical and chemical phenomena are similar to those of the classic engine combustion processes, but they occur at different pressure and temperature levels. (Stan & Guibert 2004)

A key parameter concerning combustion control through auto-ignition is the exhaust gas content in the cylinder charge. The fuel quality also affects success of the method. Auto-ignition combustion processes are being developed under different titles. Titles like Controlled Auto-Ignition (CAI), Combined Combustion System (CCS), Homogeneous Charge Compression Ignition (HCCI), and Pre-mixed Charge Compression Ignition (PCI, PCCI) are known (Ryan 2005, Seyfried 2005). A universal title low-temperature combustion (LTC) is also often used.

Conventional combustion produces both high NO_x due to high local flame temperatures and high PM emissions due to local lack of oxygen. In LTC combustion both NO_x and PM formation are suppressed. One of the key challenges is to expand the LTC operating range, as LTC operation today is possible only at moderate load (Figure 5.6).

So far, most LTC combustion experiments are limited to single-cylinder research engines. The research engines are often equipped with optical access to study injection and combustion processes. In the U.S., both Caterpillar and Cummins are working together with Sandia National Laboratory (Gehrke et al. 2007, Stanton 2007).

Many European research institutes are also working on new combustion systems, but mostly with a focus on light-duty applications. The theme was covered by the thematic network PREMTECH II "Efficient and low-emitting propulsion technologies."

PREMTECH II emphasises the interaction between the combustion concept and fuel quality. Advanced combustion will most probably require “tailored” fuels, i.e. synthetic, optimized fuels. (PREMTECH II 2005)

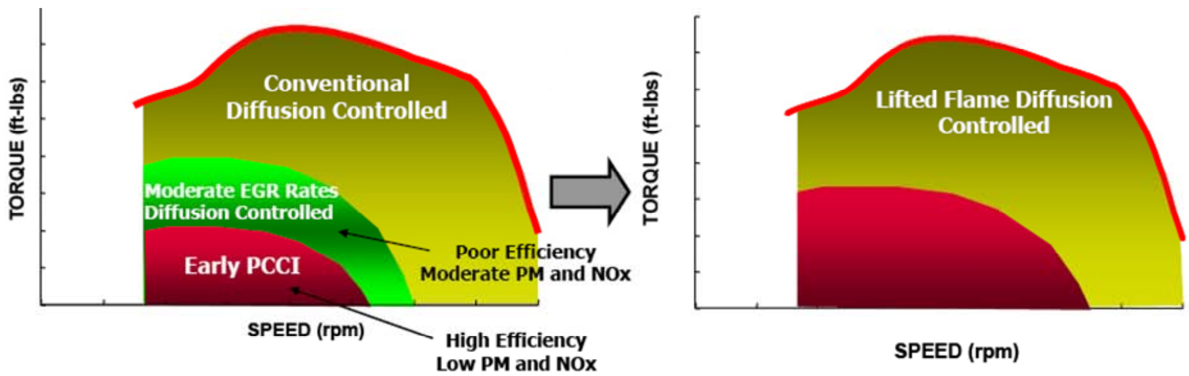


Figure 5.6. Expanding the operation range for low-temperature pre-mixed combustion (LTC/PCCI) (Stanton 2007).

For the future, Cummins is counting on significant efficiency improvement using a combination of advanced low-temperature combustion and other technical measures (Figure 5.7). The efficiency target for the U.S. DOE High Efficiency Clean Combustion (HECC) program is η > 50% for 2013. Cummins believes that advanced combustion systems, waste energy recovery, and electrically driven accessories can bring efficiency close to 60%.

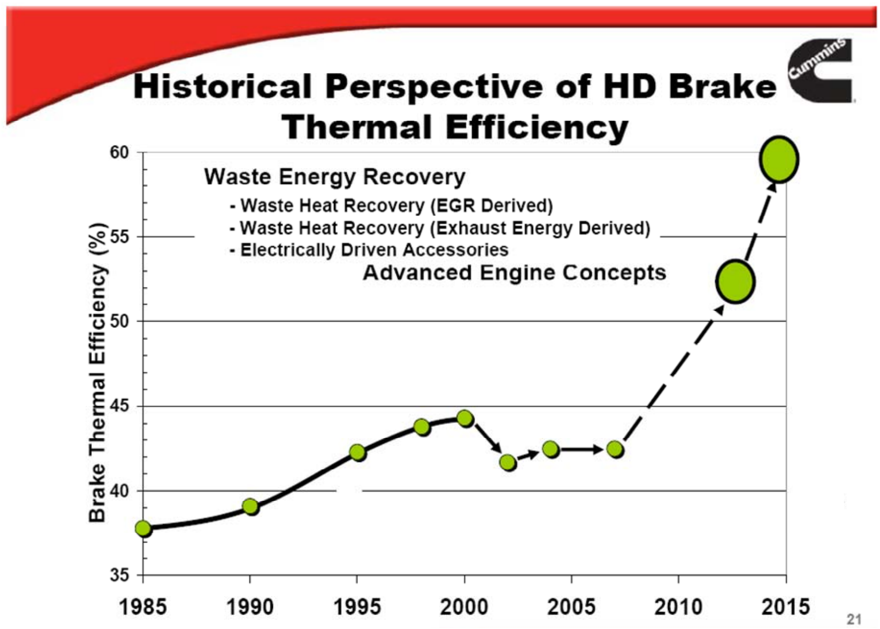


Figure 5.7. Projected increase in engine thermal efficiency (Eckerle 2007).

5.4 Engine and vehicle technology for alternative fuels

5.4.1 General

The internal combustion engine can, in principle, be operated on a variety of fuels and fuel components. Most biofuels – alcohols, biogas and biodiesel – can be used as motor fuels either as blending components or as is. Alcohols and gaseous fuels are suitable for spark-ignited engines, whereas vegetable oil and animal fat derivatives are suitable for diesel engines. Synthetic fuels resemble current fuel qualities and can be used in existing vehicles without modifications. The current production technologies for synthetic fuels emphasize diesel type products.

In reality the options are rather limited. Over the years, engines, fuels and exhaust after-treatment systems have been tuned together for optimum performance. Changing one component, e.g. the fuel, dramatically, necessitates a recalibration of the other components. Compromising reliability, performance, efficiency, exhaust emissions, or safety is not acceptable when introducing a new fuel quality. Some alternatives would be highly costly as new production capacity, refueling infrastructure as well as new vehicles would be needed.

Earlier, many alternative fuels provided benefits in reduced harmful exhaust emissions. Due to the great progress in engine, fuel and catalyst technology, emissions benefits from alternative fuels can no longer be taken for granted. Some biofuels may even increase emissions. However, some alternatives like methane, hydrogen, and some synthetic fuels still render emission benefits. For the future, the impacts of various fuels on greenhouse gas emissions will become an increasingly important issue. Fuel efficient vehicles, on the other hand, are currently a more cost effective way to reduce greenhouse gas emissions than to implement biofuels on a large scale.

Some alternative fuels or alternative fuel components can enhance engine performance. Ethanol and derivatives like ETBE are used to increase the octane rating of gasoline. Some synthetic diesel components have extremely high cetane, and FAME biodiesel can be used as a lubricity additive.

The dominance of conventional fuels (gasoline, diesel) is partly based on high energy density and easy storage. Limited operating range is a limiting factor especially in the case of gaseous fuels (see Figure 4.2). Also, ethanol requires larger fuel storage than conventional fuels – 1.7 times larger compared to diesel fuel.

5.4.2 Vehicle adaptation to alcohols

Alcohols (methanol, ethanol) can be used either for blending into gasoline and, with some preconditions, as a fuel itself. Alcohol is characterized by:

- high octane rating
- oxygen contained in the alcohol enhances combustion to some extent
- heat value 45–60% of that of gasoline
- high latent heat of evaporation
- poor lubricity
- increases gasoline vapor pressure when used for low-level blending
- polar compound, may cause corrosion
- modified engines can run on neat or almost neat alcohol.

Ethanol is widely used for blending into gasoline. With ethanol concentrations up to some 10% normally no vehicle modifications are needed.

Ethanol is preferred over methanol for better stability and water tolerance, smaller risk of corrosion, and lower toxicity. It is possible that methanol is phased out as a gasoline component. From an engine and an end-use point of view ethers are preferred over alcohols. Ethers have less affinity to water, are less corrosive and have less effect on vapor pressure than alcohols.

Diesel-ethanol emulsion fuels have been studied in Brazil, Sweden, and the U.S. In Brazil and the U.S. emulsion fuels have been approved for some special services. Adding ethanol to diesel lowers cetane number, lubricity and fuel stability. These issues can at least partly be addressed by using proper fuel additives. Additives cannot, however, alleviate the issue of flash point; even the addition of a small amount of ethanol lowers the flash point of the fuel so that for safety reasons it has to be treated in the same way as gasoline. This creates major problems in a working environment accustomed to handling diesel fuel (Nylund et al. 2005). One can, therefore, predict that diesel-ethanol emulsions will remain niche fuels.

Spark-ignition engines for neat alcohol

Alcohols have a long tradition as racing fuels. The cooling effect (high latent heat of evaporation) and high octane rating make it possible to increase engine output compared with gasoline. Gasoline engines can run on neat alcohol under the condition that fuel flow is increased significantly and that cold starting is facilitated. Startability on neat alcohol is poor due to low vapor pressure and high boiling temperature. For general use fuel alcohol is typically blended with 15% gasoline (E85, M85).

Electronically controlled fuel systems provide some fuel flexibility, meaning also that the engine can, based on closed-loop feedback, adjust to some variation in fuel composition. True Flexible Fuel Vehicles (FFVs) can operate on any fuel from gasoline up to 85% alcohol. The FFV system is requires a fuel detection system based on either a physical or virtual fuel sensor to determine fuel alcohol concentration. The alcohol fuel also has to be taken into consideration in choosing materials for the fuel system. Figure 5.8 lists necessary engine and fuel system modifications with increasing ethanol concentration. Gasoline blends containing 5% ethanol do not require modifications, whereas E85 fuel might require modifications for several components.

The added cost for a vehicle manufacturer to produce FFV vehicles is rather limited, especially since fuel detection today can be handled computationally without added hardware. Currently FFV vehicles are common in Brazil, Sweden and the U.S. FFVs have been a success especially in Brazil (de Carvalho 2006).

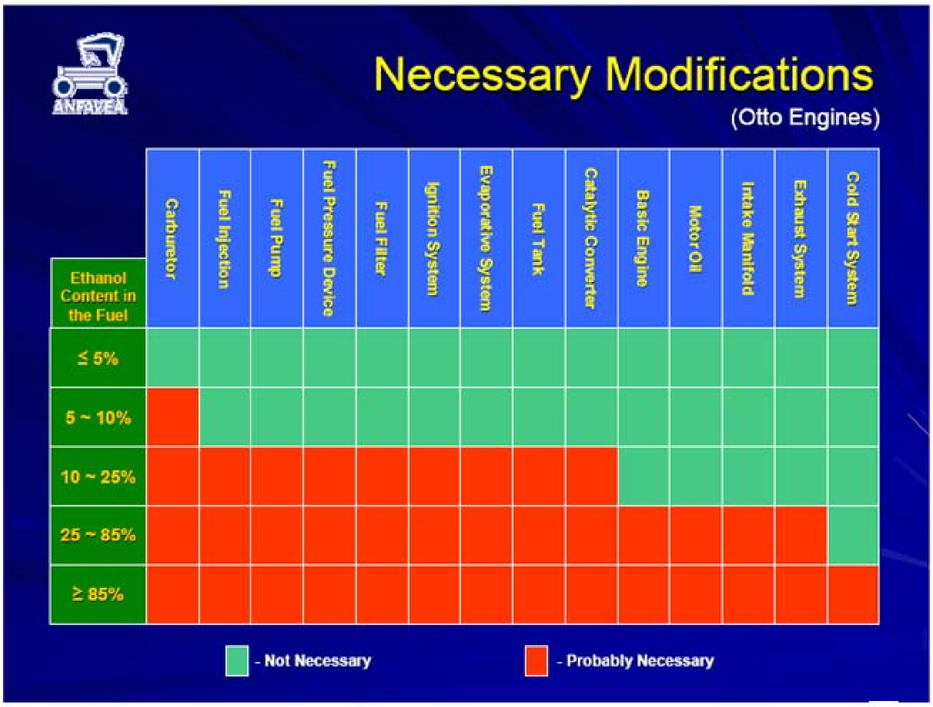


Figure 5.8. Modifications necessary with alcohol fuels (Joseph 2005).

FFV technology provides fuel flexibility at moderate cost, and therefore it can be expected that FFV vehicles will grow in numbers globally. Drawbacks of FFV technology include poor performance at low temperature and incompatibility with fuel direct injection. Using direct fuel injection spray and mixture formation very much depends on fuel properties such as evaporation characteristics, density, and viscosity. A direct injection tuned for gasoline will therefore not operate properly on E85.

With a standard size fuel tank, E85 will provide shorter range than gasoline (see Figure 4.2).

Alcohols in diesel engines

Alcohols as such are not suitable for diesel combustion, due to low ignition quality. If high-concentration alcohol is going to be used in compression ignition engines either the engine or the fuel has to be modified. In the past, Detroit Diesel manufactured glow-plug equipped heavy-duty engines to use methanol or ethanol, but due to many problems the production was discontinued.

Ethanol treated with ignition improver and lubricity additive can be used as fuel in conventional diesel engines, although some engine modifications are still needed. Since 1989 the Swedish company Scania has delivered altogether 600 buses for additive-treated ethanol. The engine modifications include, e.g., increased compression ratio (28:1), a special high-capacity fuel injection system, and a catalyst to control aldehyde emissions (Johansson 2006).

An ignition improver additive significantly increases the cost for running heavy-duty vehicles on ethanol fuels. Thus, it would be desirable to eliminate the need for this additive.

5.4.3 Vehicle adaptation to esterified biodiesel (FAME)

Conventional biodiesel can be used in diesel engines in the same way as ethanol can be used in spark-ignited engines, i.e., either as a blending component or as a fuel itself. As in the case of ethanol, using neat biodiesel may cause some problems, especially in cold conditions. Using neat FAME might require some modifications to the engine, mainly changes in gaskets, hoses, and elastomers. FAME is a strong solvent, and can dissolve deposits in the fuel systems of old vehicles, causing clogging of fuel filters.

One issue regarding FAME that has arisen recently is the incompatibility with vehicles equipped with particle filters. In light-duty applications, the manufacturers periodically use late injection to increase exhaust temperature and facilitate particle filter regeneration. With high boiling FAME, there is a risk for fuel dilution of the engine oil. This again can lead to engine seizures. Some contaminants in FAME, such as phosphorus, can contribute to filter clogging. (VDA 2006)

Straight vegetable oil is not suited for conventional high speed diesel engines.

5.4.4 Vehicle adaptation to synthetic fuels

Synthetic fuels derived from natural gas, biomass, and even coal are high quality fuels, attractive for use in a diesel engine. The FT diesel fuel has no sulfur, almost no aromatics, and a high cetane number. FT diesel provides excellent emission performance with reduced NO_x and PM emissions. The FT diesels, GTL, CTL, and BTL may take a leading position on market, depending on e.g., price and technology development.

From an end-use point of view synthetic fuels are a convenient option as no engine modifications are needed. FT fuels can be used as a blending component or even as is. In the latter case lubricity additives may be needed. Running on pure FT diesel an engine's power output can be reduced somewhat (5%) due to low fuel density. An engine can be run on 100% synthetic diesel with standard settings, and this will reduce NO_x and PM emissions. Alternatively, at least in theory, the engine manufacturer could recalibrate the engine to give improved fuel efficiency at a given emission level.

Vegetable oils and animal fats can be converted into a product resembling FT diesel using hydrogenation. Tailored synthetic fuels might be the only option to meet the fuel requirements of future advanced combustion systems (see 5.3).

Fischer-Tropsch can also render gasoline components. Little information is available on the performance of FT gasoline. Rehnlund (2007) reports that FT gasoline does not provide the same kind of performance benefits as FT diesel.

5.4.5 Vehicle adaptation to gaseous fuels

Gaseous fuels like methane, propane, and butane are inherently clean-burning fuels, which in favorable conditions give a soot-free combustion and less harmful exhaust components than conventional liquid hydrocarbon fuels. Gaseous fuels do not provide the same flexibility as liquid fuels. Most engines using gaseous fuels are either dedicated engines optimized for one specific fuel or bi-fuel engines capable of running on either gasoline or the gaseous fuel.

Natural gas (methane)

Methane (and LPG) is well suited for spark-ignition engines. It is relatively easy to convert a gasoline engine to gaseous fuels. The main components of a gaseous fuel system are fuel tanks, pressure regulators, and the gas feed system. However, to achieve low overall exhaust emissions, advanced engine technologies and control systems have to be applied. Engines which work well in steady-state emission testing do not necessarily perform so well in real life service involving a lot of transient operation. Current regulations require engines operating on gaseous fuels to comply with on-board-diagnostics (OBD) regulations.

The power loss switching from gasoline to e.g., natural gas using a simple conversion system is in the order of 10%. Power loss can be avoided either by charging the engine or by optimizing the engine for natural gas by increasing the compression ratio. Increasing the compression ratio is possible due to the high octane rating of methane.

Most heavy-duty gas engines of today are diesel engines converted to spark-ignition, Otto cycle engines. At this stage, there is still room for technical improvements to enhance the emission performance, efficiency, and to some extent, even the reliability of natural gas fuelled engines and vehicles. In normal service, current gas engines can consume 25–35% more energy than their diesel counterparts. New engine technologies and electronics like variable valve timing, EGR, skip-fire etc. can help to enhance the performance of gas engines. Ultimately, when the level of technical sophistication of heavy-duty gas engines is at the same level as for the conventional technologies, natural gas engines should have clear advantages from an environmental point of view, both regarding toxic and CO_2 emissions, over conventional fuels.

Westport Innovations has actively developed direct injection for natural gas engines to improve fuel efficiency. The direct injection systems for natural gas rely on late-cycle high-pressure injection of gas into the combustion chamber. Natural gas has a higher ignition temperature than diesel, and therefore, an ignition aid (diesel pilot spray) is needed (Westport). Westport Innovations is working together with several engine manufacturers, e.g., Cummins, Isuzu, and MAN, but Westport’s technology has not been commercialized yet.

Methane is normally stored under pressure (typically 200 bar, compressed natural gas CNG). In light-duty vehicles and city buses CNG can provide sufficient cruising range, but CNG is not suited for long-haul trucks. LNG delivers more range, and LNG is used in some trucking operations in the U.S. For energy density, LNG is roughly equivalent to ethanol (Figure 4.2). International standards are in place to secure safety of high pressure CNG components and installations.

LPG

From an engine point of view, natural gas and LPG are roughly equivalent, although natural gas (methane) has higher octane rating than LPG. Due to lower pressure, LPG refueling and storage (typically 10 bar) is technically easier compared with natural gas (typically 200 bar). However, for safety reasons, natural gas is often preferred over LPG, regardless of the higher pressure level. LPG is heavier than air; natural gas is lighter. In a possible leak situation natural gas vents off easily, whereas LPG can accumulate e.g., in floor drains.

DME

DME is clean-burning, sulfur-free, with extremely low particulate emissions. DME resembles LPG in many ways. DME, however, has good ignition quality, and is therefore suited for diesel combustion. A dedicated DME vehicle might not require a particulate filter but would need a purpose-designed fuel handling and injection system, as well as a lubricating additive (Green Car Congress 2006b).

Originally DME was used as a propellant for aerosols. Appendix 1 shows the properties of DME in comparison with diesel fuel. DME is a rather difficult-to-use motor fuel because of the extremely low viscosity, low lubricity, and high volatility. For a diesel engine, special high-pressure injection systems with anti-leak systems have to be designed. Low lubricity and cavitation in various parts of the fuel system may also cause problems.

At least the following companies have been involved in development of DME engines or equipment for DME engines: AVL (Austria), Denso, Nissan Diesel, TNO (Holland), and Volvo. Nissan Diesel has demonstrated a DME truck with a conventional in-line type injection pump (Oikawa et al. 2005). Volvo, on the other hand, has implemented common-rail injection when developing a DME engine within the European AFFORHD project (McCandless 2004).

Hydrogen

A primary advantage of hydrogen over other fuels is that its only major oxidation product is water vapor; its use produces no CO_2. Combustion of hydrogen in air can result in the formation of NO_x, but it may be reduced down to low levels by a proper design and operation (MacLean & Lave 2003). Fuel cell vehicles are discussed in Chapter 5.5.4.

Because fuel cell powerplants are not likely to reach the power level of high power internal combustion engines, an early market introduction of hydrogen in the automotive sector could be facilitated by a faster parallel build-up of vehicles with hydrogen powered internal combustion engines. Therefore the U.S. DOE has put hydrogen fuelled ICE vehicles on the agenda as a way to speed up hydrogen infrastructure development. FC vehicles are still too expensive and too low in numbers to really drive the process (Goguen 2004). The link-up of gasoline and hydrogen with bi-fuelled gasoline/hydrogen vehicles would also allow a smooth market introduction.

The energy content of hydrogen is low on a volume basis. It can be stored as a gas, a cryogenic liquid, using a solid, or with a carbon-based medium, such as methanol or hydrocarbon fuels. Boil-off is a specific problem with liquid hydrogen (MacLean & Lave 2003).

BMW has worked on hydrogen for ICEs since 1982. One of the key features of hydrogen as a fuel for ICEs is the possibility to run on extremely lean mixtures without a need to throttle the engine (Peschka 2004). The Hydrogen 7 is BMW's latest BMW hydrogen-powered demonstrator. The vehicle is equipped with a 6 liter V12 bi-fuel engine delivering 191 kW on both gasoline and hydrogen. The hydrogen fuel is stored in liquid form. Range on hydrogen is 200 km, and in addition the car has a gasoline tank for 500 km (BMW 2007).

Earlier on BMW had a hydrogen demonstrator with a PEM fuel cell unit serving as an auxiliary power unit (APU) to produce electricity for subsystems such as air conditioning even when the ICE was switched off.

MAN has built hydrogen fuelled buses. Since 2005, two vehicles, one with an ICE and one with a fuel cell engine, have been operational on the Munich airport. The hydrogen ICE engine is based on MAN's natural gas engine. MAN will also deliver hydrogen fuelled buses to Berlin. In 2008, 14 buses should be in service. MAN is developing a new turbocharged, lean-burn hydrogen engine with direct fuel injection. Power output is 200 kW, and maximum thermal efficiency 40%. (MAN 2007)

Ford is also working on hydrogen fuelled ICE vehicles. Ford Motor announced it will begin production of its commercial hydrogen-powered internal combustion engine shuttle buses. Eight of the E-450 shuttle buses will go to tourist destinations in Florida. The 12-passenger shuttle is equipped with a 110 l gasoline equivalent, 350 bar hydrogen fuel tank supplied by Dynetek. The E-450 is propelled by a re-engineered version of Ford's 6.8-liter V-10 engine. (Green Car Congress 2006c)

5.5 Alternative power trains

5.5.1 General

Many experts predict a switch from mechanical power trains towards electric powertrains (see Figure 5.3). Full electric powertrain means among other things more accurate control, less emissions, and more freedom in designing the architecture of the vehicle.

Battery electric vehicles are going through still waters for the moment. These vehicles have not been able to meet the expectations on performance and operating range. However, recently many new battery electric initiatives have been launched e.g., in France and Japan, and a comeback is expected around 2010. Development is focused on lithium-ion batteries.

Sales of hybrid vehicles are increasing rapidly, although the absolute numbers are still small. Hybrid vehicles provide the autonomy that battery electric vehicles lack. The great advantage of autonomous hybrid technology is the possibility to reduce both energy consumption and exhaust emissions without the need for new infrastructure. Hybrid technology as such is fuel neutral.

The newest trend for hybrid vehicles is plug-in hybrids with increased energy storage capacity providing additional electric-only range. If ample power supply is available and progress in battery technology is made, plug-in hybrids could increase the amount of electric energy in transport significantly.

Future market penetration of fuel cell vehicles depends on many issues such as availability of hydrogen, hydrogen refueling infrastructure, and cost and reliability of fuel cell power plants.

5.5.2 Hybrid technology

There are several viable configuration options for hybrid vehicles. However, most systems so far have good compatibility to traditional powertrains. Japan is the forerunner in hybrid applications for passenger cars. In the U.S., the manufacturers are now introducing hybrid systems for sport utility vehicles (SUVs). The French manufacturer PSA has announced the first diesel hybrid passenger car (PSA 2007). In the heavy vehicle sector, hybrid propulsion systems are mostly used in city buses, but hybrid systems are becoming available also for delivery vehicles and small size trucks.

All types of vehicles benefit from hybridization. In relative terms, the biggest fuel efficiency gains are achieved for gasoline engines and spark-ignited gas engines. The efficiency improvements with hybrid technology in conjunction with ICEs are due to two major advantages. Firstly, hybrid technology makes it possible to smooth out the operation of the ICE and to run the ICE on loads providing best fuel efficiency. Secondly, recuperating braking energy otherwise lost as heat, significantly contributes to improved efficiency. In the case of fuel cell vehicles hybridization increases the durability of the fuel cell engine significantly by smoothing loads.

Fuel savings using HEV systems are dependent on the duty cycles. City bus services, with regular stop-and-go driving patterns, are ideal for hybrid applications. Fuel savings of more than 30% can be achieved (Chandler & Walkowicz 2006).

As there are several different types of hybrid vehicles, the hybrid-electric drive definition is aggravated by the fact that the technology has many forms and different labels to describe them. The highest level distinction can be made based on the power flow in the powertrain. This divides the vehicle designs into two categories – series and parallel hybrid designs. Both of them are currently commercialized, and each has its advantages.

In the series hybrid system the ICE and the electric motor provide equivalent amounts of work. In the parallel hybrid system the ICE dominates while the electric motor provides assistance. In mixed systems the ratio is variable (Figure 5.9).

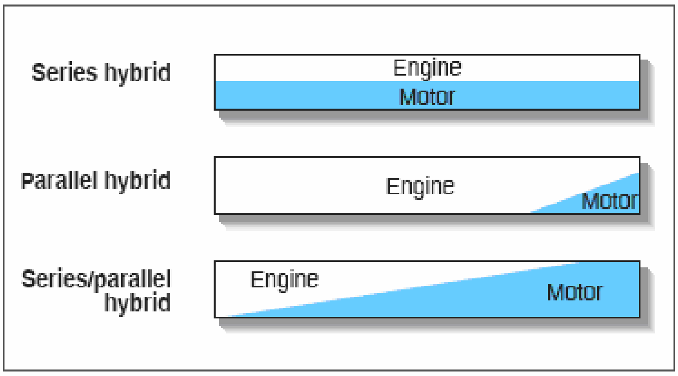


Figure 5.9. Contribution of ICE and electric motor in different hybrid systems (Toyota 2003).

The best known hybrid vehicle Toyota Prius utilizes a rather complicated mixed system. The system comprises a battery pack, two inverters, two electric motors/generators, and a mechanical power-split device based on planetary gears. The smaller electric motor on the crankshaft acts as starter and generator. The second electric motor is the actual traction motor. The power of the ICE is 57 kW and the power of the traction motor 50 kW. (http://www.toyota.com/prius/index.html)

Honda is also providing hybrid vehicles, currently two models, the Civic and the Insight. These vehicles are parallel hybrids with simpler configuration than the Prius. In the case of the Civic the power of the ICE is 70 kW and the power of the electric motor 15 kW. (http://automobiles.honda.com/civic-hybrid/)

Allison Transmissions, which is a part of the GM group, is supplying parallel hybrid systems for buses. Two systems are available, E^P40 and E^P50. For accelerations, maximum power output (ICE + electric motor) is 261 kW and 298 kW, respectively.

Allison does not state the power of the electric motor directly, but the power rating of the inverter unit is 150 kW. (Allison 2007).

A hybrid vehicle is more complicated and more difficult to manufacture compared with conventional vehicles. The battery and battery recycling are of crucial importance in the whole process. Lead-acid batteries are being replaced by more advanced battery types. Currently recycling of NiCd, Ni-MH and Li-ion batteries is still in its infancy. Toxic emissions can be generated during the life cycle of a battery. These emissions might become a problem when hybrid vehicles really penetrate the market. (Hybrids for road transport 2005)

Super-capacitors may be a solution for energy storage when high power density and high cycle numbers are needed rather than high energy density. Capacitors store energy in an electrostatic field rather than as a chemical state as in batteries. Super-capacitors, or ultra-capacitors as they are also called, look very much like batteries. They have a low energy density of less than 15 Wh/kg but a very high power density of 4,000 W/kg. Typical specification for automotive applications is 10 to 200 Farads and 100 Volts. They are very fast in charge and discharge, and can be charged and discharged in seconds. Expected life is more than 500,000 cycles. (mpower)

Plug-in hybrids are now receiving a lot of attention, especially in the U.S. A plug-in hybrid electric vehicle (PHEV) is a hybrid which has additional battery capacity and the ability to be recharged from an external electrical outlet. PHEVs are commonly called "grid-connected hybrids," "gas-optional hybrids" (GO-HEVs), "full hybrids," and are sometimes called HEV-30 (for instance, to denote a hybrid with a 30-mile (50 km) electric range, compared to a HEV-0 (a non-plug-in hybrid). However, Ford, GM, and Toyota have all used the term "Full Hybrid Technology" to describe configurations that allow electric-only operation at low speeds.

PHEVs can also operate in a mixed-mode where both gasoline and external electricity are used simultaneously to increase gasoline mileage for a particular range, usually at least double that of its electric-only range, but highly dependent upon the stage length between rechargings. Compared to conventional vehicles, PHEVs can reduce air pollution and dependence on petroleum, and lessen greenhouse gas emissions that contribute to global warming. Plug-in hybrids use no fossil fuel during their all-electric range if their batteries are charged from renewable energy sources. Other benefits include improved energy security, fewer fill-ups at the filling station, the convenience of home recharging, opportunities to provide emergency backup power in the home, and vehicle to grid applications. (Wikipedia a)

As of September 2007, plug-in hybrid passenger vehicles are not yet in production. However, Toyota, General Motors, Ford, and Chinese automaker BYD Auto have announced their intention to introduce production PHEV automobiles. BYD expects to introduce their PHEV-60 sedan in the second half of 2008. Toyota Prius and General Motors plug-ins are expected in 2010. Conversion kits and services are available to convert production model hybrid vehicles to PHEVs. Most PHEVs on the road in the U.S. are conversions of models from 2004 or later of the Toyota Prius hybrid car, which have had plug-in charging added and their electric-only range extended. (Wikipedia a)

5.5.3 Electric vehicles

The battery electric car has been around as long as the internal combustion engine car. Production numbers of battery-electric vehicles have never been high. With the exception of the 1907–1937 Detroit Electric car, production numbers have typically been in the range of 100–1,000 units. Historically, EVs have had issues with high battery costs, limited travel distance between battery recharging, charging time, and battery lifespan, which have limited widespread adoption. Toyota, Honda, Ford and General Motors all produced EVs in the 90s in order to comply with the California Air Resources Board's Zero Emission Vehicle Mandate. In the 90s some 5,000 electric vehicles were supplied for California, but only some 1,000 remain in service. GM produced the extravagant EV-1 electric vehicle. In Europe, companies like PSA (Peugeot/Citroen) and Renault offered battery-electric cars. Ford acquired the Norwegian electric car company Th!nk, but production was discontinued. (www.evworld.com, Wikipedia b)

Deep-cycle lead batteries are expensive and have a shorter life than the vehicle itself, typically needing replacement every 3 years. Ongoing battery technology advancements have addressed many of the problems related to EVs; many models have recently been prototyped, and a handful of future production models have been announced. Nowadays nearly all new EVs incorporate less-toxic NiMH or lithium battery packs, which will be valued in case the batteries need to be exchanged. (Wikipedia b)

Tethered vehicles are one form of electric vehicles. Trolley buses are used in many places around the world, e.g., in Holland, Switzerland, Eastern Europe, and China, but also in North-America, both in Canada and the U.S. Up-to-date vehicles are supplied by companies like Irisbus and New Flyer.

5.5.4 Fuel cell vehicles

A fuel cell (FC) is a device that generates electricity through an electrochemical process in which the energy stored in a fuel is converted directly into DC electricity. Because electrical energy is generated without combusting fuel, fuel cells are extremely attractive from an environmental stand point. All fuel cells have the same basic operating principle. An input fuel is catalytically reacted (electrons removed from the fuel elements) in the fuel cell to create an electric current. A single fuel cell generates a very limited amount of power (electricity). In practice, many fuel cells are usually assembled into a stack. (DoD Fuel cell)

The stack itself has no moving parts. However, a power unit in a vehicle or in a power plant needs handling systems for fuel and oxygen, fuel recirculation and after-treatment circuits, a cooling system, humidifier, start-up devices, and electronics for control and power shaping. Typical components are reformer, various blowers, heat exchangers, afterburners etc. The auxiliaries, often called "balance-of-plant" (BOP) can make up 50–70% of the total system cost.

The following characteristics are attributed to fuel cells (Fuel Cells Canada 2006):

- Fuel cells produce energy through electrochemical conversion of the fuel
    - they produce zero or very low emissions, depending on the fuel used.
- Fuel cells produce power at efficiencies much higher than conventional power systems such as the internal combustion engine.
    - this efficiency contributes to the environmental benefits of the fuel cell.
- Fuel cells have few moving parts and thus require minimal maintenance, reducing life cycle costs of energy production.
- Fuel cells operate efficiently at part load and in all size configurations.
- Fuel cells are modular in design, offering flexibility in size and efficiencies in manufacturing.

The basic fuel for fuel cells is hydrogen. The low-temperature Proton Exchange Membrane (PEM) fuel cell used for vehicles operates with pure hydrogen only. A fuel processor or reformer is needed when using other fuels than hydrogen (hydrocarbons, alcohols). Interest has moved away from reformer-based systems to the direct use of hydrogen. Currently fuel cells require very pure hydrogen. The issues of fuel quality and fuel quality requirements have to be addressed before FC vehicles can enter the general market.

Figure 5.10 shows the operating principle of a PEM fuel cell (as well as a phosphoric acid fuel cell PAFC). PEM fuel cells work with a polymer electrolyte in the form of a thin, permeable sheet. Efficiency is approximately 40 to 50%, and operating temperature is approximately 80 °C. Cell outputs generally range from 50 to 250 kW. The solid, flexible electrolyte will not leak or crack and these cells operate at a low enough temperature to make them suitable for homes and cars.

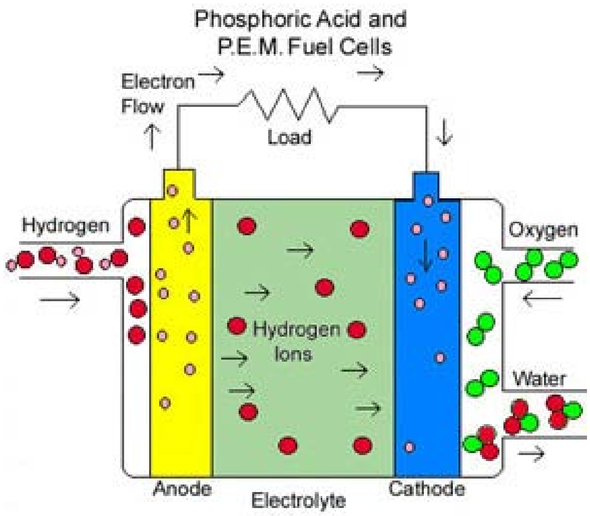


Figure 5.10. The working principle of PAFC and PEM fuel cells (Smithsonian 2001).

The fuel cell is an interesting power source option for future road vehicles. The main features of hydrogen-fuelled FCs are zero emissions and higher efficiency compared with gasoline engines especially on partial loads. The main challenges currently are high price and limited durability.

In the long run FC engines may become a serious competitor to internal combustion engines. Ten years intensive development of FC technology has brought FC vehicles to the point where more or less "one-off" vehicles have been thoroughly tested, and the most advanced manufacturers are moving into limited series production of tens of vehicles. Demonstrations are under way especially in California and Japan, and FC vehicles are also demonstrated in cities like Washington D.C., Singapore, and Berlin. Many automotive manufacturers (OEMs) have demonstrated their interest in FC vehicles. Regarding passenger cars, e.g., former Daimler-Chrysler, Ford, GM, Honda, and Toyota are active in FC vehicle development. GM believes that it can start selling FC vehicles within 4–9 years. Honda has announced that the company will start limited sales of FC vehicles already in 2008. (www.hyweb.de/News/gazette.html)

Figure 5.11 shows Honda's newest FCX fuel cell vehicle. Technical data for the car is presented in Table 5.1.

Table 5.1. Technical data for Honda FCX (Honda 2007).

Number of passengers		4
Motor	Max. Output	95kW (129PS)
	Max. Torque	256N•m (26.1kg•m)
	Type	AC synchronous motor (Honda mfg.)
Fuel Cell Stack	Type	PEFC(proton exchange membrane fuel cell, Honda mfg.)
	Output	100kW
Fuel	Type	Compressed hydrogen
	Storage	High-pressure hydrogen tank (350atm)
	Tank Capacity	171*l*
Dimensions (L×W×H)		4,760 × 1,865 × 1,445mm
Max. Speed		160km/h
Energy Storage		Lithium Ion Battery
Vehicle Range*		570km

For heavy-duty vehicles, included on the list are manufacturers like EvoBus, Hino, Irisbus, MAN, Neoplan, New Flyer, Nova Bus, and Van Hool. EvoBus produced more than 30 Mercedes-Benz Citaro FC buses for the CUTE project (CUTE 2006).

Figure 5.11. Honda's new FCX fuel cell vehicle launched in September 2006.

The greenhouse gas emissions related to hydrogen production are decisive for the overall well-to-wheel emissions for hydrogen pathways. Depending on the process used for hydrogen production, the emissions vary in a wide range. Apparently, hydrogen produced from non-fossil sources offers low overall GHG emissions but, for example, CO_2 capture and sequestration could reduce the level of GHG emissions from fossil hydrogen pathways.

5.6 Status and outlook for alternative vehicle technologies

5.6.1 General

The world vehicle population is some 800 million (Manufacturing Exec 2007). The vehicle population in EU 25 is 247 million, 237 million in US, 75 million in Japan, 26 million in China, and 29 million in Russia (Statistical Pocketbook 2006). Figure 5.12 shows a projection for light-duty vehicle numbers, with a tripling of vehicles by 2050.

Current world transportation fuel use is estimated at some 1,600 million tons/a (IFP 2007). The share of alternative fuels is rather limited, on the order of 55 million toe/a, i.e. some 3% of the total usage. The amount of biofuels is some 20 million toe/a, i.e. less than 1.5% of the total usage. The most important alternative transportation fuels, in order of volume, are ethanol, LPG, natural gas, and biodiesel. Ethanol and LPG are equal in size (see Table 5.3). Methanol is used as a gasoline blending component in the form of MTBE. Synthetic fuels are produced from natural gas and coal in a couple of plants.

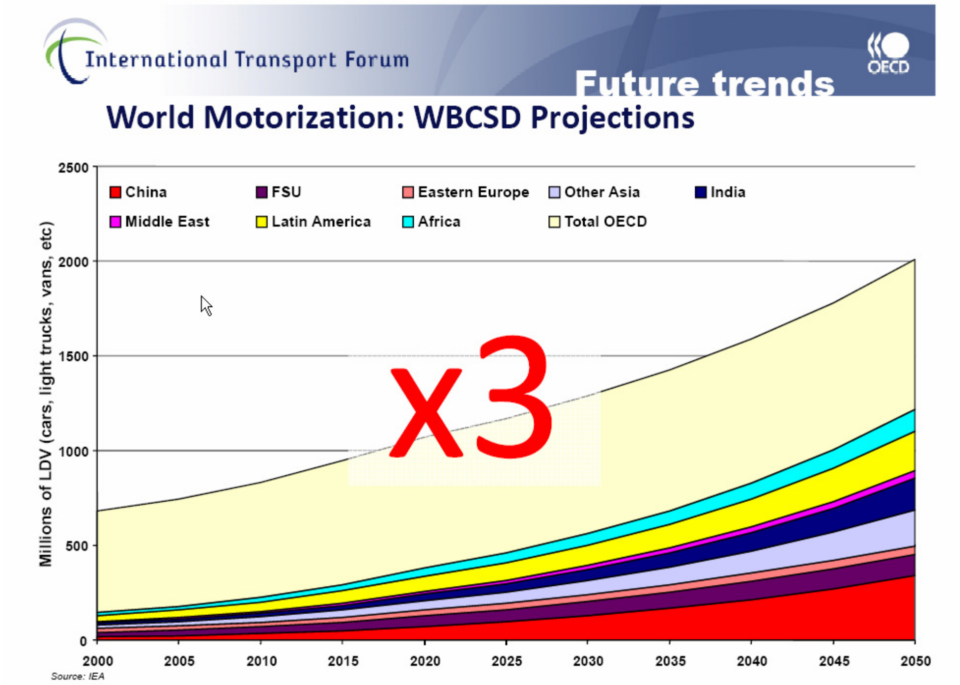


Figure 5.12. Projections for world light-duty vehicle numbers (Short 2007).

Diesel is currently the main fuel for heavy-duty vehicles. In Europe, the share of diesel passenger cars is increasing rapidly. The average share of diesels in new registrations was some 50% in 2005. All European manufacturers are interested in introducing diesel passenger cars also to the North American market. DaimlerChrysler, Audi, and Volkswagen have jointly established the BLUETEC brand name as the designation for clean diesel passenger cars and SUVs marketed in the U.S. and Canada. Diesels eligible for sales in all 50 U.S. states, will be launched in 2008 (as model year 2009 vehicles). (DieselNet 2006)

If the European trend for diesels continues and spreads, this will have an impact on the future portfolio of transportation fuels. However, there are several studies showing that the dieselization trend will not go on forever. Automotive News Europe/Italiaspeed report that share of diesel cars will be some 65% of European new-car sales by 2010, but fall below 40% after 2015. Rinolfi from Fiat Research Centre points out that to meet the limits beyond 2010 diesels will need costly exhaust after-treatment equipment. This may lead the diesel share to drop below 40% of the European market after 2015. (Italiaspeed 2006)

A study by TIAX and Global Insight, "The Future of Heavy-Duty Powertrains", predicts that HCCI will power nearly 40% of heavy-duty vehicles by 2020 (Table 5.2), and that 20% of the heavy-duty vehicles will be equipped with a hybrid power train (Global Insight 2005). Large scale implementation of HCCI type combustion will also have impacts on the fuel pool.

Table 5.2. Heavy-duty engine technology projection for 2020. (Global Insight 2005). Bottoming cycle diesel means an engine with a combined cycle system to recover waste heat and turn it into mechanical or electrical power.

Global Market Shares of Engine Technologies
Baseline Scenario 2020

Conventional but Highly Evolved Diesel	Advanced, Bottoming-Cycle Diesel	Mixed-Mode HCCI	Full HCCI	Spark Ignition
30%	*25%*	*15%*	*25%*	*5%*

In the U.S., the EIA is maintaining a database for alternative fuel vehicles and hybrids. In this database detailed information on vehicle numbers can be found. The dominating technology is FFV vehicles, with some 750,000 vehicle delivered in 2005. The second largest group was hybrids with some 140,000 vehicles. Only some thousand of vehicles on gaseous fuels were delivered. The total fleet of FFVs in the U.S. is more than 6 million units.

Table 5.3. Estimated numbers of alternative fuel vehicles in use in the U.S. (EIA 2007).

Fuel Type	2003	2004	2005
Compressed Natural Gas (CNG)	114,406	118,532	117,699
Electric [a]	47,485	49,536	51,398
Ethanol, 85 percent (E85) [b, c]	179,090	211,800	246,363
Hydrogen	9	43	119
Liquefied Natural Gas (LNG)	2,640	2,717	2,748
Liquefied Petroleum Gas (LPG)	190,369	182,864	173,795
Other Fuels[d]	0	0	3
Total	533,999	565,492	592,125

Table 5.3 shows numbers of vehicles running on alternative fuels. In fact, very few FFVs, some 250,000 units, actually ran on E85 in 2005. For the auto manufacturers,

FFVs are a loophole in the CAFE requirements as basically only the gasoline portion of E85 is taken into account (Wuebben 2005).

In Japan, the Organization for the Promotion of Low Emission Vehicles (LEVO) keeps track of vehicle numbers. There, both clean and fuel efficient conventional vehicles, alternative fuel vehicles, and hybrids are considered low emission vehicles (Table 5.4). In the case of Japan, clean fuel efficient conventional gasoline vehicles totally dominate the low emission vehicle listing.

Table 5.4. Low emission vehicle numbers in Japan (Takada 2007).

Current Penetration on LEVs in Japan

	Methanol 1)	CNG 2)	Hybrid 3)	EV 4)	Clean Energy Vehicle 5) *	TOTAL
Passenger Vehicle	–	1,447	341,971	246	14,434,224	14,777,888
Truck LD MD, HD	576	4,127 14,008	4,185	17	586,590	609,503
Bus	–	1,329	329	1	–	1,659
Special Vehicle	–	2,901	–	13	–	2,914
Small V.	–	7,650	403	248	8,064,682	8,072,98.
TOTAL	576	31,462	346,888	525	23,085,496	**23,464,947**

As of March 2007

Source : 1) LEVO (Cumulative Total Number)
2) The Japan Gas Association (JGA)
3) / 4) Japan Automobile Research Institute (JARI) – As of March 2006 (Estimated Number)
5) Japan Automobile Manufactures Association, Inc. (JAMA) – FY2000-FY2006 (Cumulative Total Number)
*:Vehicles that already meet recommended fuel economy targets for 2010 and are certified as low-emission vehicles (LEVs) in compliance with an official LEV certification procedure.

LEVO

5.6.2 Hybrid vehicles

World hybrid vehicle sales in 2006 were some 380,000 units. Vehicle numbers for 2006 were 255,000 for the U.S., 89,000 for Japan and 40,000 for Europe. In 2006, only three manufacturers offered hybrid vehicles, Toyota/Lexus, Honda and Ford. On the U.S. market, the market shares were 75, 15 and 10%, respectively.

The hybrid car market, although modest in terms of the overall light-vehicle market, is growing steadily. This growth is a result of penetration of the hybrid car into the U.S. and Japanese Markets. In Europe, hybrid car sales remain relatively low due largely to a lack of general consumer awareness and limited product choice. (Hybridcar 2007, Takada 2007)

Figure 5.13 shows the development of hybrid vehicle sales in the U.S. In the past five years the number of hybrid sales numbers in the U.S. grew tenfold from some 9,500 in 2000 to 83,000 in 2004. According to the Electric Drive Transport Association (EDTA), hybrid sales more than doubled from 2004 to 2005, then again with a more moderate increase from 2005 to 2006. The figures from the Electric Drive Transport Association and from Hybridcar differ somewhat from EIA's figures.

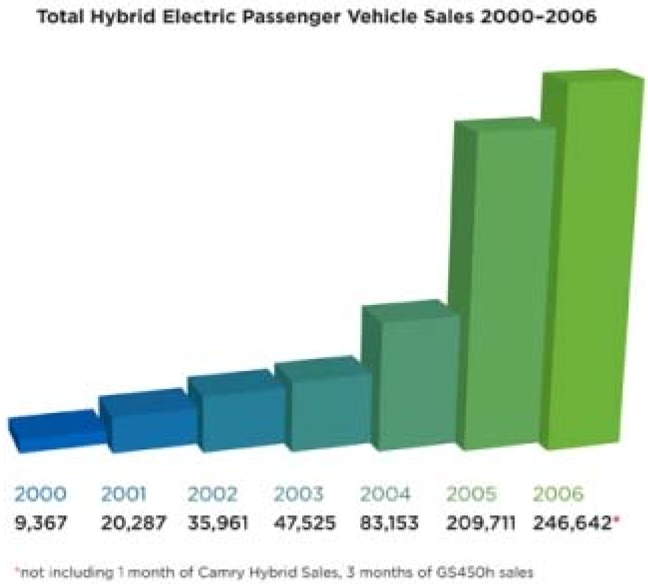


Figure 5.13. U.S. hybrid vehicle sales (EDTA 2007).

J.D. Power and Associates predicts a sales figure of 345,000 units for 2007. This would represent a market share of around 2%. (J.D. Power 2007)

Researchers are divided regarding the long-term growth potential of the hybrid car market. J.D. Power and Associates estimate the hybrid car market will account for 3.5% of the U.S. market by 2010. Other researchers give more optimistic projection for the market. ABI Research & Automotive Technology Research Group sees the hybrid market penetration at between 5–6% of the overall U.S. light-vehicle market. According to the most recent update of the J.D. Power and Associates Automotive Forecasting Services Hybrid-Electric Vehicle OutlookSM, U.S. hybrid-electric vehicle sales volumes are anticipated to grow by 268 percent between 2005 and 2012. Hybrid vehicle sales are expected to grow from approximately 212,000 vehicles in 2005 to 780,000 by 2012. In 2007 there were 15 hybrid models available in the U.S. market. By 2012 this number is likely to increase to over 50 models. (Hybridcar 2007)

In Japan, the current hybrid vehicle population is some 350,000 units, and sales in 2006 were some 90,000 units. (Takada 2007)

In 2006 European hybrid sales totaled 39,880 units with Toyota/Lexus accounting for over 91 percent of the market. Toyota's hybrid car sales reached 36,470 units in 2006, with cumulative European sales reaching 69,674 units. Honda hybrid sales reached 3,410 units in 2006 up 154% over 2005 hybrid sales of 1,345 units. Cumulative sales (2000–2006) of Honda hybrids in Europe totals over 8,000 units. (Hybridcar 2007)

The European manufacturers have been slow in implementing hybrid technology. One of the reasons for this is focus on fuel efficient diesel vehicles. PSA (Peugeot/Citroen) has announced that it will bring diesel hybrids based on Peugeot 308 and Citroen C4 consuming only 3.4 litres of fuel per 100 km on the market in 2010. (PSA 2007)

No exact figures on heavy-duty hybrid vehicles are available. The total number is probably in the range on some thousands of units (New York has some 400 hybrid buses). Allison Transmission has delivered some 500 hybrid systems to Canada and the U.S., and signed the first deal to supply hybrid systems for Europe in September 2006. (Green Car Congress 2006d)

The total number of hybrid trucks and buses in Japan is some 4,500. A rather wide selection of hybrid vehicles is available in Japan.

The dissemination of hybrid vehicles is, contrary to many other alternative technologies, not hindered by the need of new infrastructure. So far, the hybrid vehicles are designed for conventional fuels – gasoline and diesel. There are, however, no serious obstacles why hybrid technology could not be applied to, e.g., FFV vehicles or natural gas vehicles. In fact, the 2006 Well-to-wheel study by EUCAR, Concawe, and JRC points out that especially natural gas vehicles would benefit from hybridization (WTW 2006). Most probably some U.S. hybrids are already capable of running on E85.

IEA's WEO 2006 contains some projections on vehicle technology (Figure 5.14). Today some 75% of the fleet is fuelled by gasoline and 25% by diesel. Hybrids do not show at the world level yet. In the Base Case Scenario, the share of hybrids is only some percent units in 2015, whereas in the Alternative Policy Scenario the share of hybrid could be as high as 20%. The corresponding figures for 2030 are 8% and 76%, respectively.

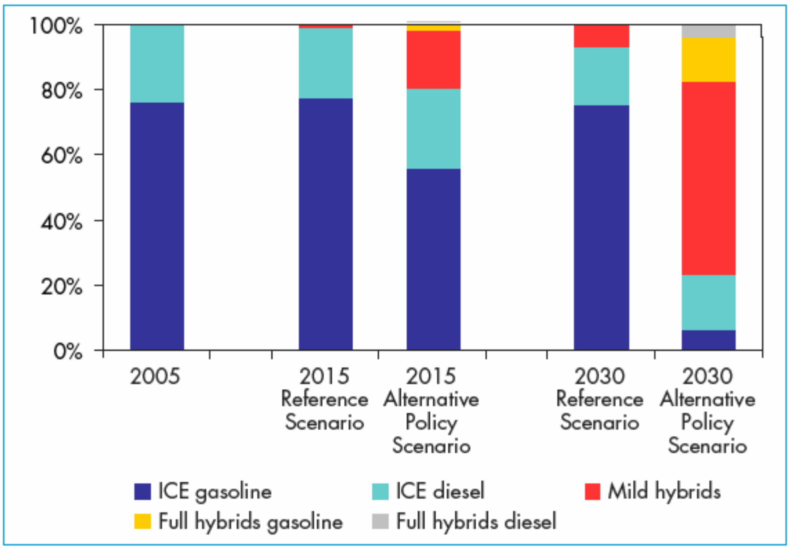


Figure 5.14. IEA 2006 WEO 2006 projections for vehicle technology (IEA WEO 2006).

Exxon Mobil predicts that hybrids with advanced ICEs will account for 30% of the new vehicle sales in the U.S. by 2030 (Figure 5.15).

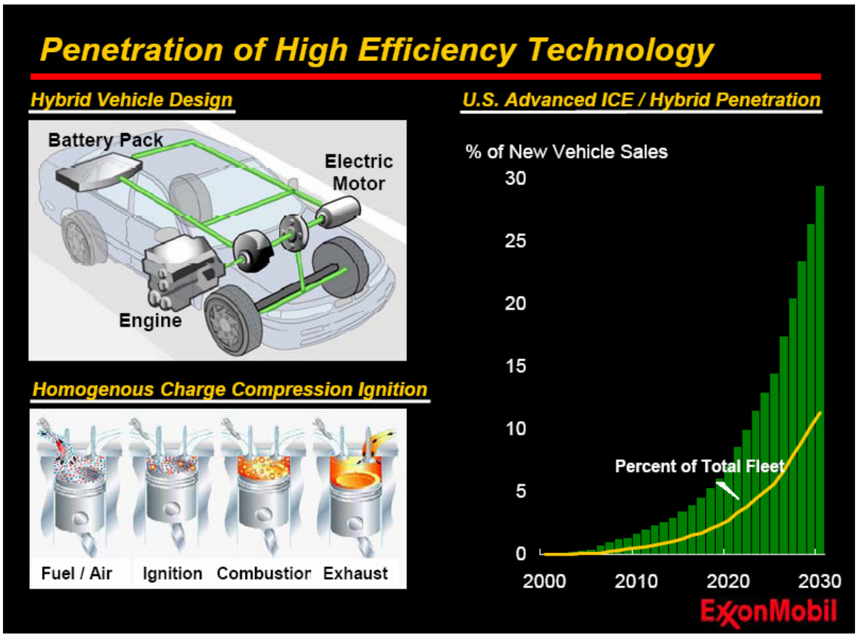


Figure 5.15. Exxon Mobil's prediction of high efficiency vehicle penetration in the U.S. (ExxonMobil 2006).

5.6.3 Electric vehicles

The supply of battery-electric vehicles has almost disappeared, although new models are expected by 2010. In Japan, the sales of EVs dropped to only 3 units in 2005 (Takada 2006b). In France, only 6 EVs were sold in 2005 (ADEME 2006). According to EIA figures, some low-speed, neighborhood electric vehicles or electric bicycles were supplied in the U.S. (AFDS 2006).

The reasons for this development are, on one hand, insufficient performance and range, and on the other hand, advances in hybrid vehicle technology. However, battery electric vehicles will profit of the development in hybrid vehicles, especially in plug-in hybrids with increased battery capacity. As for pure battery electric vehicles, in 2005 Mitsubishi and Subaru announced that they will launch lithium-ion battery equipped small cars before 2010. Toyota is also working on EVs (www.evworld.com). SVE (Société de véhicules électriques), an electric vehicle developer jointly created by the French companies Heuliez and Dassault, is working through a company called Cleanova which is developing an EV based on the small Renault Kangoo van. The Kangoo will also be available with a small range-extender ICE (www.clenova.com).

Washington DC is planning a 25 million USD project to bring back trolley buses that last rumbled along its streets during the 60s. The revival will begin next year with a 2-mile line in southeastern Washington. City planners are looking beyond the dreams of nostalgia buffs for trolleys to help spur economic development, cut pollution, and ease traffic congestion. (The New York Sun, December 29, 2006).

5.6.4 Alcohol vehicles

Alcohol vehicles are one of the largest categories of alternative fuelled vehicles in the world. Only in the U.S. there are more than 6 million FFVs capable of running on ethanol fuel. However, a totally different question is how many of these vehicles actually run on E85 fuel.

The situation in Brazil is different, as alcohol fuels are actually used in large volumes. Brazil's Proalcool program started back in 1975. All gasoline sold in Brazil contains 20–25% ethanol by law. E100 technology was introduced in 1980, FFV technology in 2003. FFV vehicles provide several benefits compared with the old neat ethanol vehicles.

FFV numbers are growing rapidly. Brazil started producing FFVs in March 2003. In 2003, 49,000 units were sold. FFV numbers reached 1 million in November 2005, 2 million in August 2006, and 3 million in March 2007 (ICIS Chemical Business 2007).

Figure 5.16 shows monthly sales of FFVs. In 2006, 8 manufacturers were offering altogether 43 different FFV models for the Brazilian market (Henry Joseph Jr. 2006). Some manufacturers even offer vehicles that can run on gasoline, ethanol, and natural gas. Now FFVs account for close to 90% of passenger car sales.

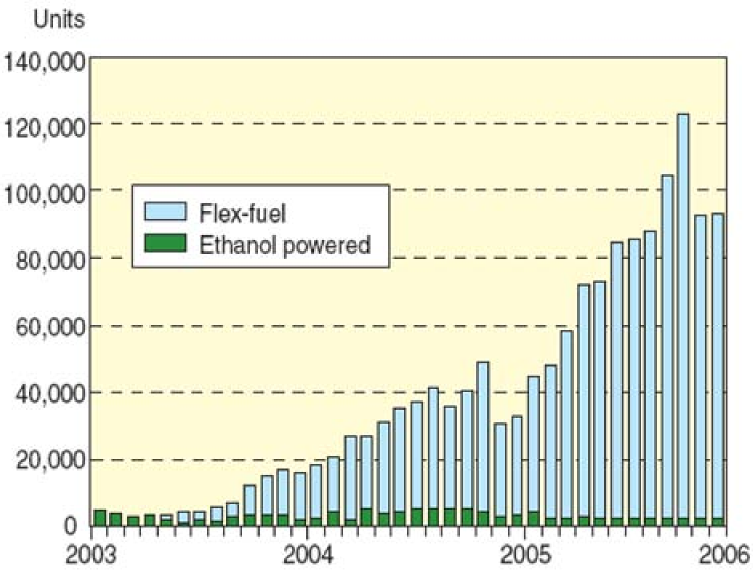


Figure 5.16. Brazilian alcohol fuel vehicle sales (IFP 2007).

Today FFVs totally dominate the supply of alternative fuel light-duty vehicles in the U.S. The EPAct listing of AFVs for 2007 includes 29 different FFV models, but only one CNG model. GM and Ford have discontinued their lines of OEM natural gas vehicles. (EPAct 2006)

Currently Scania is the only manufacturer producing ethanol buses. At the end of 2006 there were 490 buses running on ethanol in Sweden (www.miljofordon.se). Ethanol buses are also running on trial in Spain, Italy and Poland. Until now, Scania has produced some 600 ethanol buses. (Nordström 2006)

The total number of vehicles capable of running on neat or nearly neat ethanol is thus some 10 million, the same order of magnitude as the world LPG vehicle population. Relative to the whole world vehicle fleet, 10 million is some 1.3%. It is easy to foresee that FFV numbers will continue growing. When manufacturing a car, the additional cost for E85 compatibility is rather marginal.

5.6.5 Natural gas vehicles

The world natural gas vehicle population is growing rapidly, and was some 6.5 million in June 2007 (IANGV 2007). The largest markets are Argentina (1.65 M vehicles), Pakistan (1.55 M vehicles) and Brazil (1.4 M vehicles). These are also the markets where growth is most rapid. The greater part of the fleet is quite simple, after-market conversions, which necessarily don't meet European or North-American criteria for low-emission vehicles. Natural gas vehicles are also able to run on cleaned biogas. Figure 5.17 shows the growth in natural gas vehicle numbers.

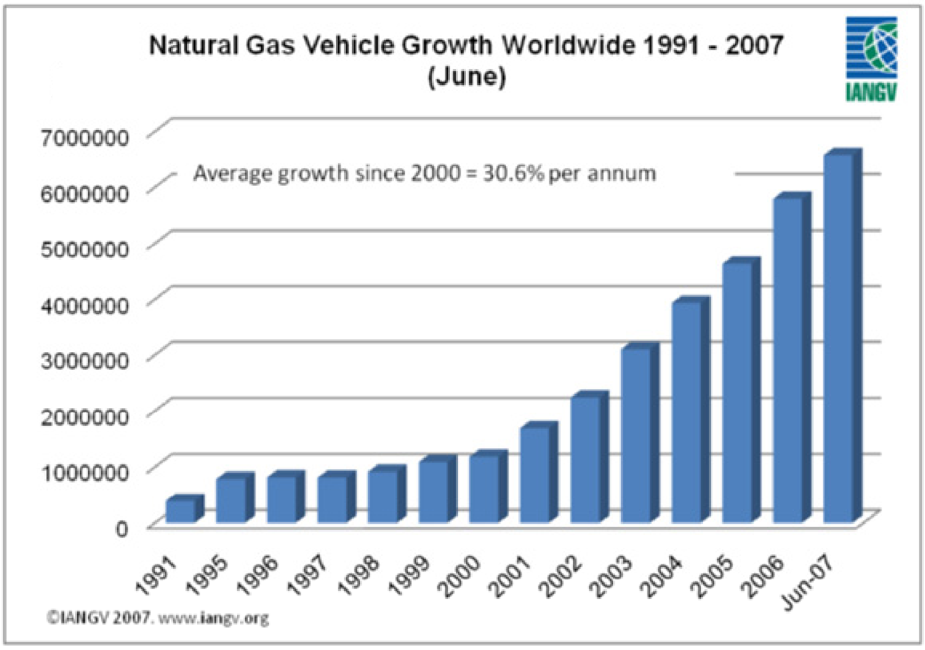


Figure 5.17. Development of natural gas vehicle numbers (IANGV 2007).

There are some 800,000 CNG vehicles in Europe. Italy has, by far, the biggest fleet, some 400,000 vehicles. Germany has some 55,000, Sweden some 13,000 and France some 10,000 and methane (CNG and biogas) vehicles. In the U.S. there are some 147,000 CNG vehicles, and in Japan some 31,000 CNG vehicles. The U.S. is the only market which is stagnant. (IANGV 2007)

Although most CNG vehicles in the world are conversions, volumes are high enough for OEM manufacturers to be able to offer CNG vehicles. Some of these vehicles are built on the assembly line by the OEMs themselves, some by sub-contractors off-the-line. Technology for light-duty CNG vehicles is well established, and the vehicles provide adequate performance and reliability. In the case of OEM vehicles, fuel storage can be arranged so that the gas tank will not intrude on passenger or luggage compartment.

Heavy-duty CNG vehicles are not as mature as light-duty vehicles. The main reason for this is the manufacturers of heavy-duty vehicles are more willing to invest in diesel technology than in natural gas technology. However, the supply of both OEM passenger cars and buses is fairly good. Supply of light- and heavy-duty trucks, on the other hand, is not that abundant, at least not in Europe.

CNG vehicles require a dedicated, high-pressure refueling system. The “chicken-and-egg” problem is often discussed in conjunction with natural gas vehicles. Without a refueling network for CNG, nobody will buy CNG vehicles. On the other hand, if no vehicles are available, it is not worthwhile to create a refueling infrastructure. For light-duty vehicles bi-fuel technology provides flexibility when the refueling network is sparse and additional operating range, when needed. Typically the ratio between CNG vehicles and refueling stations varies from 20 to 800. Normally, to reach profitability, a fast-fill CNG refueling station should serve at least 100 light-duty vehicles, or a smaller number of buses consuming the equivalent amount of fuel.

Currently, fossil natural gas dominates in methane fuelled vehicles, but biogas can be used as well after proper purification. As mentioned in Chapter 4, Sweden is one of the champions in biogas for vehicles. The first biogas refueling station in Germany opened in 2006 in Jameln. In Austria, an Action Plan for Biomethane calls for 50,000 NGVs and 200 CNG Stations by 2010 to establish a base for methane vehicles. A five point action plan is targeted to dramatically develop the use of biomethane for use in transport in the next years (NGV Global July 12, 2006). In Bern, Switzerland, a fleet of Volvo buses is running on biogas (DieselNet News, September 2005).

5.6.6 LPG vehicles

In 2004, some 17 million tons of LPG was used in transportation, meaning that the share of LPG in transportation fuels is approximately 1%. The total LPG vehicle fleet is some 10 million units. The use of LPG is, however, concentrated to certain markets. Five countries, Korea, Japan, Poland, Turkey, and Australia use more that 50% of the automotive LPG. Poland scores the highest share of LPG in transportation, 16%. Other countries reaching a share above 10% are Korea, Bulgaria, Turkey, and Lithuania. (www.worldlpgas.com)

As in the case of CNG vehicles, most LPG cars are after-market conversions, but some OEM LPG vehicles are available. In Central Europe, in countries like Belgium, Holland, France, Germany and UK, the LPG refueling network is quite dense.

5.6.7 DME vehicles

Only limited numbers of DME vehicles have been produced so far. For example, Nissan Diesel and Volvo have built prototype vehicles. Volvo, however, has plans to develop DME further (Landälv 2005).

Figure 5.18 shows Nissan Diesel's view on DME development. DME might become a real alternative around 2015. DME, however, requires new fuel production capacity, a new refueling system and new vehicles, so the threshold to commercialization is quite high.

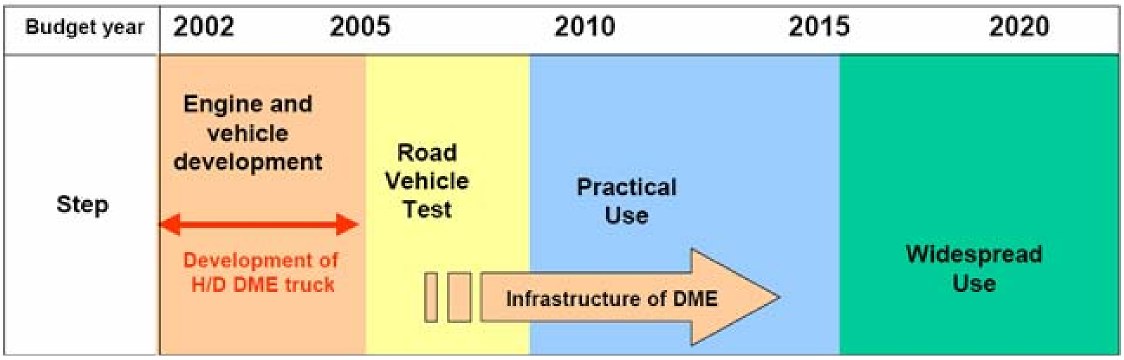


Figure 5.18. Nissan Diesel's view on development of DME as a vehicle fuel (Oikawa et al. 2005).

5.6.8 Hydrogen vehicles

Currently hydrogen fueled vehicles, both ICE and FC powered, are counted in figures of tens or maybe hundreds. DaimlerChrysler announced in March 2006 that the company had manufactured in total more than 100 fuel cell vehicles. This figure includes 36 buses, among these the Citaro buses for the CUTE project, and 60 A-type fuel cell passenger cars.

Honda has announced limited production of fuel cell cars in 2008. GM will begin building and deploying a 100-vehicle fleet of Equinox fuel cell vehicles in 2007. The 700 bar hydrogen storage systems for these Equinox fuel cell vehicles are based on Quantum's Type IV (polymer-lined, all-composite) ultra-lightweight tank technology, incorporating advances in materials, material utilization, and optimized design, yielding benefits proprietary to GM. (Green Car Congress 2006e)

Figure 5.19 shows EIA's projection of fuel cell vehicle sales in the U.S. Sales will reach 1,000 units annually in 2015 and 4,000 units in 2030. The total vehicle stock of FC will be some 50,000 units in 2030, which in comparison with the current vehicle stock of some 230 millions is negligible.

The IEA Hydrogen Co-ordination Group evaluated prospects for market penetration of hydrogen and fuel cell vehicles until 2050. In the most favorable scenario, hydrogen usage in transport sector could be 12.5 EJ/y, and the market share of fuel cell vehicles could be as high as 30% by 2050 (Figure 5.20). Total hydrogen use by 2050 would be over 22 EJ (world energy demand 468 EJ in 2004). In less optimistic assumptions, market share of hydrogen is very low. Investments in the transport sector would be 0.1–1.0 trillion USD in pipelines, 0.2–0.7 trillion USD for refueling stations and 1.0–2.3 trillion USD for FC vehicles. (IEA 2005b)

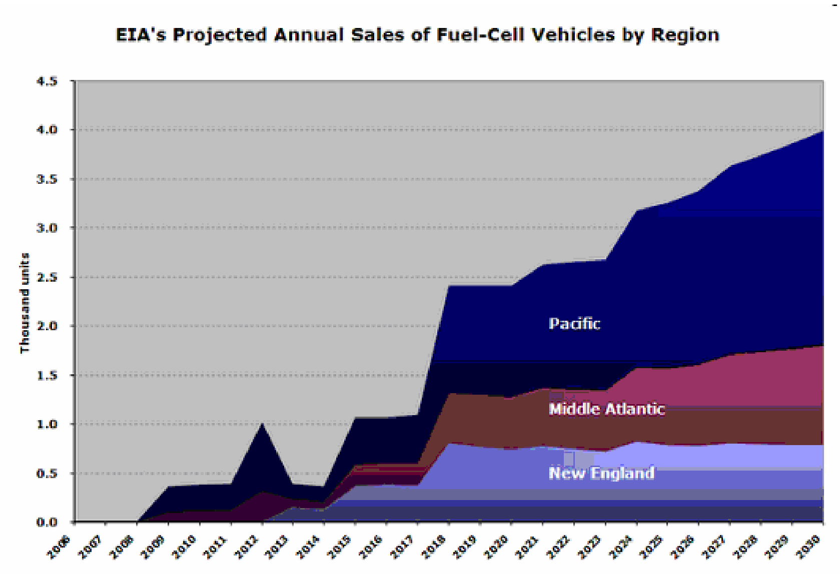


Figure 5.19. Projection for FC vehicle sales in the U.S. (Green Car Congress 2006e).

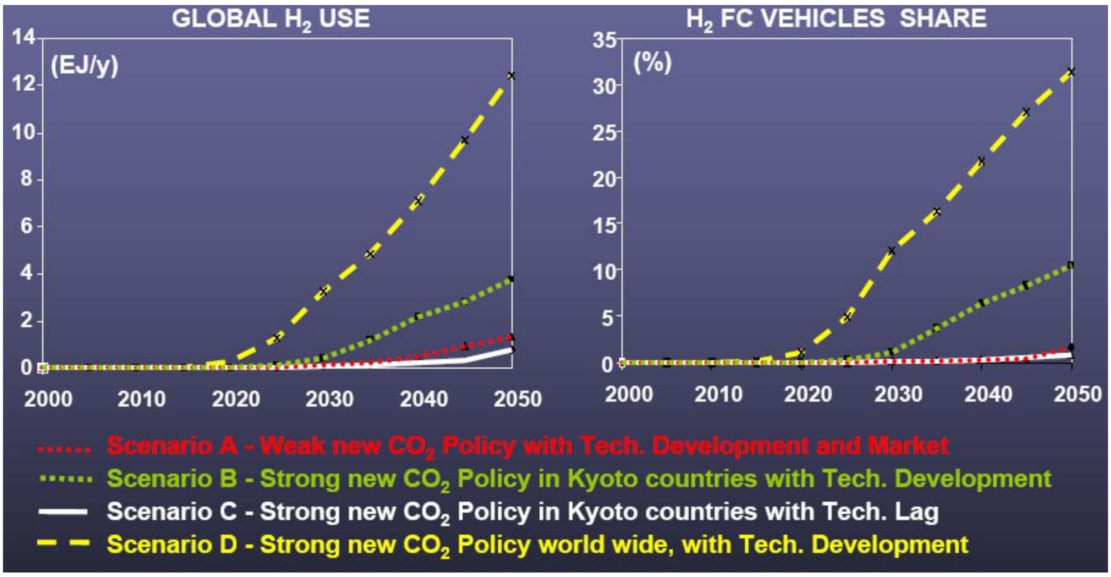


Figure 5.20. The IEA Hydrogen Co-ordination Group scenarios on market penetration of hydrogen and fuel cell vehicles for transportation. (IEA 2005b).

The European Commission's website for hydrogen research states as follows (http://ec.europa.eu/research/leaflets/h2/index_en.html):

"Taking Europe away from its 20th century dependence on fossil fuels to an era powered by hydrogen and electricity will require careful strategic planning. A gradual transition will be required and a preliminary European road map has been sketched out for the production and distribution of hydrogen – as well as fuel cells and hydrogen systems – with the goal of moving to a hydrogen-oriented economy by 2050.

Europe has a strong position in research, development and deployment of the key technologies essential for a hydrogen economy. Nevertheless, the size of the challenge means that global collaboration is required on research. International collaborative efforts between Europe, America and Asian countries are already being initiated in key areas of research.

Depending on local circumstances, hydrogen can be produced locally or distributed from a central large-scale production plant. The costs and benefits of these various 'pathway' options are currently the subject of research.

There is already a limited hydrogen transmission system in Europe associated with the petrochemical industry, but considerable investment in infrastructure will be required to facilitate the widespread distribution of hydrogen. In the case of transport, special refuelling facilities will also be needed.

As with any fuel, safety is a paramount concern. Commonly accepted regulations, codes and standards for equipment, well-trained maintenance personnel, and operational guidelines will need to be formulated, alongside an extensive information and educational programme for the public."

6. Exhaust emissions from alternative fuels and vehicle technologies

Emissions with ethanol
- *Reductions in CO, HC, PM, NOx, 1,3-butadiene and aromatics when compared to fossil options*
- *Increase in acetaldehyde emissions when compared to fossil options*
- *Increase in evaporative emissions, if base fuel is not adjusted for vehicles spark-ignition engines*
- *Increase in cold start emissions*

Emissions with traditional biodiesel (FAME)
- *Reduction in PM emissions*
- *Increase in the NO_x and aldehyde emissions*

Emissions with synthetic fuels (HVO, GTL, CTL, BTL)
- *Significant reduction in PM, NO_x plus aldehydes, 1,3-butadiene, benzene, particulate PAHs and mutagenicity.*

Emissions with natural gas
- *Extremely low PM emissions when compared to diesel vehicles, NO_x emissions depend on engine technology (very low with stoichiometric combustion and TWC)*
- *The unregulated emissions, e.g., formaldehyde and particle-associated PAHs, are extremely low (catalyst needed for formaldehyde control)*
- *The performance of methane can be enhanced by mixing in hydrogen.*

DME *is a clean-burning, but technically challenging motor fuel.*

Hydrogen *enables zero tailpipe emission from fuel cells vehicles (emit only water)and close to zero emissions from hydrogen fuelled ICEs.*

Greenhouse gas emissions are discussed in Chapter 7.

6.1 General trends in emission reduction

Development in vehicle emission control technologies has been significant, especially in recent years. Electronic engine controls, catalysts, and high quality fuels have contributed to this development. Currently both advanced gasoline vehicles and vehicles fueled with gaseous fuels reach very low emission levels. Diesel technology has also made good progress. By 2010–2015 increasingly stringent emission regulations in developed markets will, in a historic perspective, bring down diesel emission close to zero (see Figure 5.5, U.S. 2010 regulations, Euro VI in 2013–2014).

Predicted emission trends for Europe are shown in Figure 6.1. All emissions, except CO_2 are expected to go down. Figure 6.2 shows the development of European emission limit values. Today all new vehicles are low-emission vehicles in comparison with the vehicles of the 70s and 80s. Figure 6.3 shows a comparison of European, Japanese and U.S. emission limits for heavy- duty engines. A short summary of emission regulations is presented in Appendix 3.

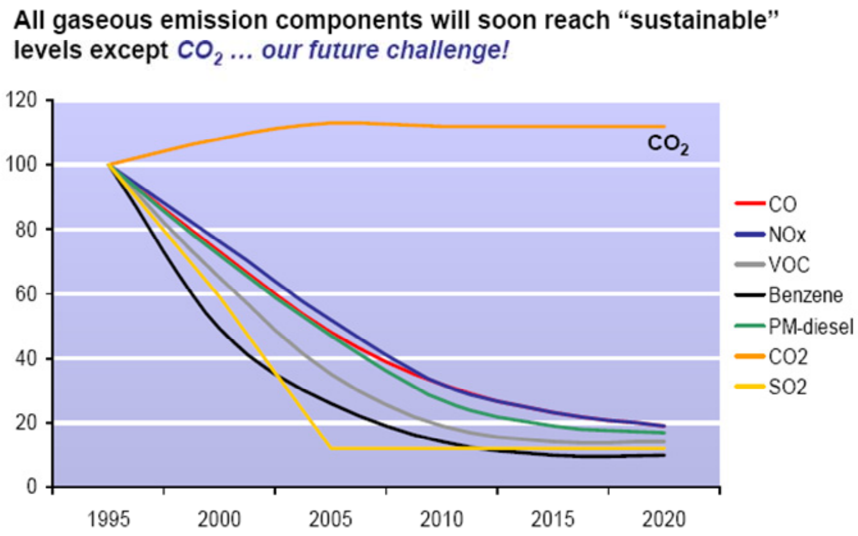


Figure 6.1. Emission trends for Europe (Röj 2006).

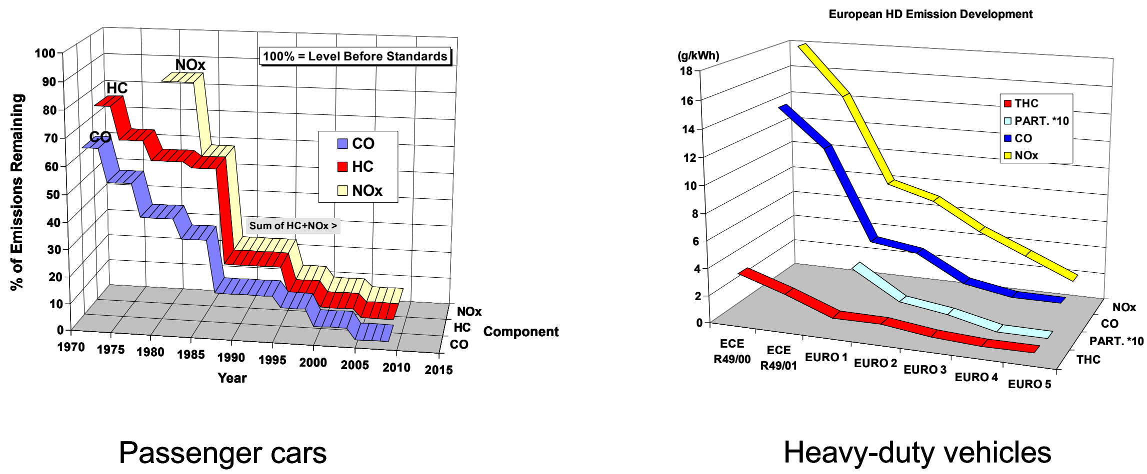


Figure 6.2. Development of European emission limit values.

Certification of light-duty vehicles is carried out by running complete vehicles on a chassis dynamometer. Results are correlated to driven distance. All around the world emission certifications for heavy vehicles are carried out by engine dynamometer tests with the parent engine, which is selected from an engine family. The reason for engine measurements is that same engines are used in several different vehicle models. The emission results of tests are declared as g/kWh for the work delivered by the engine crankshaft. Emission certification is done using reference fuels. Gasoline and diesel qualities used for certification are closely specified. For natural gas and LPG reference fuel qualities are defined, as well as emission certification protocols for both light-duty vehicles and heavy-duty engines. For many other alternative fuels the definition of emission test fuels and tests methods is still just under way.

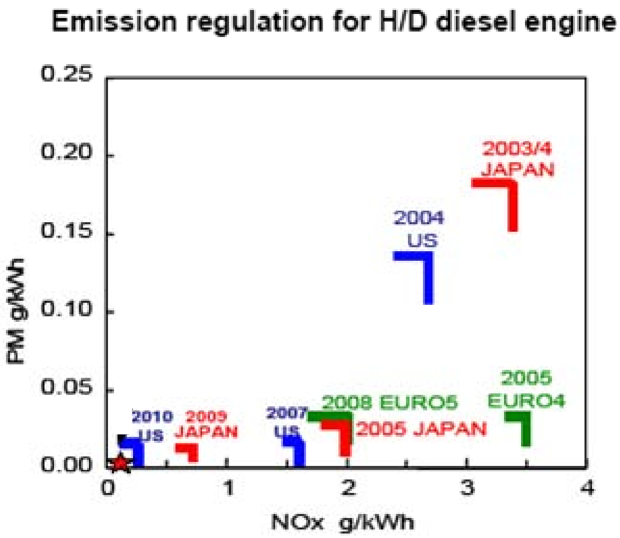


Figure 6.3. Japanese emission regulations in comparison with U.S. and European regulations (Oikawa et al. 2005).

Reducing emissions by normal means of vehicle and fuel development tend to increase energy consumption, both in fuel refining and end-use stages. However, high quality fuels are needed to reach low emissions in gasoline and diesel vehicles. Increased emissions due to, e.g., poor quality biofuels is not acceptable. Studies in Germany have shown that using straight vegetable oil can increase exhaust gas toxicity (mutagenicity) by a factor of up to 60 compared to conventional diesel fuel (Krahl et al. 2007)

Although vehicle emissions have gone down, fuels such as synthetic diesel fuel, methane and DME can still provide emission benefits over conventional gasoline and diesel. The other way round it can be said that clean fuels provide the biggest emission benefits in dirty engines.

6.2 Alcohols

Spark-ignition vehicles, low-level ethanol and ethers

Today ethanol is mainly used in the form of low level blends. In the U.S. ethanol concentration is 10%, in Brazil 20–25%, and in Europe 5%. In Europe, however, the major part of ethanol is used in the form of ETBE. Only in a couple of countries, e.g., Sweden, use 5% ethanol in gasoline.

It is generally accepted that up to 10% ethanol can be blended into gasoline without modifications to current vehicles (see Chapter 5). However, older cars may encounter problems with fuel system materials (BAFF). Ethanol producers tend to be in favor of blends up to 20% ethanol. The automotive companies are against blends containing over 10% ethanol and issue warnings about warranty validity (Environment Australia 2002).

Many studies have reported reductions in tailpipe CO, HC, PM, 1,3-butadiene and aromatics with low-concentration gasoline/ethanol blends, whereas aldehyde emissions and NO_x, especially at higher concentrations, tend to increase (Figure 6.4). With older cars, enleanment of the mixture leads to decreased CO emission, but for current cars with closed-loop systems and catalysts, benefits are gained only at cold start or heavy acceleration. (Environment Australia 2002)

Aldehydes in exhaust gases are considered a health risks. All oxygenates, including ethanol, emit higher aldehyde concentrations than non-oxygenated gasoline. However, the Royal Society of Canada has concluded that the risks of increased aldehyde emissions from ethanol blends are negligible, due to low absolute emissions relative to other hazardous emissions (CRFA). With ethanol blends, acetaldehyde emissions increase substantially (e.g. 200%), but formaldehyde emission is typically unchanged. (Manitoba).

Volatile organic compounds (VOC, evaporative emissions, and tailpipe HCs) are reactive compounds, and therefore significant sources of ground-level ozone formation. Ethanol blends reduce tailpipe HC emissions when compared to gasoline (CRFA). However, evaporative emissions increase with increasing vapor pressure, if the base fuel is not adjusted for a blend. In some countries, like Canada, the volatility of ethanol blends must match gasoline limits, but in some countries higher volatility is allowed for ethanol blends (Distillery Network).

A Swedish report on evaporative emissions related to blending of ethanol into gasoline points out the importance of cold start and evaporative emissions (1/3 of the road HC's in Sweden are evaporative emissions). The Swedish program for in-use testing showed that 40% of the cars exceeded the 2 g limit value for evaporative emissions, whereas in

Germany with a similar test program, the corresponding percentage was only 10%. This was thought to be due to the 5% addition of ethanol in Swedish gasoline (Åsman 2006). It is also thought that ethanol increases evaporative emissions through permeation, i.e., by leaking through plastic materials in hoses and fuel tanks.

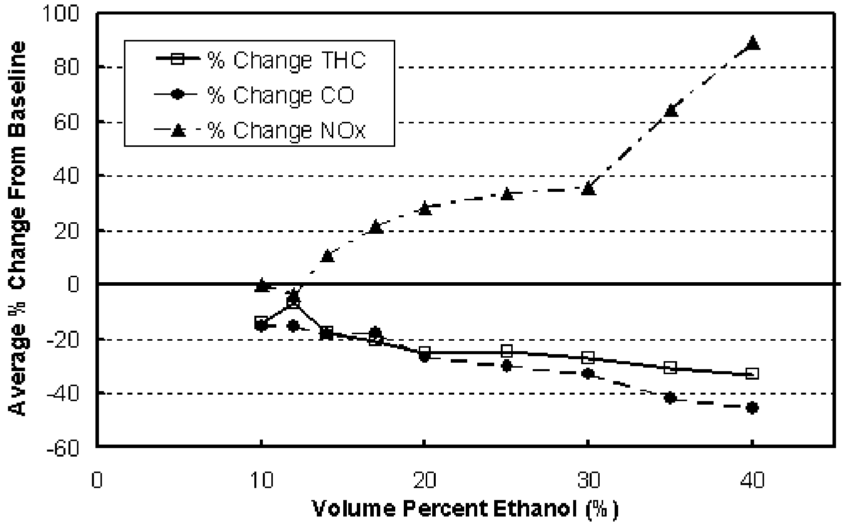


Figure 6.4. The effect of ethanol content on CO, HC and NO_x emissions with cars from 1990 or later (Environment Australia 2002).

In general, ethers such as MTBE and ETBE are excellent gasoline components, resulting in less problems e.g. related to evaporative emissions than ethanol. (Aakko et al. 2002)

A recent Swedish study reports emissions with E5, E17 and E43 for four new Euro 4 gasoline vehicles. The test simulated refueling or actually "misfueling" gasoline vehicles with E85. Three of the four vehicles did not meet the emission limits when tested on E17 and E43. However, high ethanol concentration resulted in an OBD malfunction signal only in one car. Figure 6.5 shows emission results for one of the cars. The vehicles performed better than expected on high ethanol concentrations as all vehicles could be driven on E43. (Karlsson 2006)

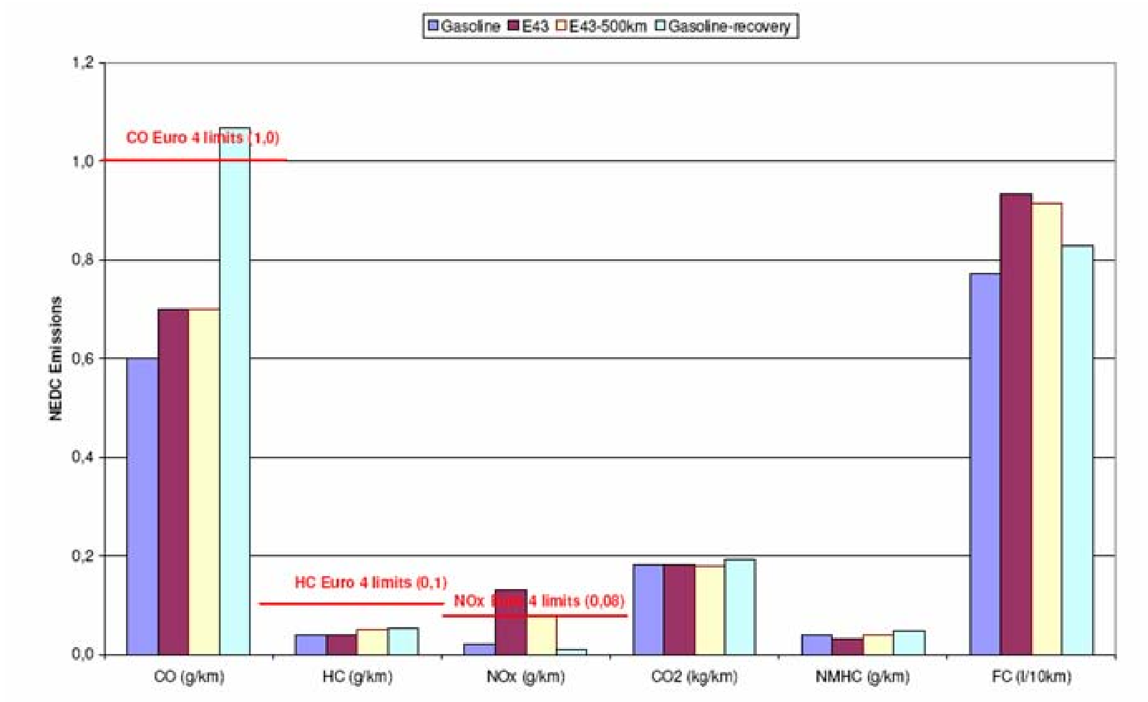


Figure 6.5. Emissions with high concentration of ethanol in a gasoline vehicle. Emissions were not normalized when switching back to gasoline. (Karlsson 2006)

High concentration ethanol – FFV vehicles (E85)

FFVs can operate on unleaded gasoline or any mixture of gasoline and ethanol up to 85% of ethanol. Some 15% gasoline is needed to improve the cold-startability of ethanol by increasing the vapor pressure (gasoline ~70–100 kPa vs ~17 kPa for ethanol). A small portion of gasoline also improves safety as the flame becomes clearly visible.

The E85 Handbook states that the reduction in emissions depends on how well the emissions control system and engine are designed and "tuned" for ethanol. Compared to gasoline, most FFV cars using E85 produce lower CO and the same or lower levels of HC emissions. NO_x emissions are about the same for ethanol and gasoline vehicles. Emissions resulting from fuel evaporation are lower for E85 than for gasoline (E85 Handbook). The Canadian Renewable Fuels Association (CRFA) estimates that with an optimized engine, the potential for NO_x reduction for E85 is some 20%, and the potential for exhaust VOC reduction some 30% or more, the latter due to a lower vapor pressure.

Ethanol Express (2001) evaluated a total assessment of toxic emissions with E85 and gasoline using CARB and the U.S. EPA risk factors. E85 results in a large increase in the acetaldehyde emissions when compared to gasoline. However, when the general "toxicity potency" of the fuels is taken into account, it is noted that emissions from E85 are less harmful than from reference gasoline, since acetaldehyde is evaluated to be less toxic than e.g. 1,3-butadiene and benzene (Ethanol Express 2001).

In 2005, the Swedish laboratory AVL MTC carried out emission measurements on FFV vehicles on assignment from the Swedish Road Administration. Three Ford Focus FFV vehicles were tested in parallel at +22 and -7 ^oC with various ethanol blends. In this case increasing ethanol concentration increased CO and HC, particle and aldehyde emissions, but significantly reduced NO_x emissions in the test conducted at +22 ^oC. Particle emissions doubled when the ethanol concentration increased from 5 to 85%. The effect of fuel ethanol concentration on aldehyde emissions is shown in Figure 6.6. The results for -7 ^oC are not valid for comparison as electrical block heaters were used with the E85 fuel.

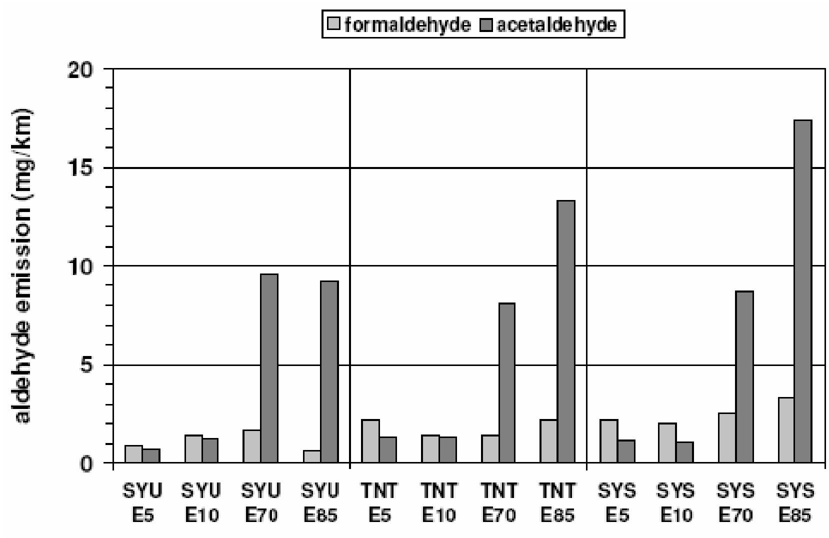


Figure 6.6. The effect of fuel ethanol concentration on aldehyde emissions at +22 ^oC (SYU, TNT and SYS are vehicle identifications) (de Serves 2005).

Current FFVs do not perform well in cold conditions without block heaters. On assignment from two motoring magazines, the Technical Research Centre of Finland tested a Saab 9-5 at +22 and -7 ^oC, and in this case without block heater. Figure 6.7 shows the results for CO, HC and aldehydes at -7 ^oC. Going from gasoline to E85, CO increased by a factor of 2, HC by a factor of 7, formaldehyde by a factor of 11 and total aldehydes by a factor of 24.

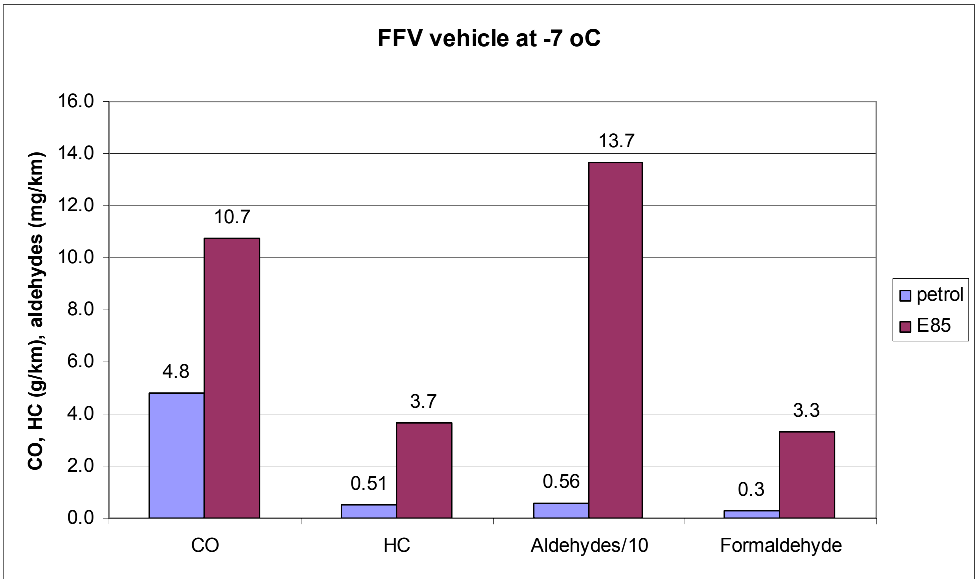


Figure 6.7. Cold temperature emission results with gasoline and E85 (Tekniikan Maailma 2007).

Compression-ignition engines running on ethanol

Currently Scania is the only manufacturer supplying heavy-duty ethanol engines. Scania's technology is based on additive-treated (ignition enhancer, lubricity additive) ethanol. Scania is now into the third generation of ethanol engines. The first generation engine, the 11 liter 260 hp engine introduced in 1989, had an emission level equivalent to Euro 3 (2000/2001 level). Scania's second generation ethanol engine, launched with a new bus range in 1996, was based on the 9-litre engine. Available on the Scania OmniCity low-floor city bus, the engine produced 230 hp and achieved Euro 4 emission levels (2005/2006 levels). (Nordström 2007)

Both these engines were, in a way, some 10 years ahead of the emission regulations.

The new 3rd generation ethanol unit is an adaptation of Scania's latest 9-litre diesel engine with air-to-air charge cooling and exhaust gas recirculation, EGR. The engine has been certified for both Euro 5 and the voluntary EEV standard. Power is now 270 hp and torque a full 1200 Nm, resulting in excellent response and driveability. (Nordström 2007)

It is worth mentioning that Scania's ethanol hybrid concept bus debuted at the UITP congress in Helsinki in May 2007. The full-size, low-floor city bus fulfils the Euro 5 and EEV emission limits. Energy storage is based on super capacitors, which are much more robust than batteries in heavy-duty operation. Twelve ethanol buses equipped with Scania's hybrid-drive system will start regular operation in Stockholm in 2008 and 2009, in cooperation with the city's public transport operator and access to proven technology. (Press release, 15 May 2007, www.scania.com)

6.3 Biodiesel (FAME)

Fatty acid methyl esters (FAME), known as the traditional biodiesel, generally show lower particle emissions when compared with diesel fuel. However, NO_x emissions might increase with increasing share of FAME (Figure 6.8). With high concentration the increase in NO_x emissions might be problematic. Today, many engine manufacturers have difficulties in fulfilling the stringent emission requirements, especially regarding NO_x emissions. At one point Scania banned the use of 100% FAME in its Euro 3 emission level engines due to FAME's tendency to increase NO_x. The effects of a 5% blend on emissions are negligible.

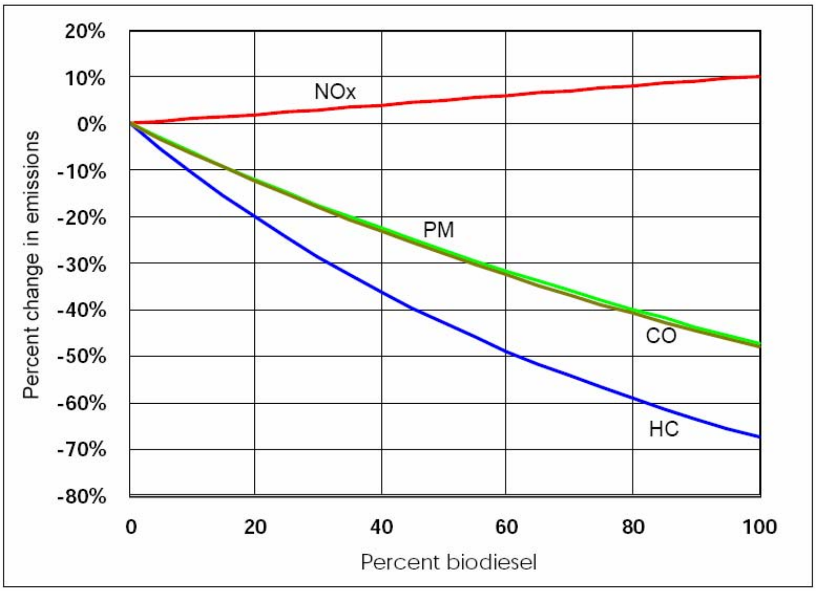


Figure 6.8. The effect of fatty acid methyl ester (biodiesel) concentration on regulated exhaust emissions (EPA 2002).

Krahl et al. (2007) report on emissions with diesel, RME, straight vegetable oil, modified straight vegetable oil and GTL in a Euro 3 certified HD engine. Figure 6.9 shows NO_x and PM emissions. Compared with standard diesel, RME reduces particle emissions significantly, but increases NO_x emissions. GTL, on the other hand, reduces both NO_x and PM emissions, but is less efficient than RME for PM reduction. The unmodified straight rapeseed oil increases both NO_x and PM emissions. Krahl et al. also carried out biological testing. Figure 6.10 shows an example on Ames mutagenicity results. The results are alarming for straight vegetable oil as mutagenicity increases significantly.

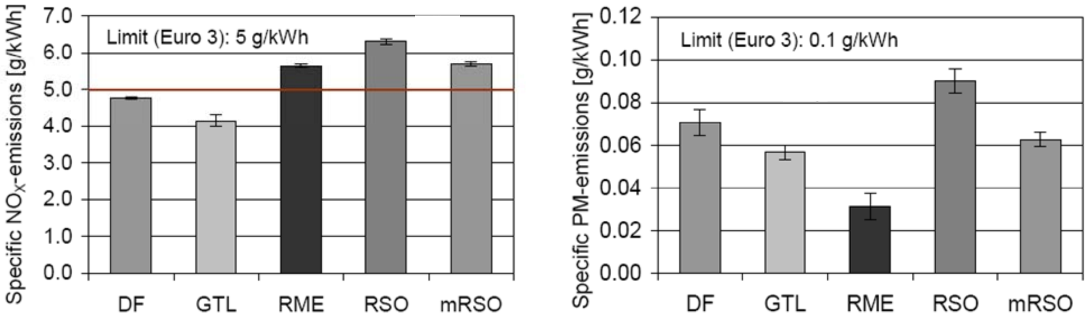


Figure 6.9. NO_x and PM emissions with diesel fuel, GTL, RME and unmodified (RSO) and modified (mRSO) straight vegetable oil (Krahl et al. 2007).

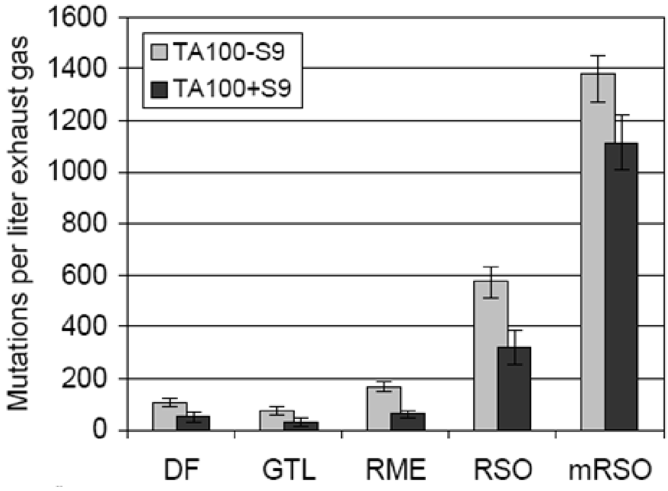


Figure 6.10. Numbers of revertants in tester strain TA100 with and without S9 of particle extracts from tested fuels (diesel fuel, GTL, RME and unmodified (RSO) and modified (mRSO) straight vegetable oil) (Krahl et al. 2007.)

Krahl et al. summarize the results: *"Compared with the reference diesel fuel the two RSO qualities significantly increased the mutagenic effects of the particle extracts by factors of 10 up to 60. RME extracts had a moderate but significant higher mutagenic response. GTL samples did not differ significantly from diesel fuel. Concerning the regulated emissions, the results remained below the margins except a up to 15% increase of NO_x for the tested bio fuels."*

Straight vegetable oil has entered the transport fuel market in Germany, and the experts are very concerned about this phenomenon.

6.4 Synthetic diesel and diesel by hydrotreatment (paraffinic diesel)

Fischer-Tropsch diesel (Gas-to-Liquids GTL, Coal-to-Liquids CTL, and Biomass-to-Liquids BTL) and hydrotreated vegetable oil (HVO) are clean-burning paraffinic fuels, which result in substantial benefits in tailpipe emissions when compared with conventional diesel fuel. Figures 6.9 and 6.10 also demonstrate the benefits of paraffinic fuel over both conventional diesel and FAME.

NO_x and PM emissions are important with regard to urban air quality. If the diesel engine is optimized for FT or HVO diesel, even greater emission reductions can be achieved thanks to the very high cetane number and high hydrogen-to-carbon ratio of paraffinic diesel. Alternatively, the NO_x reduction could be traded for reduced fuel consumption.

FT and HVO fuels can be blended with diesel at any ratio with little or no modifications. Figure 6.11 shows the effect of GTL blends on the emissions of a light-duty diesel vehicle. GTL will reduce emissions even at a 20% concentration.

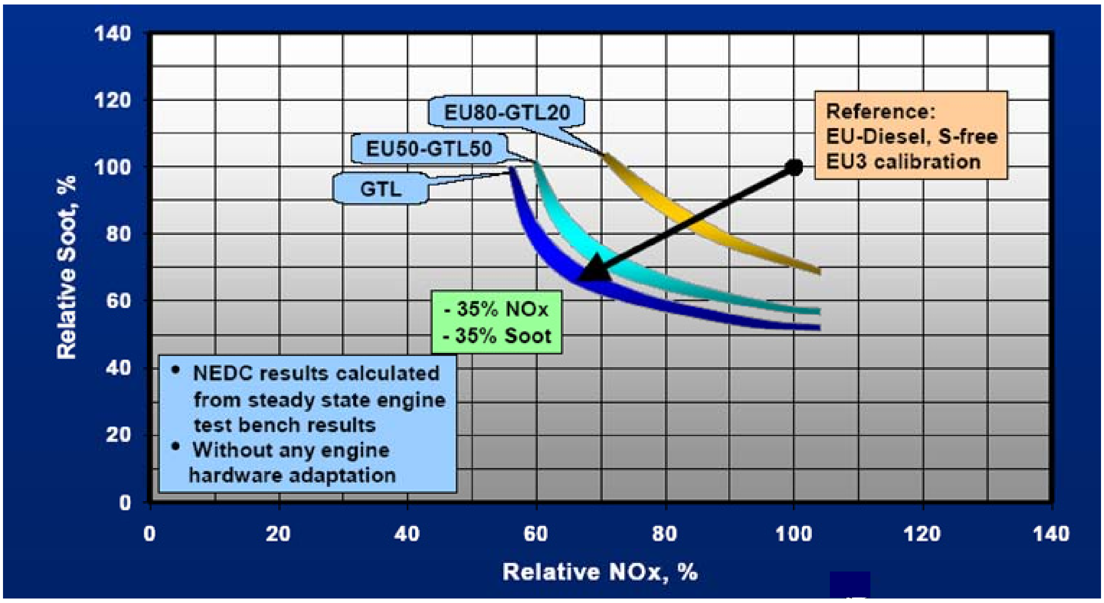


Figure 6.11. The effect of GTL diesel on passenger car NO_x and PM emissions (Maly 2004).

The Alliance for Synthetic Fuels in Europe (ASFE) has summarized the influence of synthetic FT diesel on exhaust emissions (Figure 6.12). The emission reductions with engines optimized for FT diesel are substantial. NO_x and PM emissions can be close to half of emissions with conventional diesel fuel.

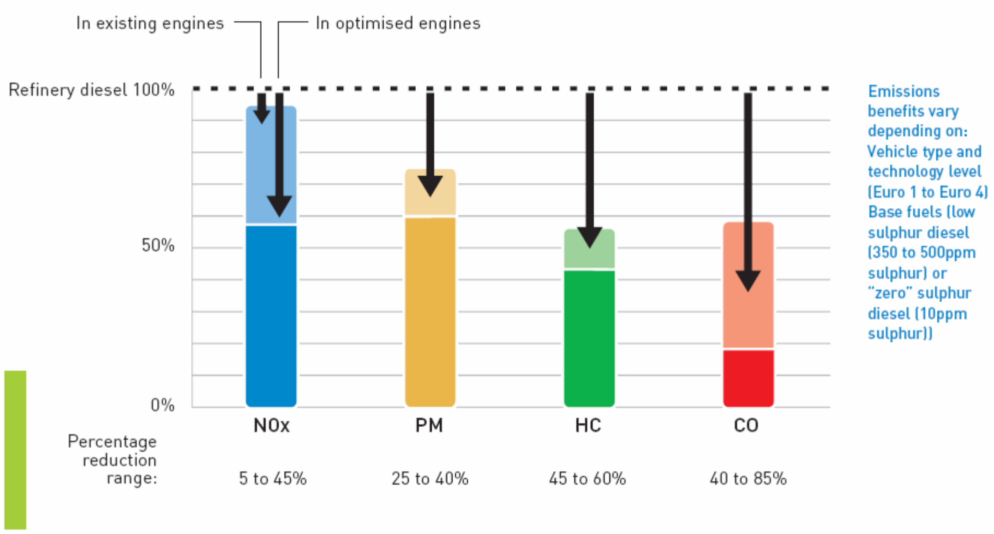


Figure 6.12. A summary of emission reduction potential with FT diesel in conventional and optimized engines (ASFE).

In the same way as FT diesel, HVO results in significant emission reductions. Emission results have also been reported for NExBTL. Figure 6.13 shows a summary of emission results from two HD engine manufacturers (engines tests) and the Technical Research Centre of Finland (bus tests on a chassis dynamometer). NOx reductions vary from 7 to 18% and PM reductions from 19 to 46% in engines with standard calibration. (Mikkonen 2007)

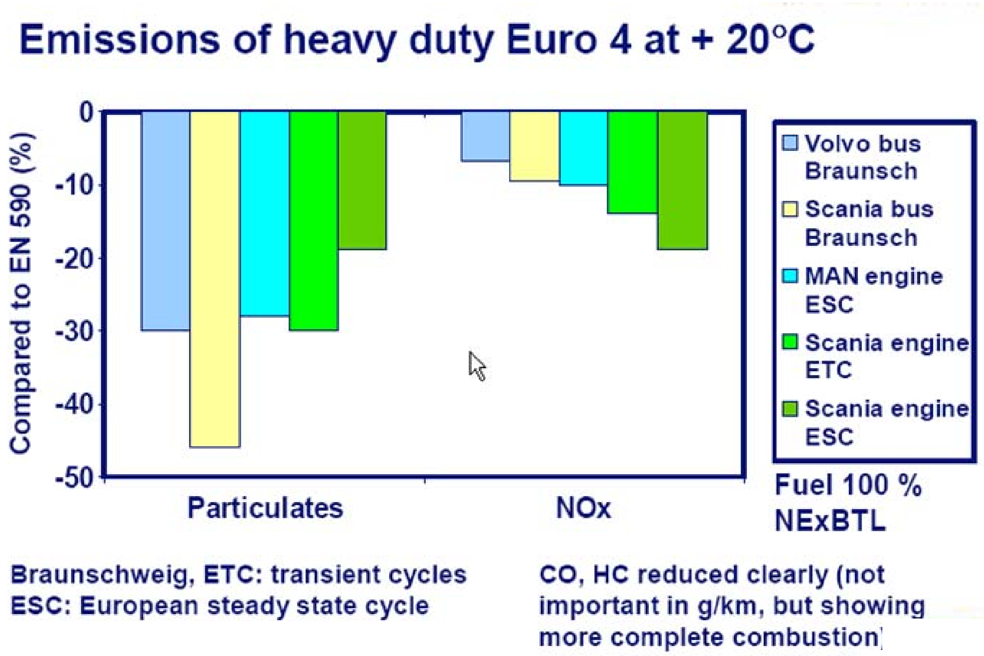


Figure 6.13. Emission reductions with 100% NExBTL (Mikkonen 2007).

NExBTL has also been tested in passenger cars. Rantanen et al. (2005) compared emissions from NExBTL blends with emissions from Swedish Environmental Class 1 and sulfur free EN590 diesel. NExBTL also reduces gaseous toxic emissions such as aldehydes, 1,3-butadiene, benzene, and in addition, particulate phase PAHs and mutagenicity. (Rantanen et al. 2005)

All synthetic diesel fuels are helpful in reducing local pollution. However, only those fuels being of bio-origin will reduce GHG emissions. Well-to-wheel GHG emissions for GTL are roughly equivalent to those of conventional diesel. Massive production of CTL fuels would actually increase CO_2 emissions dramatically. In the future, CO_2 could be captured and sequestrated when processing GTL and CTL fuels, but CCS does not remove the fossil carbon from the fuel itself.

6.5 Gaseous fuels

Natural gas (methane)

Natural gas is an inherently clean burning fuel with particulate emissions close to nil and low exhaust toxicity. NO_x emissions have to be controlled either during combustion using lean-burn combustion or using a combination of stoichiometric combustion and three-way catalyst. Lean-burn engines should also be catalyst equipped to control formaldehyde emissions. Optimized engines with after-treatment devices produce very low regulated and unregulated emissions both in light-duty and heavy-duty applications. Thus, CNG is a very promising option in urban vehicles to reduce local pollution and harmful health effects.

As an example on the emission performance natural gas (methane) it can be mentioned that the U.S. EPA has recognized the dedicated Honda Civic CX as the cleanest ICE equipped car in the world.

Natural gas is commonly used in city buses all over the world. Recently, several studies have been performed to measure and compare the emissions of conventional diesel buses and natural gas buses. Different studies may show diverging results for several reasons. At this stage of technological development of natural gas buses, vehicle configurations can vary significantly from vehicle to vehicle. In the U.S., manufacturers have preferred lean-burn combustion, and many CNG vehicles lack even oxidation catalyst. In Europe, more focus has been given to emission reduction, and in general, the European CNG vehicles are more sophisticated than their U.S. counterparts. This will change, as both European and U.S. manufacturers are moving towards stoichiometric combustion in conjunction with EGR.

In 2003–2004, VTT carried out a comprehensive emission test program for diesel and natural gas buses. Seven modern buses, three diesel and four CNG vehicles (one Euro 3 and three EEV certified), were tested on a chassis dynamometer for emission performance. The measurements covered regulated emission components as well as a number of unregulated emission components. VTT summarized the results as follows (Nylund et al. 2004):

"The results demonstrate that regarding particle mass and number emissions, the CNG vehicles, on average, are equivalent to CRT filter equipped diesel vehicles. The particle matter (PM) emissions of both CRT diesel and CNG vehicles were some two orders of magnitude lower compared with the baseline diesel engine. No abnormity could be found regarding the numbers of nanoparticles emitted from CNG vehicles. The formaldehyde emission of the catalyst equipped CNG vehicles was low, as well as the emission of polyaromatic hydrocarbons components (PAH). The genotoxicity of CNG emissions was extremely low, determined by the Ames mutagenicity tests and calculated as a reference value per unit of driven distance. As for NO_x emissions, CNG vehicles provide similar or superior emission performance, depending on the emission certification class."

In Italy, Instituto Superiori di Sanita and Instituto Motori – CNR conducted a joint study on exhaust emission toxicity. Measurements were performed in an engine dynamometer using two IVECO engines: the stoichiometric IVECO 8469.21 CNG engine with three-way catalyst and the corresponding IVECO 8360.46R diesel engine. The old European ECE R49 13 mode cycle was used for testing. The diesel engine was run on baseline diesel fuel and a blend containing 20% bio-diesel (FAME). (Turrio-Baldassarri et al. 2006)

Figure 6.14 shows results for regulated exhaust emissions. The NO_x emission of the CNG engine was as low as 0.1 g/kWh, and PM emission was below 0.01 g/kWh. The 20% bio-diesel blend had negligible effects on NO_x and PM emissions.

The interesting part of the study is the results of unregulated emissions. Figure 6.15 shows particle-associated PAHs and nitro-PAHs. The conclusions are quite clear. The results showed that the SI CNG engine emissions, with the respect to the diesel engine, were nearly 50 times lower for carcinogenic PAHs, 20 times lower for formaldehyde, and more than 30 times lower for PM. A 20 to 30 fold reduction of genotoxic activity was estimated. A very high reduction of NO_x was also measured. The 20% bio-diesel blend emissions were shown to be very similar to diesel fuel. (Turrio-Baldassarri et al. 2006)

As for CO_2 emissions, natural gas as a motor vehicle fuel has some advantage over gasoline and is comparable to diesel with current technology. It has been projected that with 2010 technology, CO_2 emissions of natural gas vehicles will be 16% lower compared with gasoline vehicles and 13% lower compared with diesel vehicles (AFCG 2003). Biogas results in significant reductions of WTW greenhouse gas emissions.

The performance of methane can be enhanced by mixing in hydrogen, typically 5–20%. Hydrogen increases speed of combustion and, especially in lean-burn gas engines, reduces the emissions of unburned methane and nitrogen oxides. Hythane is a registered trademark of Brehon Energy PLC. Hythane demonstrations have been carried out e.g. in the U.S. and Sweden.

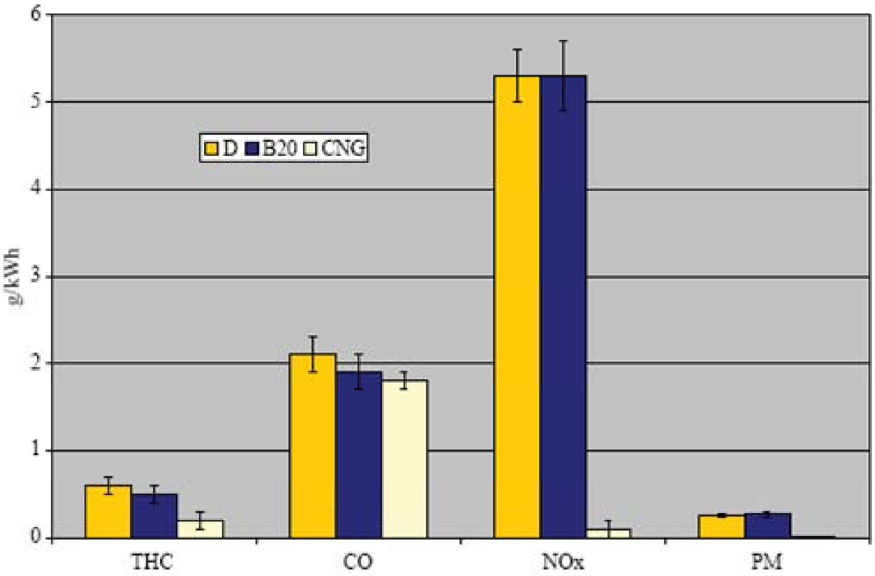


Figure 6.14. Results for regulated emissions (Turrio-Baldassarri et al. 2006).

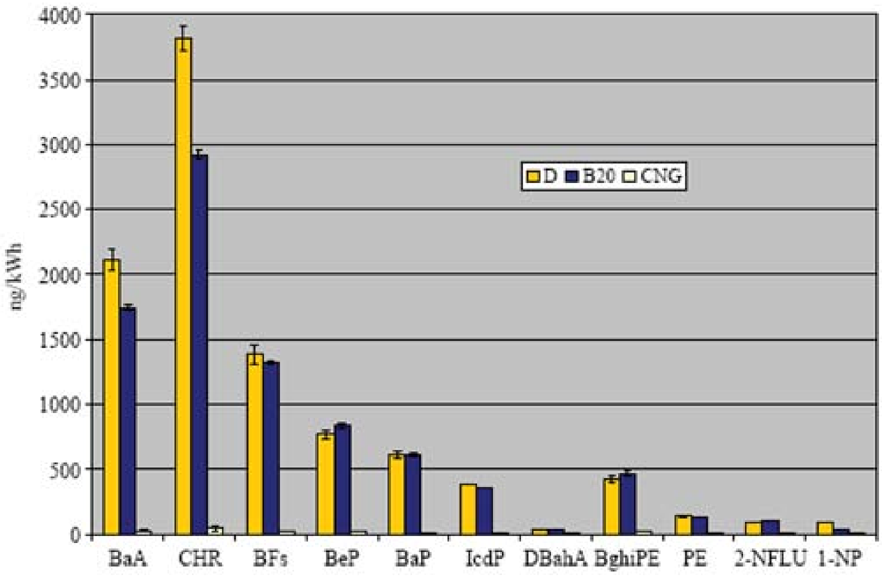


Figure 6.15. Particle-associated PAHs and nitro-PAHs emitted with D, B20 blend and CNG (Turrio-Baldassarri et al. 2006).

DME

Emission data for DME is scarce in comparison with natural gas. Volvo's first DME demonstrator, a B10BLE bus was completed in 1999. The engine was based on the diesel version DH10A and the target was to achieve unchanged performance compared with the baseline diesel engine in terms of power, noise emissions, and reliability. As regards to exhaust emission level, the target was set at a conservative level (NO_x < 3g/kWh and PM < 0.05 g/kWh), due to the project's main target being the feasibility of DME as a motor fuel in general, and not optimum emission performance.

Hansen & Mikkelsen (2001) report on the performance of the bus. Emission results were excellent compared with emission standards for heavy-duty diesel engines. The overall poor efficiency of the engine was caused by the limitations in injection characteristics and the parasitic losses in the injection system.

Volvo has not released detailed emission data on the second generation DME truck, developed within the AFFORHD project. Volvo just states that the FM9 truck delivers 300 hp, complies with Euro 5 emission regulations, has same efficiency as the baseline diesel truck, and is low in noise. (Landälv 2005)

However, detailed emission data is available for Nissan Diesel's DME truck tested according to the new Japanese transient JE-05 test (Figure 6.16). Due to fuel properties and the implementation of both EGR and NO_x storage catalysts, NO_x emissions are extremely low, 0.11 g/kWh. Particle emissions are also extremely low, 0.001 g/kWh. Figure 6.16 demonstrates that the emissions of the DME engine are below the levels of the oncoming U.S. 2010 regulations.

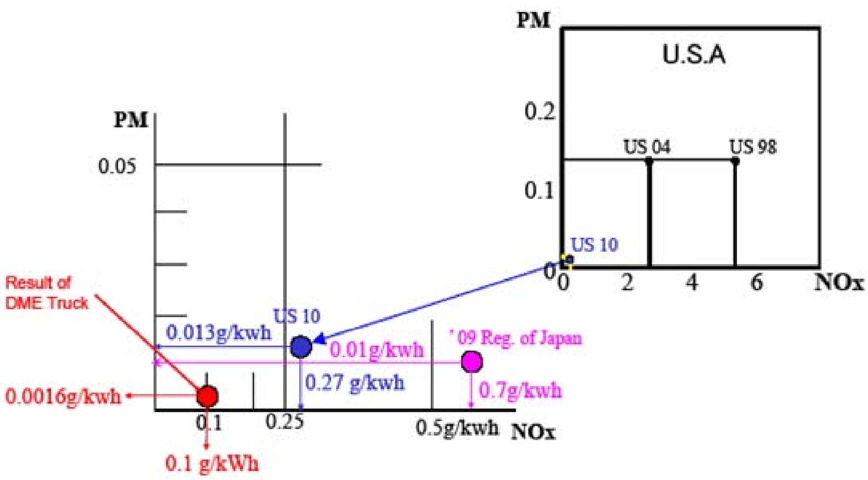


Figure 6.16. Emission performance of Nissan Diesel's DME engine in relation to oncoming U.S. 2010 emission regulations (Green Car Congress 2006b).

Hydrogen

It is easy to report emission data for fuel cell vehicles, because, in practice, they are zero -emission vehicles regarding end-use emissions. This is demonstrated by the fuel cell engine technical specification of the Mercedes-Benz Citaro FC bus. The rows for emission read 0.000. When burned in an ICE hydrogen can create some NO_x emissions. In addition, the lubricant of the engine may produce some hydrocarbon emission or even particulates. Figure 6.17 shows emission data for MAN's hydrogen IC engine. NO_x emission is 0.4 g/kWh, and particle emissions below detection limits.

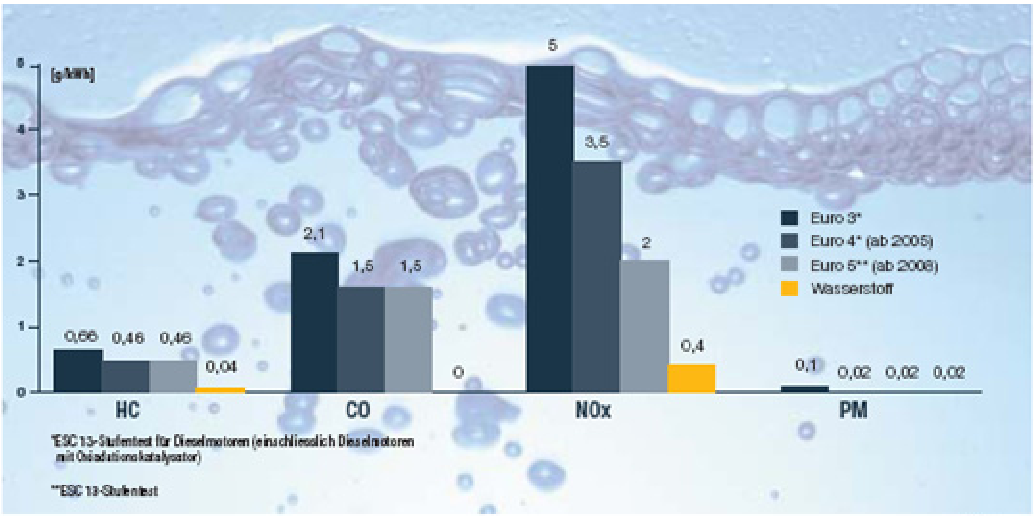


Figure 6.17. Emissions values for MAN's hydrogen ICE. Wasserstoff = hydrogen. (MAN)

6.6 Hybrid vehicles

There is little numerical emission data available for hybrid passenger cars. Most U.S. documentation simply states fulfillment of a certain emission category. The U.S. DOE has, however, published a leaflet comprising numerical emission data on the previous generation Toyota Prius hybrid vehicle. The Prius has been bench-marked against two other Toyota models, Corolla and Camry. The reported NO_x value for Prius was 0.009 g/mile, whereas the Californian SULEV limit value is 0.02 g/mile. Fuel consumption was 5.1 l/100 km (46 mpg) for Prius and 7.5 l/100 km (31.6 mpg) for Corolla. (DOE)

In the U.S., the Advanced Vehicle Testing Activity (AVTA), which supports DOE's FreedomCAR & Vehicle Technologies Program is monitoring several advanced vehicle fleets, including hybrid bus fleets. The main objective of AVTA projects is to provide comprehensive, unbiased evaluations of advanced technologies. The interim report from King County Metro contains emission data for the parallel-hybrid buses using GM

Allison E^P50 technology. Table 6.1 shows chassis dynamometer data for fuel economy and emissions for four different duty cycles (hybrid results relative to diesel version).

In chassis dynamometer testing, fuel economy is improved by 30–75%, i.e., fuel consumption is reduced by 23–43% with the hybrid. The reduction in NO_x roughly follows fuel consumption, i.e., NO_x reduction is 18–39%. PM emissions vary significantly from test cycle to test cycle, and the benefit for hybridization is 0–93%. This is surprising, as both vehicles (baseline diesel and hybrid) are equipped with particle filters. This indicates that for an extreme cycle, like the Manhattan cycle, the hybrid system smoothes engine operation so much that particle emissions are significantly reduced.

Table 6.1. KC Metro chassis dynamometer test results (Chandler & Walkowicz 2006).

	Manhattan	OCTA	CBD	KCM
Fuel Economy (mpg, % increase)	74.6%	50.6%	48.3%	30.3%
Fuel Consumption (gpm, % reduction)	42.9%	33.7%	32.8%	23.4%
NOx (gpm, % reduction)	38.7%	28.6%	26.6%	17.8%
PM (gpm, % reduction)	92.6%	50.8%	97.1%	Ns
CO (gpm, % reduction)	ns	32.0%	48.0%	59.5%
THC (gpm, % reduction)	ns	ns	75.2%	56.3%

Note: gpm = gallons per mile; mpg = miles per gallon; ns = not statistically significant at 95% confidence level or not enough data to determine; THC = total hydrocarbon.

7. Well-to-wheel greenhouse gas emissions and efficiency

CNG, LPG, biogas, DME, and hybrids

- *High costs for GHG savings with hybrids, CNG and LPG.*
- *Low cost for GHG savings with biogas from waste.*
- *DME offers good energy and GHG balance, but would require modified vehicles and infrastructure.*

Liquid fuels

- *GHG balance of traditional biofuels depends on production route, by-products and emissions from agriculture. Balance for ETBE depends on ethanol origin.*
- *Cellulosic ethanol: good energy and GHG balance at tolerable costs.*
- *GHG emissions with GTL higher than for diesel; high GHG emissions for CTL if CCS is not applied.*
- *BTL provides GHG benefits, but energy use is high. Costs of GHG savings comparable to traditional biodiesel.*

Hydrogen

- *Results depend on production routes. Marginal benefits at high costs if produced from natural gas. High GHG emissions using electrolysis and EU-mix or US-mix electricity. Low GHG emissions from renewables or nuclear energy.*
- *GHG emissions higher for hydrogen ICEs than for NGVs. Only little GHG benefits with on-board reformers.*

Other aspects

Near-zero-emissions possible only with electricity, hydrogen and biofuels. Diesel engines and fuel cells are the most efficient energy converters. Hybrids offer a significant improvement. Vehicle size is an important factor and can overrule differences between fuel/technology options.

IEA WEO 2006 projects that energy-related CO_2 emissions will increase by 1.7% per year, from 26 to 40 billion tons between 2004 and 2030, if no preventive actions are taken. Rogner (2005) reported that the global CO_2 emissions are projected to range from 29 to 44 $GtCO_2$ in 2020 and 23 to 84 $GtCO_2$ in 2050. The major CO_2 source is related to power production, representing some 41% of the CO_2 emissions, and the transport sector is second with a share around 20% of the emissions.

A study for the European Commission pointed out that, in the reference case, greenhouse gas emissions (i.e., CO_2, CH_4, N_2O, HFC, and SF6) will double, from 425 ppmv to over 900 ppmv, from the level in 2000 by 2100, and this would result in a 3 °C increase in temperature. (Criqui et al. 2003)

EIA IEO 2006 reported projections for CO_2 emissions in the reference case and in the Kyoto Protocol case. The increases in CO_2 emissions by 2030 are mainly originating from non-OEDC countries (Figure 7.1). Increasing usage of fossil fuels in the world means that even in the Kyoto Protocol case there would be an increase in global CO_2 emissions.

One option to reduce greenhouse gas emissions outside the transport sector is CO_2 capturing and storage (CCS). The most suitable targets for this are large stationary sources and processes with streams of high CO_2 concentrations. There are, however, many aspects, technical, environmental and economical, which affect the true feasibility of CO_2 capture and storage technologies and the long-term viability of CCS is not yet proven. Today CCS is demonstrated in a few storage facilities. CCS global storage potential is estimated to be at least 2000 $GtCO_2$ (about 80 years of current emissions) (IEA Energy Technology Essentials 2006). Life time or residence time of CO_2 in the atmosphere is about 200 to 300 years. The decay rate (similar to radioactivity) is in the order of 50 to 70 years (Finckh 2007).

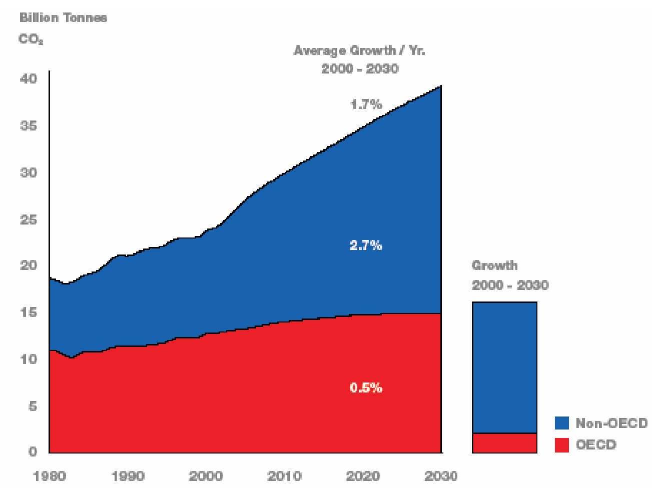


Figure 7.1. World CO_2 emissions from OEDC and non-OEDC countries (EIA IEO 2006).

Evaluation of different future fuel and vehicle options is a complicated process, which should take into account all sustainability aspects from production to end-use. Life cycle assessments (well-to-wheel evaluation) of greenhouse gases and efficiency are among the most important tasks. Well-to-wheel CO_2 emissions from different transport modes were evaluated in the Sustainable Mobility Project (Figure 7.2, WBCSD 2004). Significant improvement in the energy efficiency of vehicles was assumed over the projection period. However, the reductions in energy consumption would not compensate the projected growth in the transport activities. This results in increase in GHG emissions for each transport mode in each region. (WBCSD 2004)

Light-duty vehicles account for the biggest share of transport related CO_2 emissions. The second largest mode is freight trucks, and this share is increasing. The share of CO_2

emissions from air traffic, and to lesser extent marine transport, is also increasing over the projected period. CO_2 emissions from air traffic will almost catch up with the emissions from freight trucks by 2050. Rail traffic, buses, and 2- and 3-wheelers represent only a fraction of the CO_2 emissions from transport sector. (WBCSD 2004)

As in the case of total CO_2 emissions, the increase in transport CO_2 emission will mostly also take place in non-OEDC countries, because growth in transport activities is high in developing regions. In addition, clean vehicle technologies and fuels will be introduced later, and to lesser extent, in developing countries than in the developed world. (WBCSD 2004)

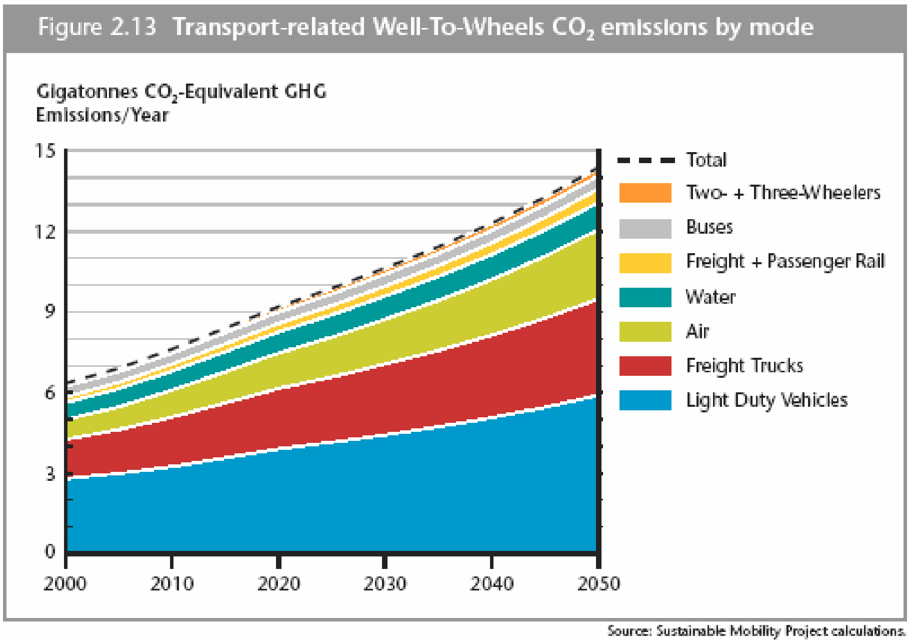


Figure 7.2. Transport related Well-To-Wheel CO_2 emissions by mode and by region (WBCSD 2004).

Discussions on energy options should consider all energy sectors. One of the basic issues is that the cost of CO_2 avoidance in power production is currently much lower (well below $50 per CO_2 ton) than in the transport sector (Figure 7.3). Very few options in the transport sector can show similar cost efficiency level for CO_2 avoidance as the power sector.

In 2006, EUCAR, CONCAWE, and JRC updated an extensive well-to-wheel analysis of different fuel/powertrain options. The analysis covers GHG emissions, energy use, and costs associated with different pathways to mitigate CO_2 emissions. Fuel production pathway and powertrain efficiencies were taken into account. Practicality, potential, and availability for the main alternative and biofuels were discussed.

EUCAR, CONCAWE, and JRC noticed that a shift to renewable/low carbon routes may offer a significant GHG reduction potential, depending on technology selections. Costs and GHG reductions were not always in-line (Figure 7.4). The report points out that no single potential "low carbon" fuel exists, but a number of technologies will be needed. Blends with biocomponents in conventional fuels and niche applications of alternative fuels can sometimes produce GHG reductions at reasonable cost. Synthetic fuels and hydrogen from coal or gas offer substantial GHG savings, if combined with CO_2 capture and storage (CCS). The study also pointed out that to maximize GHG savings, transport may not be the best sector for renewable energies.

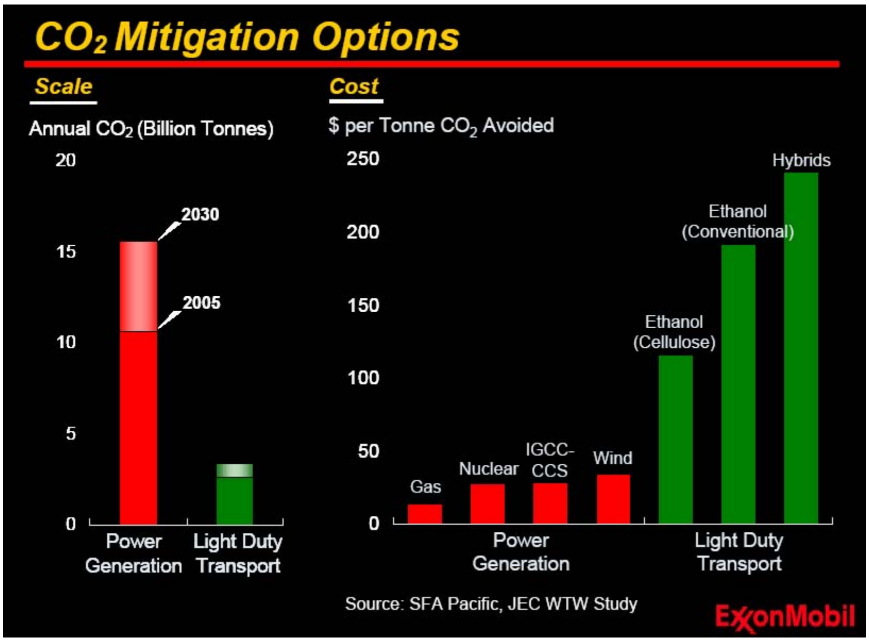


Figure 7.3.Comparison of the costs of CO_2 avoidance in power production and power generation (ExxonMobil 2006).

The following conclusions were drawn from the 2006 WTW study (WTW 2006):

CNG, LPG, biogas, DME, and hybrids:

– Energy efficiency of vehicles will improve. Costs for CO_2 avoidance with hybrids exceeds 1000 €/t CO_2.

– CNG is in between of gasoline and 2010+ diesel. CNG and LPG show high cost per avoided CO_2 ton.

– Biogas from waste provides low cost GHG savings.

– DME from natural gas or biomass -> better energy and GHG balance than for liquid fuels, but DME would require modified vehicles and infrastructure.

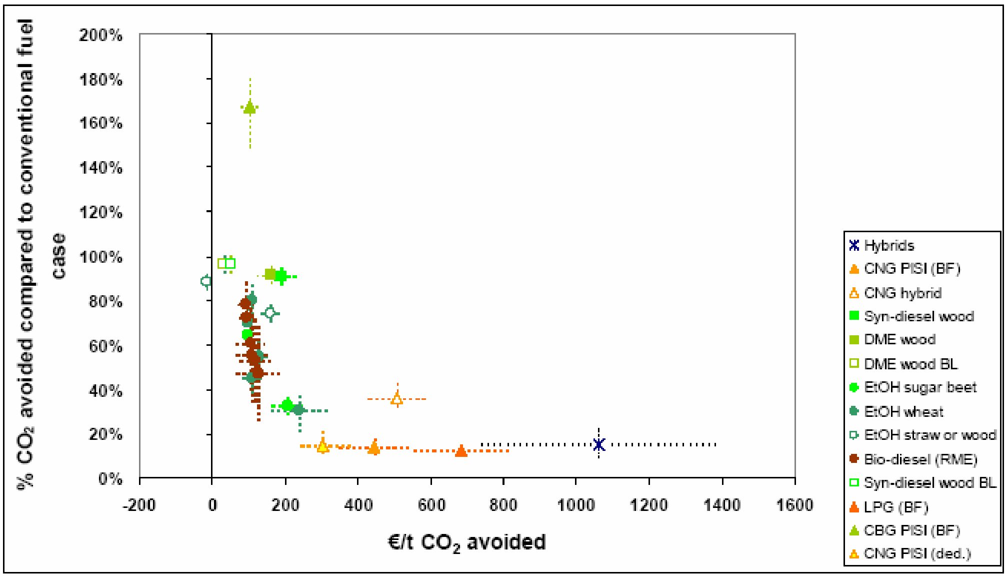


Figure 7.4. The costs and potential of different pathways to reduce CO_2 emissions, oil price 50 €/bbl (WTW 2006).

Liquid fuels:

- The balance of ethanol and biodiesel strongly depends on production processes and by-products plus emissions from agriculture. Cellulosic ethanol – good energy and GHG balance at tolerable costs.
- ETBE results are proportional to ethanol origin.
- GHG emissions with GTL higher than for diesel; high GHG emissions for CTL.
- BTL biodiesel provide GHG benefits, but energy use is high. The costs of GHG savings comparable to traditional biodiesel.

Hydrogen:

- Results depend on production routes. From natural gas, savings only in fuel cell vehicles at high costs. GHG emissions are high using electrolysis (EU-mix electricity). Hydrogen from renewables or nuclear energy offers low GHG emissions.
- WTW energy use and GHG emissions are higher for hydrogen ICEs than for CNG vehicles (currently, natural gas is the only viable and cheap source of hydrogen).
- On-board reformers offer little GHG benefits.

IEA has analyzed the potential of various fuel/vehicle technologies to reduce CO_2 emissions (IEA 2004). This report stated that only electricity, hydrogen, and biofuels can yield a near-zero-emissions transport system. The report also points out that efficiency improvement is very important.

The following CO_2 saving potentials were estimated (IEA 2004):

- Intelligent transport system: max 10–50%
- Higher ICE/hybrid efficiency: max 10–50%
- Electric vehicles (renewable electricity and/or CCS): over 90%
- Fuel cell vehicle (renewable electricity and/or CCS): over 90%
- LPG, CNG, DME (fossil): possibly 10–50%
- Ethanol, methanol, biodiesel (current): max 10–50%
- 2nd generation biofuels: possibly over 90%
- Hydrogen, fossil: possibly 10–50%
- Hydrogen, renewable/CCS: over 90%
- Electricity, renewable/CCS: over 90%.

There are different pathways to use remote natural gas in transport. A comparison of using remote natural gas in the form of CNG, methanol or FT diesel shows well-to-tank (upstream) losses of 38% for methanol, 40% for FT diesel, and 19% for CNG (Ramesohl 2003). In vehicles, methanol and CNG would be used in spark-ignition engines with higher energy consumption compared with diesel. When calculating an efficiency of 30% for spark-ignition engines and 40% for diesel engines, the CO_2 emission per kWh work on the engine would be 1,200 g for methanol and roughly 900 g for FT diesel and CNG. It should be noted that Ramesohl used a high estimate for FT conversion efficiency.

Well-to-wheel greenhouse gas emissions with different FT diesel options are shown in Figure 7.5. Tailpipe CO_2 emissions with synthetic fuel are lower than with conventional diesel due to higher hydrogen to carbon ratio of FT diesel. However, overall CO_2 emissions may be higher for fossil GTL from natural gas than for conventional diesel, and clearly higher for coal-based CTL. According to ASFE, the GTL process was comparable to conventional oil (+/-5%), but CTL showed a carbon penalty, although this could be reduced through CO_2 sequestration in future. BTL offered clear benefits, with 60–90% reductions in WTW CO_2 emissions.

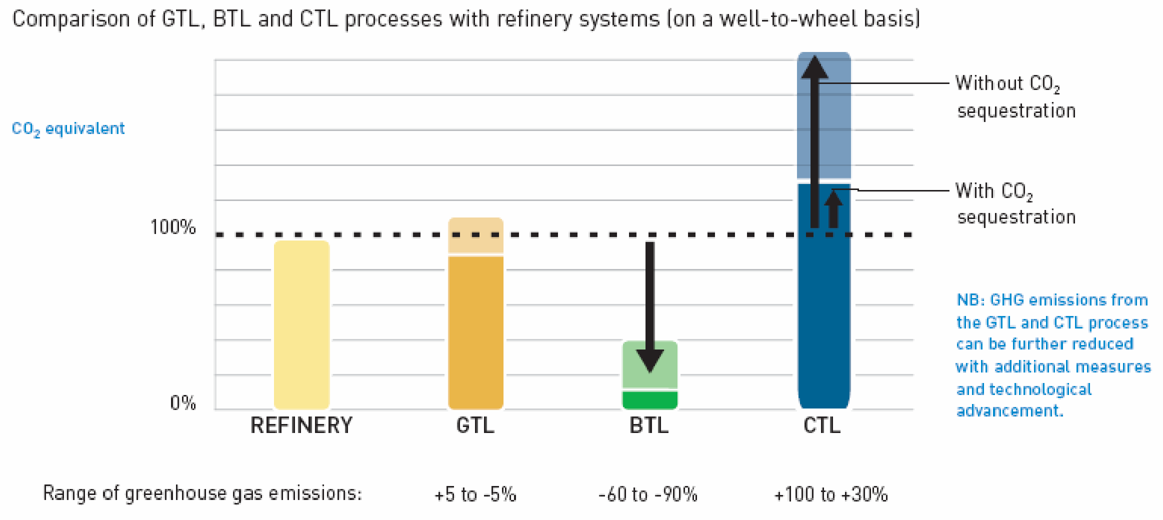


Figure 7.5. Comparison of well-to-wheel CO2 emissions from synthetic liquid fuels (ASFE).

Volvo has evaluated various HD vehicle fuel cycles based on combined well-to-wheel efficiency and CO_2 assessment (Figure 7.6). Volvo concluded that DME form natural gas is the second most efficient fossil alternative after diesel, and that biogas and DME from black liqour is the most efficient renewable options. (Jobson 2007)

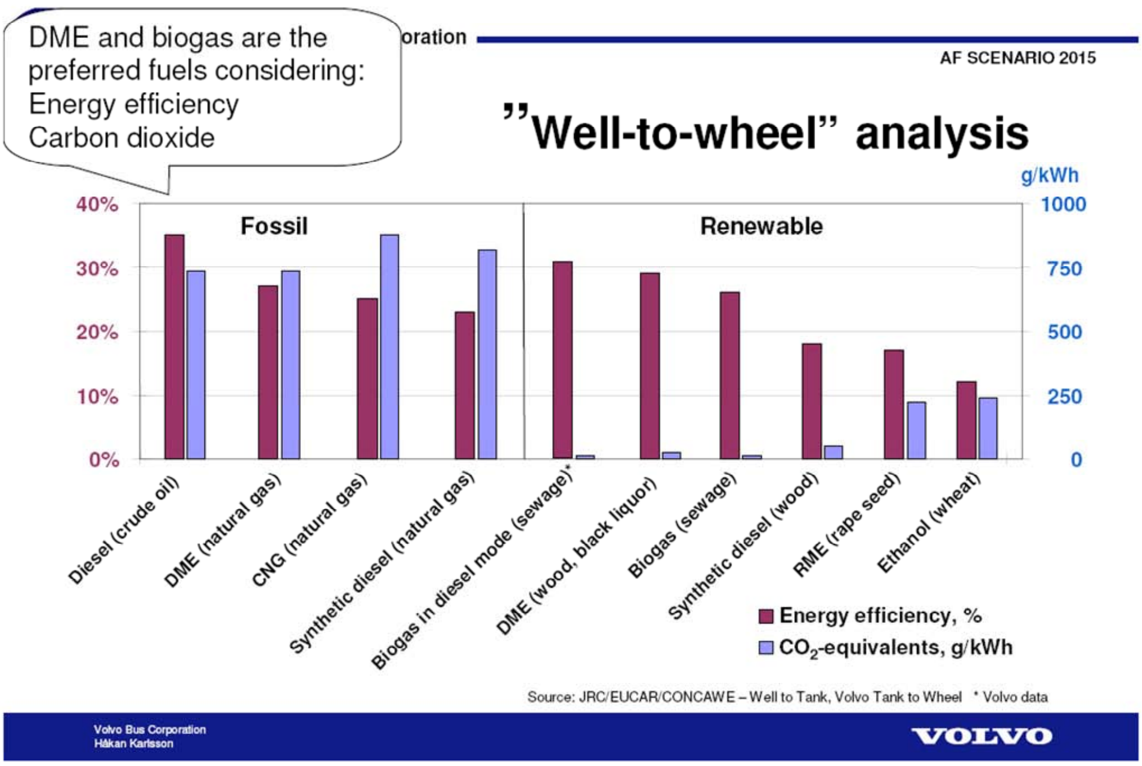


Figure 7.6. Well-to-wheel energy efficiency and CO_2 emissions of various fuels (Jobson 2007).

One life cycle assessments on hydrogen by Granovskii (2006) reported that the best results were obtained for a PEMFC vehicle using wind power to produce hydrogen via electrolysis. The GHG emission and energy consumption figures were the lowest for this combination.

Lane (2006) reported on the life cycle assessment of vehicle fuels and technologies. This study focused on commercially available options: ultra low sulfur gasoline and diesel, biodiesel, ethanol, natural gas, LPG, battery-electric, and hybrid-electric vehicles. Technologies excluded were methanol (due to high toxicity), hydrogen, GTL fuels, DME, fuel cell electric vehicles, compressed air engines, and 'Plug in Hybrid's. One key finding of the LCA study was that vehicle size is as important a determinator of emission impact as fuel/technology type. The vehicle size is strongly correlated to overall environmental impact.

8. Projections and discussion of fuel/vehicle options

8.1 Projections

There are three main drivers for the development of alternative fuels, increase in transport fuel demand, the risk of shortages of oil and/or rocketing oil prices and the need to reduce greenhouse gas emissions some 50% by 2050.

IEA and EIA predict that the world energy demand will increase by over 50% from now to 2030, if policies remain unchanged. China accounts major part of global energy consumption growth. Thus the key issues today are energy savings and improved energy efficiency.

Fossil fuels, oil, natural gas, and coal are expected to remain the major energy sources for many decades, oil being predominant until 2030. Oil's share of world energy is projected to decrease, but the demand in absolute terms will grow to some 120 mbpd by 2030 from today's 85 mbpd. Oil resources are concentrated regionally, with the largest reserves in the Middle East. Large importers will be increasingly dependent on oil producers in the Middle East and North Africa. There are abundant hydrocarbon reserves in the ground, but major technological progress and investment are needed to use such resources as deep-water and unconventional oil. Natural gas resources are more evenly distributed, but utilization of remote natural gas sources means increases in both LNG shipping and fuel prices. For economic and energy supply reasons, coal and nuclear energy may increase within the power sector despite of problems related to both of these energy sources.

IEA (IEA WEO 2006) expects renewable energy sources, mainly biomass, to account for 14% of total energy in 2030, and biofuels could cover 4–7% of world transport fuel demand. However, the highest estimates of technically feasible bioenergy reserves state that bioenergy could cover as much as 30% of world energy demand by 2030. Power and heat production is the most efficient end-use sector for biomass. Despite this, interest in biofuels for transport is enormous today.

Most of the growth in demand for energy in general as well as for transport fuels takes place in non-OECD countries. Gasoline and diesel are projected to continue as the dominant automotive fuels by 2030. The scenarios for alternative fuels vary a lot. Alternative fuels and technologies for transport are considered based on fuel security, economy, local pollution, and global warming. However, in the transport sector, end-use issues and fuel properties are more critical than in the other energy sectors. The infrastructure for transport fuels is rigid and requirements for fuel quality are tight. Fuel production processes, fuel quality, engines, and infrastructure set a number of obligations and limitations to each other. This means, e.g., that solid biomass is more efficiently used for power and heat than for liquid transportation fuels.

Biofuels based on traditional feedstocks, such as corn ethanol and vegetable oil based diesel fuels, will still be used in 2030. Traditional biofuels are typically attached with sustainability and end-use problems, but on the other hand, capital costs of processes are moderate. Hydrotreated vegetable oil provides a leap for good end-use properties. Sustainability of feedstock has to be addressed using internationally accepted criteria and rules.

Traditional biofuels might gradually be replaced by next generation synthetic biofuels. Coal and natural gas can also be used as feedstock for synthetic fuels. Generally, these fuels provide better performance than traditional fuels, and are expected to gain importance in the long run. However, processes for synfuels are rather capital-intensive resulting in modest projections by 2030. Practically, Biomass-to-Liquids (BTL) plants will come on stream as late as 2012–2015. Investments in synthetic fuels, cellulosic ethanol and BTL, are huge today.

The average cost for first generation biofuels varies from some 10–20 €/GJ, only Brazilian sugercane ethanol being cost competitive with gasoline and diesel. The current cost estimates for, e.g., lignocellulosic ethanol are higher, but with a promise of reduced cost when technology is improved. Ethanol will most probably be in greater demand than e.g., BTL-type biodiesel. This assumption is based on the fact that diesel fuel is dominant in Europe, but gasoline in those parts of the world, where yields and growing conditions for biomass are the best.

Natural gas is a quite common fuel alternative. Cleaned biogas can substitute natural gas. Biogas is already used in many countries. However, gaseous fuel require dedicated infrastructure, and this hinders large scale deployment.

Other fuels, such as DME and hydrogen will, at the most, be niche fuels in the transport sector in the medium-term. Estimates for the longer term depend on development of sustainable hydrogen production technology.

Table 8.1 and Figure 8.1 summarize the current consumption of alternative motor fuels and show projections for 2020. The projections are derived from various sources. The mandates for biofuels in Europe and in the U.S. provide additional reference. Share of alternative fuels in transport may increase from current 4% to some 11% by 2020, and share of biofuels from some 1.5% to some 6%, respectively. Major contributors would be traditional ethanol (4%) and gaseous fuels (3.5%). Share of vegetable oil based biodiesel, GTL and CTL would be below 2% each.

By 2030, alternative fuels could represent a 10–30% share of transport fuels, depending on policies. As advanced biofuels are still in their infancy, it seems probable that traditional biofuels will also be used in 2030. Whatever the fuels and the technical solutions in transport might be, energy savings should have very high priority. By 2030, energy savings surely delivers higher potential for oil savings than implementing alternative fuels. Figure 8.2 shows the projection of IEA WEO 2006 for oil consumption in the transport sector and savings achievable in the Alternative Policy Scenario by different means. IEA counts heavily on increased efficiency of new vehicles, a potential equivalent of some 5 million bpd. Even in the Alternative Policy Scenario oil consumption will increase substantially, so energy savings is a must.

Table 8.1. Current transport fuel volumes and estimates for 2020 (several sources, summary of projections by authors).

Fuel	2005		2020*)		Potential in long-term
	Consumption (Mtoe/a)	Share of transport fuels 2005 (%)	Estimated volume (Mtoe/a)	Estimated share of transport fuels (%)	
World road transport fuels	1,600		1,900		
Alcohols					
- Ethanol	18	1.1	80	4	High, if feasible processes for cellulosic feedstocks
- Methanol	3	0.2	3	0.2	End-use problems
Biodiesel					
- FAME & hydrotreated	4	0.3	30	1.5	End-use problems with FAME
- BTL	0	0	1	0.1	High, if feasible processes using cellulosic feedstocks
Other liquid fuels					
- GTL	1	0.1	20	1.0	
- CTL	7	0.4	20	1.0	
Gaseous fuels					
- Natural gas	18	1.1	40	2.0	
- Biogas	0	0	10	0.5	Reasonable for biogas
- LPG	17	1.1	20	1.0	
- Hydrogen	0	0	EU target 7 mtoe/a		
Sum alternative fuels	69	4.4	~220	~11	
Sum biofuels	22	1.4	~120	~6	

*) Sources: projection for ethanol by IFP (2007) and for GTL and CTL by ASFE. Projection for biodiesel is based on EU policy target, 10% biofuels in transport (~34 Mtoe), which would be mainly covered by FAME and HVO biodiesel, and a small share of biodiesel used in other countries. Projection for natural gas and biogas is based on the increase of natural gas vehicle population reported by GVR.

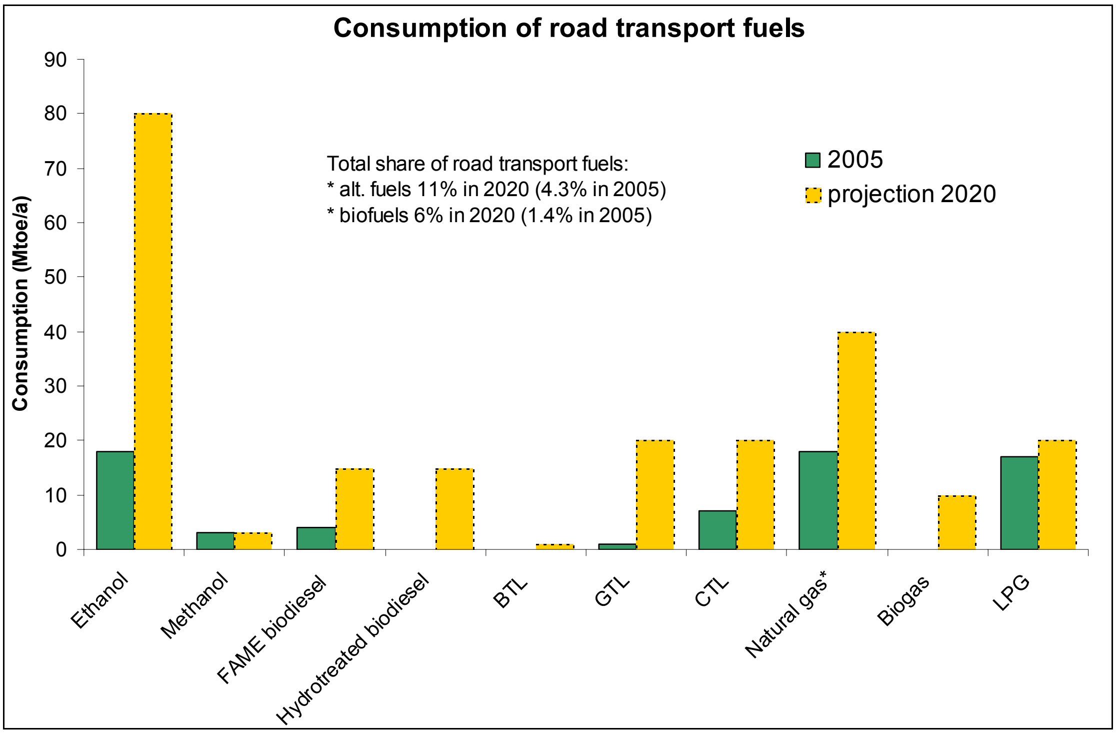


Figure 8.1. The consumption of alternative motor fuels and projections by 2020.

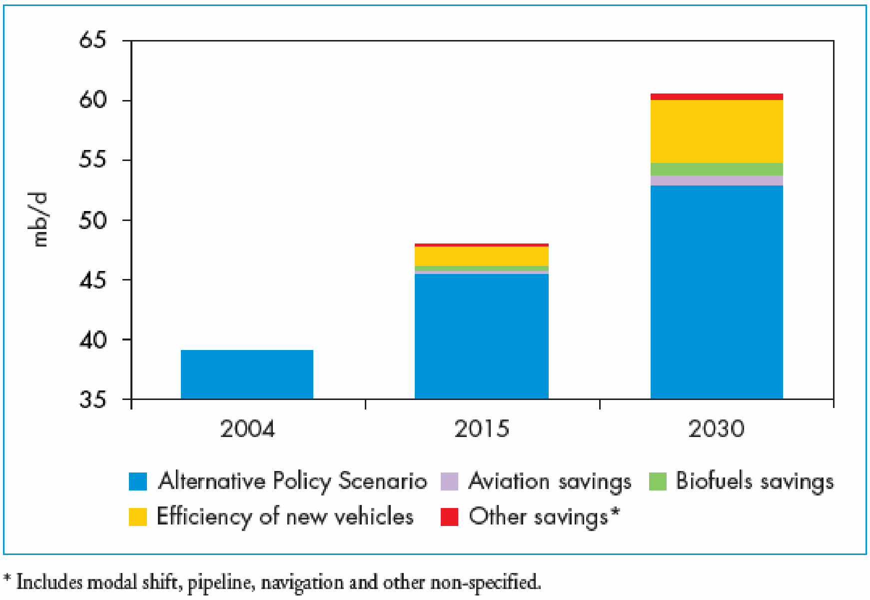


Figure 8.2. Prospects for oil consumption in transport sector and savings achievable by alternative policies (IEA WEO 2006).

8.2 Discussion

The evaluation of the benefits and drawbacks of different future fuel and vehicle technology alternatives and options should consider many factors, e.g., feedstock availability, feasibility of production process, compatibility with existing infrastructure and vehicles, and global and regional emissions and economy.

Different starting points and views on development determine the results of evaluations of energy options. In addition, it might be necessary to put effort on several pathways to serve near-term, long-term, regional, and international needs.

This Chapter analyzes alternative options for the transport sector, qualitatively, in the following categories:

1. Energy security
2. Climate change
3. Local pollution
4. Sustainable future.

ENERGY SECURITY

Energy is the key commodity to maintain modern living style, especially in the developed world. Thus, sufficient actions to ensure energy in future are needed. Fossil fuels are expected to remain the major energy source for many decades. There are, however, many problems associated with fossil fuels, most of which will turn more serious every year.

The easy reserves of fossil fuels, especially in the case of oil, are diminishing, and the proven reserves are concentrated in certain geographic regions. Utilization of unconventional resources is costly, and does not help with global warming. In addition, unconventional resources are mostly located in rural, virgin areas that should be conserved for environmental and humanitarian reasons.

The transport sector is almost totally dependent on fossil fuels. Utilization of alternative energy in transport sector is less energy-efficient and more expensive than in the other energy sectors. In this respect, it is reasonable to continue with conventional gasoline and diesel in the transport sector as far as possible. However, *it is essential that transport sector starts to prepare for a time without oil*, *or at least oil shortages*. In practice, for the transport sector this means ***finding the least bad options!***

With regards to the energy security aspect, a number of alternatives can be listed for the transport sector. All options that increase flexibility and independence of oil are valuable. However, each option has a price tag, both in the form of direct costs and external (environmental) costs. Prices as well as environmental impacts may change over time as technology develops.

There is no simple answer to the best fuel or vehicle technology. The optimum solution is most probably a combination of several technologies.

The crude oil based liquid fuels, gasoline and diesel, are potential options for transportation for many decades to come, and the "difficult" resources, including unconventional oil, are probably sufficient for transportation needs for a long time after conventional oil has run out. Synthetic fuels based on natural gas, coal, or biomass also are potential options to some extent, as well as natural gas. As a summary, the best options in terms of energy security could be as follows:

1. Gasoline and diesel from "difficult" oil resources (incl. unconventional oil)
2. Synthetic fuels from natural gas or coal
3. 2nd generation biofuels from biomass
4. 1st generation biofuels from biomass.

The first three options are completely compatible with the existing infrastructure and vehicles. First generation biofuels may require vehicle modifications, if used at high concentrations. *Energy savings will reduce the amount of fuel needed, and thereby also improve energy security.*

Both 1st and 2nd generation biofuels contribute to energy security, although it is questionable if all 1st generation biofuels are beneficial for GHG reductions and local emissions.

CLIMATE CHANGE

The energy-related greenhouse gas emissions are continuously increasing. The major source of greenhouse gases is power production, and the transport sector is the second largest emitter with a share around 20% of the CO_2 emissions. The climate change issue has brought forward many political actions to promote *renewable energy and energy savings*. Some actions against climate change resemble actions for energy security. *Energy savings* and *renewable energy* are key issues in both cases. Renewable energy reduces greenhouse gases and also supports local energy production. The major difference is that alternative fossil energy is fully acceptable for energy-security, but not necessarily regarding environmental aspects. As regards climate change, using fossil fuels is fundamentally problematic, even if preventive actions, such as CO_2 capturing and storage (CCS) technology, are used. CCS is suitable only for stationary sources, not for mobile applications.

The renewable energy options technically feasible for transport could be:

- Biomass based liquid fuels

- Biogas
- Renewable electricity
- Hydrogen produced with renewable electricity.

Biomass-based liquid fuels and biogas have the highest short-term potential for transport fuels supporting climate change targets. Hydrogen and renewable electricity could be long-term options, but major technological development and cost reduction are needed before these technologies can make a significant impact in the transport sector. Thus the future of hydrogen and electric vehicles is uncertain.

Currently the contribution of biomass to energy is rather limited. However, the potential of biomass is estimated to be sufficient to cover as much as 30% of energy demand by 2030. The largest biomass potential is provided by forests and annual crops in the southern hemisphere.

Considering that the efficiency of using biomass in the power sector is higher than in the transport sector, and keeping in mind that the atmosphere does not recognize which sector achieves the savings in the greenhouse gases, it seems reasonable, at least from short- to mid-term, to mainly use biomass in applications other than in transportation: *Use biomass where it gives the highest CO_2 savings with the lowest costs!* It should also be kept in mind that the 1st generation biofuels, especially grain based ethanol, are not necessarily effective for GHG reductions.

IEA WEO 2006 and also other studies have pointed out that *the transport sector has the highest potential for energy savings of all energy sectors*. These can be obtained through improving energy efficiency and down-sizing vehicles plus a number of other actions, such as promoting public and non-motorized transportation, improving logistics, and increasing density of population in the cities. Apparently, the transport sector is wasting energy.

As a conclusion, *in the transport sector the primary actions against climate change should be related to energy savings*.

LOCAL POLLUTION

Many cities and regions suffer from bad air quality. Emissions from modern vehicles equipped with sophisticated emission control devices are low. However, even further emission reductions can be achieved with alternative fuels and advanced technologies.

Sophisticated gasoline vehicles and diesel vehicles equipped with particle trap and/or SCR technology can be very clean regarding toxic exhaust emissions. For local pollution, the combination of engine/after-treatment technology is the determining factor, not the fuel even though some fuels, like methane, reduce local emissions. In principle, many types of fuels can be used for spark-ignition (gasoline) and compression-ignition diesel vehicles. However, the fuel alternatives providing significant emission reductions in existing vehicles are rather few. Development work to combine the low-emission characteristics of the spark-ignited engine with the high efficiency of the diesel engine is under way.

Current hybrid vehicles (grid independent) are not necessarily cost effective for CO_2 reductions, but hybrid technology provides fuel savings as well as reductions of conventional pollutants. “Plug in hybrids” and fuel cell vehicles are almost “zero” tailpipe emission vehicles. Cost effectiveness depends on technical development and greenhouse gas balance on how electricity and hydrogen is produced.

It is possible to reduce local pollution also by switching from conventional fuel to alternative fuel. Some alternative fuels such as methane, DME, and hydrogen require dedicated engines and vehicles, and cannot be implemented in the existing vehicle fleet.

Vehicles optimized for methane (natural gas or biogas) are cleaner than gasoline or diesel vehicles regarding almost all regulated and unregulated emissions. Biogas is also beneficial for reduced CO_2 emissions.

Synthetic fuels, on the other hand, are compatible even with existing vehicles. One of the best options in this case is synthetic diesel fuel, either Fischer-Tropsch fuel from synthesis gas (Sunfuel) or hydrotreated vegetable oil (NExBTL, H-Bio).

These are paraffinic, clean burning fuels, which reduce NO_x and PM emissions when compared with conventional diesel fuel. Traditional biodiesel (vegetable oil ester) is not a good option to help with local pollution problems due to increased NO_x emissions, despite the benefit in the particulate matter emission. Ethanol, as a blend with gasoline or as E85 fuel, does not significantly affect regulated exhaust emissions, but it increases some emission components, especially acetaldehyde emissions.

With respect to local air pollution, the following options are listed:

1. Electric vehicles, “plug in hybrids”, fuel cell vehicles etc.
2. CNG or biogas, latest technology and hybrids
3. Sophisticated gasoline and diesel vehicles, latest technology and hybrids
4. Synthetic Fischer-Tropsch diesel or 2nd generation biodiesel
5. Advanced combined combustion systems.

SUSTAINABLE FUTURE

Many researchers predict that automotive technology is moving towards electric power trains. Ultimately, this could mean either advanced battery electric vehicles, possibly with some kind of range extender, alternatively plug-in hybrids, or hydrogen fuel cell vehicles.

In the meantime we will continue using internal combustion engines. Fossil fuels will be available for decades in the transport sector. New combustion processes requiring tailored fuels may emerge. At the same time the fuel quality requirements of conventional engines will continue to be tightened as emission regulations get even more stringent. It is therefore easy to predict that the importance of synthetic fuels will grow in the future.

However, it is a fact that a time without oil will come sooner or later. Thus, it is essential that the transport sector starts getting prepared for a non-fossil era and oil shortages resulting in price volatility in short-term. The use of fossil fuels, both from conventional and non-conventional sources might be restricted for reasons related to environmental impacts and climate change.

The future options for non-oil or non-fossil transport are listed as follows:

1. Synthetic biomass based fuels (and lignocellulosic ethanol)
2. Electric vehicles, "plug in hybrids", hydrogen fuel cell vehicles etc.
3. Vehicles capable of using biogas and ethanol (CNG vehicles, FFV vehicles).

Natural gas and coal will be available for a longer time period than oil. Natural gas and coal based synthetic fuels are not sustainable, but they share the same kind of technology that can be used for BTL production. Thus, it is important to develop production technologies and to increase usage of synthetic fuels based on natural gas, coal but most of all, biomass. Gasification and syngas technology also make it possible to produce fuels like DME, methanol, synthetic methane, and hydrogen from solid feedstocks. CCS can help improving the overall carbon balance somewhat for CTL and GTL fuels.

Use of natural gas/biogas in special vehicles is also important, even though it is a niche solution. A combination of various alternative transport fuels/technologies provides flexibility, which is of great value when oil products are not available. Niche fuels like biogas or electricity in city transport may keep public transport and society functioning, even if some transport modes would stagnate.

Biofuels reduce greenhouse gas emissions from the transport sector when selecting the right production concepts. However, the biomass potential is not sufficient for all energy sectors, at least in short- to mid-term. A massive switch from conventional fuels to biofuels or synthetic fuels requires significant investments and a rather long lead time, not to mention if transportation were to switch over to hydrogen. World transport energy demand represents the equivalent of 2,000 electric powerplants, each with a power output of 1.5 GW (26,000 TWh).

Rapid CNG/biogas expansion is hindered by the lack of both vehicles and refueling infrastructure. Solutions providing flexibility provide added value. Current FFV vehicles, if not optimal in all respects, provide flexibility that might prove valuable in the future.

When thinking about future fuels one should keep in mind that the fuel requirements of engines change over time (e.g., switch from gasoline to diesel and ultimately to combined combustion systems). Developments in engine technology might also overcome the shortcomings of today's ethanol vehicles. Current fuel cell engines require extremely pure hydrogen.

Some researchers envisage a day when one single energy solution will cover the needs of all energy sectors. One dream is nuclear energy based on fusion instead of today's fission reaction.

When looking far away into the future, assuming that a new technology to produce energy from an abundant primary source were to exist, this energy would probably be available in the form of electricity. Electricity might be used in vehicles as is, or utilized to convert water to hydrogen.

SUMMARY OF ANALYSIS AND DISCUSSION

Alternative options for the transport sector were analyzed regarding energy-security, climate change, local pollution, and preparation for the future. In principle, it would be possible to give ratings for each technology option or pathway for the four dimensions analyzed. Table 8.2 presents an example how this could be done. As conditions, prerequisites, and policies vary from country to country, the authors leave it up to the readers to carry out their own scorings.

The major alternative fuels in transport are projected to be ethanol and methane, at least by 2020. These fuels will not provide significant help in combating climate change, as long as ethanol is not originating from cellulosic feedstocks and natural gas is not replaced by biogas.

Table 8.2. An example of scoring of various technology alternatives (suggestive, scoring by authors).

	Energy-security	Climate Change	Local pollution	Sustainable future
Energy savings	+++	+++	+++	+++
Unconventional oil	++	-	0	-
Synfuels (GTL, CTL etc.)	++	0/--	+	-
CNG in NGV	+	+/0	++	++[2)]
Biofuels, 1st generation	+	+/0	+/0	+
Biofuels, 2nd generation	++	++	+	+++
Hybrids, HEV	+	++	++	+/+++[3)]
FC vehicles on ren. H_2[1)]	+++	+++	+++	+++

+++ = very advantageous --- = very negative 0 = neutral [1)] long term option, not directly comparable with the other options [2)] biogas [3)] plug-in hybrids

As a summary, many technology and fuel options are needed in the transport sector. The most promising actions here and now are related to *energy savings*. The potential for energy savings in the transport sector is the highest of all energy sectors, and significant gains in energy security and greenhouse gas reductions can be achieved. Synthetic fuels and 2nd generation biofuels are important in many respects, especially BTL in preparation for the future. Certain vehicle technologies, such as FFVs for alcohol fuels and bi-fuel technology for gaseous fuel provide flexibility. Hydrogen and electric vehicles are promising options for the future, but today it is difficult to forecast the true potential of these technologies, especially for hydrogen fuel cell vehicles.

As the last part of discussion, the authors have the following recommendations regarding securing energy supply in road transport:

- give emphasis to energy savings and improving efficiency of the whole transport system
- favor fuel options, which give the best cost/benefit ratio, fulfill end-use quality requirements and reduce local pollution
- develop flexibility on the refinery supply side – avoid too many options on the end-use side
- limit the use of fuel alternatives requiring new infrastructure and new vehicles to applications which provide the best cost/benefit ratio (e.g., natural gas for captive urban fleets)
- fuel quality requirements change over time, be prepared for the fuel requirements of future engine concepts
- as for biofuels, focus on high quality 2nd generation fuels providing maximum potential and substitution with minimum costs and greenhouse gas emissions
- note that synthetic fuels give fuel flexibility/multi-source supply.

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Appendix 1: Fuel properties

Properties of gasoline and selected alcohols and ethers. (Several references).

	Gasoline	Methanol	Ethanol	Butanol	E85	MTBE	TAME	ETBE
Molecular weight, g/mol		32,0	46,1			88,2	102,2	102,2
Density 15 °C, kg/l	0,75	0,79	0,79	0,81	0,78	0,75	0,77	0,75
Distillation, °C	30-200	65	78	117	30-200	55	85	73
Octane number, RON	95-99	108	108	94		117	112	118
Heat value, MJ/kg	43	19,6	26,4	33	29	35	36	36
Vapor Pressure, kPa*)	60-90	32	high in blend	ok	55-85	55	14	28
Oxygen content, wt-%	0	49,9	34,7	21,6	30	18,2	15,7	15,7
Tank size equivalent	1	1,8	1,8		1,4			
Distance driven, %	100	55	70		72			
Ignition - fuel in air, %	1-8	7-36	3-19					
Stoichiometric air/fuel ratio	14,7	6,4	9		10	11,7	12,1	12,2

*) Blending vapor pressures can be very different, e.g. very high and non-linear for ethanol.

Properties of selected diesel-type fuels (Rantanen et al. 2005).

FUEL PROPERTIES	NExBTL biodiesel	GTL diesel	FAME (RME)	Diesel EN590/2005
Density @15°C [kg/m3]	775...785	770....785	≈ 885	≈ 835
Viscosity @40°C [mm2/s]	2.9...3.5	3.2...4.5	≈ 4.5	≈ 3.5
Cetane number	84...99 **)	73...81	≈ 51	≈ 53
Distillation 10 vol% [°C]	260...270	≈ 260	≈ 340	≈ 200
Distillation 90 vol% [°C]	295...300	325...330	≈ 355	≈ 350
Cloud point [°C]	- 5...- 30	0...- 25	≈ - 5	≈ - 5
Lower heating value [MJ/kg]	≈ 44	≈ 44	≈ 38	≈ 43
Lower heating value [MJ/litres]	≈ 34	≈ 34	≈ 34	≈ 36
Polyaromatics [wt%]	0	0	0	≈ 4
Oxygen [wt%]	0	0	≈ 11	0
Sulfur [mg/kg]	<10	< 10	< 10	< 10

Properties of gaseous fuels (http://www.eere.com, Vision Engineer, calculations).

FUEL PROPERTIES	CNG	Hydrogen	DME	Propane	Butane
C/H/O (%)	75/25/0	0/100/0	52.5/13/34.5	82/18/0	83/17/0
Boiling Point, °C	-162	-253	-24,9	-42,1	-0,5
Vapor Pressure @ 20 °C, bar	96	-	5,1	8,4	2,1
Liquid Density, @ 20 °C , kg/m3	0,424	0,07	668	501	610
Cetane number	-	-	>55	-	-
Octane number	120-130	130+	-	112	
Heating Value, MJ/kg	38-50	121	28,4	46,4	45,7
Auto Ignition Temperature @ 1 atm, °C	540-560		235-350	470	365
Expl./Flammability Limit in air, vol %	5.3.2015	4.1.1974	3.4.2017	2.1-9.4	1.9-8.4
AFR	17,2	34,3	9	15,7	15,5

Projection on fuel properties for future CCS fuel (Seyfried 2005).

FUEL PROPERTIES	Target	Motive
Initial builing point, °C	>150	volatility
Final boiling point, °C	<210	volatility, ignition delay
Cetane number	40…45	ignition delay
Energy density, MJ/l	35…36	compatibility
Sulphur, ppm	<10	particles, aftertreatment
Aromatics, vol-%	<2	particles, NOx
Polyaromatics, weight-%	<0.5	particles, NOx
CFPP, °C	≤ -20	winter sustainability
Lubricity @ 60°C, µm	< 460	pump/injector durability

Appendix 2: Fuel specifications

Selected legislation and standards on quality of diesel fuel.

	European*) 2003/17/EC	European EN 590:2004	USA (2D) ASTM D975	Japan, Quality Assur. Law	WWFC:2006 Category 4
Fatty acid methyl ester, wt-%		≤5		≤0.1	non-detectable
Ethanol/methanol content, vol-%					non-detectable
Total acid number, mg KOH / g					≤0.08
Triglycerides, wt-%				≤0.01	
Cetane Number	≥ 51.0	≥ 51.0	≥ 40.0	≥ 45****)	≥ 55.0
Density at 15 °C, kg/l	≤0.845	0.820-0.845			0.820-0.840
Viscosity @ 40 °C, mm2/s		2.00-4.50			2.0-4.0
Sulphur, mg/kg	≤50 /≤10	≤50 /≤10*)	≤500 /≤15**)	≤50	≤10
Flash Point, °C		>55			>55
Distillation					
evaporated at 250 °C, vol-%		<65			
evaporated at 350 °C, vol-%		≥85			
T90, °C			282-338	≤360	≤320
T95, °C	≤360	≤360			≤340
Final Boiling Point, °C					≤350
Total aromatics, wt-%			<35		<15
PAH (di+), wt-%	≤11	≤11			<2.0
Carbon residue, wt-%		≤0.30	≤0.35		≤0.20
Ash, wt-%		≤0.01	≤0.01		≤0.001
Ferrous Corrosion					light rusting
Copper Corrosion		class 1	Max. No. 3		class 1
Particulate contamination, mg/kg		≤24			≤10
Appearance					Clear and bright
Water content, mg/kg		≤200			≤200
Oxidation stability, g/m3		≤ 25			≤ 25
Lubricity HFRR, µm		≤460	≤520***)		≤400
Injector cleanliness, % air flow loss					≤85
Foam volume, ml					≤100
Foam vanishing time, sec.					≤15
Metals					non-detectable
Biological growth					zero

*) From January 2005, max. 10 ppm S diesel must be available "on an appropriately balanced geographical basis".
From January 2009, max. 10 ppm S diesel; currently 8% limit is proposed for PAH (di+) content

**) From mid-2006 max. 15 ppm S diesel must be available

***) From 2005

****) Cetane index

Selected legislation and standards on properties of gasoline. 2003/17/EC to be revised.

	European*) 2003/17/EC	European EN 228:2004	USA ASTM D4814	WWFC:2006 Category 3	WWFC:2006 Category 4
RON	≥95	≥95		≥95	≥95
MON	≥85	≥85		≥85	≥85
RVP summer, kPa	≤60.0	****)			
Density, kg/m3		720-775		715-770	715-770
Sulphur, mg/kg	≤50/≤10	≤50/≤10*)		≤30	≤10
Lead content, g/l	≤0.005	≤0.005			
Distillation		****)		****)	****)
evaporated at 100 °C, vol-%	≥46.0				
evaporated at 150 °C, vol-%	≥75.0				
Olefins, vol-%	≤18.0	≤18.0		≤10.0	≤10.0
Aromatics, vol-%	≤35.0	≤35.0		≤35.0	≤35.0
Benzene, vol-%	≤1.0	≤1.0		≤1.0	≤1.0
Oxygen content, wt-%	≤2.7	≤2.7		≤2.7	≤2.7
Oxygenates, vol-%					
-methanol**)	≤3	≤3			
-ethanol	≤5	≤5			
-iso-propyl alcohol	≤10	≤10			
-tert-butyl alcohol	≤7	≤7			
-iso-butyl alcohol	≤10	≤10			
-ethers (≥C5)	≤15	≤15			
-other oxygenates***)	≤10	≤10			
Oxidation stability, min		≥360		≥480	≥480
Unwashed gums, mg/100 ml				≤30	≤30
Existent gum, mg/100 ml		≤5		≤5	≤5
Copper strip corrosion		Class 1		Class 1	Class 1
Appearance		Clear and bright		Clear and bright	Clear and bright
Metals, Phosphorus, Silicon				non-detectable	non-detectable
Other tests				*****)	*****)

*) From January 2005, max. 10 ppm S diesel must be available "on an appropriately balanced geographical basis".
E10 spesification is proposed with 3.5 wt-% oxygen content and new limits for individual oxygenates.
**) Stabilising agents must be added
***) Other mono-alcohols and ethers with final boiling point according to EN228:1999.
****) Various volatility classes
*****) Various requirements on e.g. cleanliness and deposits

Appendix 3: Exhaust emission regulations

European emission limit values for passenger cars and heavy-duty engines (DieselNet).

		CO	THC	NMHC	HC+ NOx	NOx	PM	Smoke
Light-duty gasoline		g/km	g/km	g/km	g/km	g/km	g/km	
Euro 1	1993	2,72			0,97			
Euro 2	1997	2,2			0,50			
Euro 3	2000	2,3	0,200			0,15		
Euro 4	2005	1,0	0,100			0,08		
Euro 5	2008	1,0	0,100	0,068		0,06	0,005	
Euro 6**	2014	1,0	0,100	0,068		0,06	0,005	
Light-duty diesel		**g/km**	**g/km**	**g/km**	**g/km**	**g/km**	**g/km**	
Euro 1	1993	2,72			0,97		0,14	
Euro 2	1997	1,0			0,70		0,08	
Euro 2, DI up to sep-1999					0,90		0,10	
Euro 3	2000	0,64			0,56	0,50	0,05	
Euro 4	2005	0,5			0,30	0,25	0,025	
Euro 5	2008	0,5			0,23	0,18	0,005	
Euro 6**	2014	0,5			0,17	0,08	0,005	
Euro 5, -7°C		15	1,8					
Heavy-duty, steady-state		**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	m-1
Euro 1, ECE R49	1993	4,5	1,1			8,0	0,36	
Euro 2, ECE R49	1997	4,0	1,1			7,0	0,15	
Euro 3, ESC/ELR	2000	2,1	0,66			5,0	0,10	0,8
Euro 4, ESC/ELR	2005	1,5	0,46			3,5	0,02	0,5
Euro 5, ESC/ELR	2008	1,5	0,46			2,0	0,02	0,5
EEV		1,5	0,25			2,0	0,02	0,15
Heavy-duty, transient ETC		**g/kWh**	**CH4**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	
Euro 3	2000	5,45	1,6	0,78		5,0	0,16	
Euro 4	2005	4,0	1,1	0,55		3,5	0,03	
Euro 5	2008	4,0	1,1	0,55		2,0	0,03	
Euro 6 CI - A*)**)		4,0	0,16			0,4	0,01	
Euro 6 PI - A*)**)		4,0	0,66			0,4	0,01	
EEV		3,0	0,65	0,40		2,0	0,02	

* CI=engines fuelled with diesel and ethanol PI=engines fuelled with natural gas or LPG
A=scenario similar to US limits, NH3 limit 10 ppm
**Gray colour = proposal

US Federal emission limits for passenger cars, Tier 2 Permanent Bins, FTP 75 (g/mile) (DieselNet).

Bin#	Intermediate life (5 years / 50,000 mi)					Full useful life				
	NMOG*	CO	NOx	PM	HCHO	NMOG*	CO	NOx**	PM	HCHO
8	0.100 (0.125)	3.4	0.14	-	0.015	0.125 (0.156)	4.2	0.20	0.02	0.018
7	0.075	3.4	0.11	-	0.015	0.090	4.2	0.15	0.02	0.018
6	0.075	3.4	0.08	-	0.015	0.090	4.2	0.10	0.01	0.018
5	0.075	3.4	0.05	-	0.015	0.090	4.2	0.07	0.01	0.018
4	-	-	-	-	-	0.070	2.1	0.04	0.01	0.011
3	-	-	-	-	-	0.055	2.1	0.03	0.01	0.011
2	-	-	-	-	-	0.010	2.1	0.02	0.01	0.004
1	-	-	-	-	-	0.000	0.0	0.00	0.00	0.000

* for diesel fueled vehicle, NMOG (non-methane organic gases) means NMHC (non-methane hydrocarbons)

** average manufacturer fleet NOx standard is 0.07 g/mile for Tier 2 vehicles

California LEV II emission limits for passenger cars and LDVs (g/mile) (DieselNet).

Category	50,000 miles/5 years					120,000 miles/11 years				
	NMOG	CO	NOx	PM	HCHO	NMOG	CO	NOx	PM	HCHO
LEV	0.075	3.4	0.05	-	0.015	0.090	4.2	0.07	0.01	0.018
ULEV	0.040	1.7	0.05	-	0.008	0.055	2.1	0.07	0.01	0.011
SULEV	-	-	-	-	-	0.010	1.0	0.02	0.01	0.004

EPA emission limits for heavy-duty diesel engines (g/bhp·hr) (DieselNet).

	HC	CO	NOx	PM
Heavy-Duty Diesel Truck Engines				
1988	1.3	15.5	10.7	0.60
1990	1.3	15.5	6.0	0.60
1991	1.3	15.5	5.0	0.25
1994	1.3	15.5	5.0	0.10
1998	1.3	15.5	4.0	0.10
Urban Bus Engines				
1991	1.3	15.5	5.0	0.25
1993	1.3	15.5	5.0	0.10
1994	1.3	15.5	5.0	0.07
1996	1.3	15.5	5.0	0.05*
1998	1.3	15.5	4.0	0.05*

California emission standards for heavy-duty diesel engines (g/bhp·hr) (DieselNet).

	NMHC	THC	CO	NOx	PM
Heavy-Duty Diesel Truck Engines					
1987	-	1.3	15.5	6.0	0.60
1991	1.2	1.3	15.5	5.0	0.25
1994	1.2	1.3	15.5	5.0	0.10
Urban Bus Engines					
1991	1.2	1.3	15.5	5.0	0.10
1994	1.2	1.3	15.5	5.0	0.07
1996	1.2	1.3	15.5	4.0	0.05

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Status and outlook for biofuels, other alternative fuels and new vehicles

Abstract

The report presents an outlook for alternative motor fuels and new vehicles. The time period covered extends up to 2030. The International Energy Agency and the U.S. Energy Information Administration predict that the world energy demand will increase by over 50% from now to 2030, if policies remain unchanged. Most of the growth in demand for energy in general, as well as for transport fuels, will take place in non-OECD countries. Gasoline and diesel are projected to remain the dominant automotive fuels until 2030. Vehicle technology and high quality fuels will eventually solve the problem of harmful exhaust emissions. However, the problem with CO_2 still remains, and much attention will be given to increase efficiency. Hybrid technology is one option to reduce fuel consumption. Diesel engines are fuel efficient, but have high emissions compared with advanced gasoline engines. New combustion systems combining the best qualities of gasoline and diesel engines promise low emissions as well as high efficiency.

The scenarios for alternative fuels vary a lot. By 2030, alternative fuels could represent a 10–30% share of transport fuels, depending on policies. Ambitious goals for biofuels in transport have been set. As advanced biofuels are still in their infancy, it seems probable that traditional biofuels will also be used in 2030. Ethanol is the fastest growing biofuel. Currently the sustainability of biofuels is discussed extensively. Synthetic fuels promise excellent end-use properties, reduced emissions, and if produced from biomass, also reduced CO_2 emissions. The report presents an analysis of technology options to meet the requirements for energy security, reduced CO_2 emissions, reduced local emissions as well as sustainability in general in the long run. In the short term, energy savings will be the main measure for CO_2 reductions in transport, fuel switches will have a secondary role.

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This outlook report reviews the situation for motor fuels and vehicle technology analysing the aspects of energy security, climate change, local emissions as well as sustainability. The focus is on alternative fuels, biofuels and new vehicle technologies in the time perspective until 2030. The study was carried out within IEA Advanced Motor Fuels Implementing Agreement and within the EU Bioenergy Network of Excellence (NoE). Gasoline and diesel are projected to remain the dominant automotive fuels until 2030. Vehicle technology and high quality fuels will eventually solve the problem of harmful exhaust emissions. The problem with greenhouse gas, CO_2, still remains, and much attention will be given to increase efficiency. Hybrid technology is one option to reduce fuel consumption. Diesel engines are fuel efficient, but have high emissions compared with advanced gasoline engines. New combustion systems combining the best qualities of gasoline and diesel engines promise low emissions as well as high efficiency. By 2030, alternative fuels could represent a 10–30% share of transport fuels, depending on policies. Ambitious goals for biofuels in transport have been set. Currently the sustainability of biofuels is discussed extensively. Synthetic fuels promise excellent end-use properties, reduced emissions, and if produced from biomass, also reduced CO_2 emissions. In the short term, energy savings will be the main measure against climate change in transport, fuel switches will have a secondary role.

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