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S T O A

Alternative Technology Options for Road and Air Transport

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Study

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Executive Summary

In the transport sector, despite a number of political initiatives, the energy demands as well as greenhouse gas emissions are growing at an alarming speed. This holds true especially for road and air transport. Recent volatility in oil prices as well as the corresponding political instabilities in important oil-exporting countries has -again - brought the oil dependence of these sectors as well as related issues of energy security and economic perspectives to public and political attention. One option to break through the vicious circle between economic growth, energy demand in transport and oil dependence is to substitute oil-based fuels and propulsion technologies with alternative technologies. A wide range of non oil-based options for road and air transport has been developed in the last decade, and some technologies are already commercialised. However, it is currently impossible to predict which technologies will emerge as the front-runners for Europe.

In this context the project aims at compiling a catalogue that offers a sound and concise but not too detailed overview of Alternative Technology Options for Road and Air Transport. Its objective is to contribute to improved transparency and governance of this highly complex and often controversial field. Relevant options are described technically and assessed with regard to their economic perspectives, their contribution to substitute fossil fuels in transport and their potential to reduce greenhouse gas emissions as well as other pollutants.

This was compiled on the basis of available literature and by structured discussions with experts from science, industry and stakeholder organisations. One conclusion of this research is that virtually all experts agreed on three main factors that are responsible for the current discussion on alternative fuels:

- The prognosticated phase out of oil and other fossil resources
- Potential impacts of climate change
- Competitive advantages

If there were not be a debate on the phase-out of oil and on the risks of climate change, alternative fuels and propulsion technologies would probably not be discussed in such an intensive and diversified way. According to interviews conducted in the course of this project there is a broad basis for the opinion that “something new” has to come more or less quickly. The catalogue begins with an introduction into the issues. In doing so, it illustrates that there are far more than 200 source-fuel-drive-infrastructure combinations discussed in this context which implies an immense complexity. For the purpose of the catalogue, about 20 most relevant pathways were selected and clustered in five technological mainstreams: hydrogen and fuel cells, battery electric vehicles, hybrid-technology, biofuels and natural gas. In principle, it is likely that innovative technological developments will become faster implemented and established in the road sector, since in the air sector the tight security standards make it much more difficult to introduce new technologies which always means a challenge in terms of security.

A wide range of technological pathways are being discussed for the road sector; some of them experience first steps of commercialisation others are still in the stage of basic research. In the long run, hydrogen combined with fuel cells seems to be a promising technology whereby serious technological problems remain unsolved, amongst them for instance questions concerning the performance of fuel cells, or from where large amounts of “clean” hydrogen may be taken. Different routes are being discussed including the generation of hydrogen from natural gas, from renewable sources, from coal and from nuclear power. Recently, the only affordable way of large-scale hydrogen production is via steam-reformation from natural gas. From a mid-term perspective, this route might support the market penetration of hydrogen and of fuel cells. The crucial point is that, in this case, hydrogen is derived from a fossil source.

Hydrogen production from renewable sources (wind, photovoltaic, solarthermal, water) via electrolyses is often regarded as a kind of silver bullet since it enables close to zero emissions of greenhouse gases (GHG). But it is not clear if, at which time, and in which regions the production of hydrogen from renewable sources will be feasible at larger scales and at reasonable costs. A “clean” production of hydrogen from nuclear power is feasible as well. Controversies are related to nuclear power itself and to the finiteness of uranium resources. In terms of climate security the coal-route will be only suitable if it is combined with CO_2 sequestration and storing (CSS) – a technology that is still in the stage of basic research.

Hybrid technology is currently high on the agenda and extends its market shares. It offers a possibility to save energy and emissions by using established technologies and infrastructures. Whatever fuel and propulsion technology will be dominant in 20-30 years, it seems to be highly likely that hybrid technology will be part of the propulsion system. It is an important component of most fuel cell concepts and there seems to be a high potential to further improve the efficiency of conventional fuels. This “hybridisation” at the same time means an “electrification” of the drive train technology and, thus, supports a more dominant role of the electric engine in general.

The commercialisation of pure electric cars (Battery Electric Vehicles) strongly depends on the development of suitable batteries. In spite of decades of research and development activities, decisive technological breakthroughs regarding batteries are not in sight. Yet, a surprising breakthrough in battery technology is not completely impossible and would surely entail radical changes to both the transport and the energy sector.

Biofuels can be derived from a wide range of biomass and might serve as a relatively clean “bridging” or “additional” technology. So-called first generation fuels, mainly biodiesel and bioethanol, are the only renewable transport fuel option that is commercially deployed toady. The production process is comparatively uncomplicated. Second generation biofuels are produced by synthesis, in most cases from synthesis gas which is then treated in a so-called “biomass-to-liquid” process (BTL). A decisive benefit of BTL is the opportunity to define the properties of such “designer fuels” by setting the synthesis parameters; engine and fuel can be very well adjusted to each other. For second generation biofuels the whole plant or other forms of biomass can be used to produce fuel, in contrast to the production of “first generation” biofuels where only parts of the plants (oil, sugar, starch) are used. Biogas as well has the potential to contribute to climate and energy security. Blends with natural gas are imaginable. It is estimated that roughly between 20% and 30% of EU27 road transport fuels in 2030 could be covered by biofuels derived from European biomass (e.g. energy crops, agricultural and forestry residues, organic fraction of municipal solid waste). Imports of biomass are critically discussed since they might go at the expense of ecological sensitive areas.

Natural gas technology (CNG) is feasible in the transport sector and has the potential to bring at least mid term improvements in terms of energy security and GHG emissions – whereby it is crucial that real “gas-engines” are being developed. But in particular its possible contribution to energy security strongly depends on the overall demand on natural gas. It is likely, that CNG vehicles will become at least established for niche applications (e.g. in larger fleets, in inner cities). Autogas (LPG) is a relatively uncomplicated technology. It offers environmental benefits at relatively low costs. It is becoming rather popular in several European countries. Since both CNG and LPG are based on fossil feedstock they must be considered as bridging technologies. They might help to pave the way for “cleaner” gaseous fuels such as hydrogen, bio-methane or DME.

Regarding the air sector, presently there is no alternative propulsion system to the gas turbine in sight. Research on alternative fuels and alternative fuel sources as well as on new propulsion technologies is in early stages. Yet, the pros and cons of biofuels and hydrogen for aviation are discussed in this report.

The technologies compiled in this catalogue are all promising but all have clearly weak points and bottlenecks. Each single technological pathway faces difficulties in terms of serving the complete future fuel demand of the EU27. Innovations will be needed in order to tackle the three central challenges in this field: climate change, energy security and competitive challenges. However, in the long run the predicted phase-out of oil would make business-as-usual impossible for all oil-based technological contexts. A phase-out of oil would, at the same time, exert pressure on European innovation regimes – "something new" has to come. Policy strategies should remain flexible and open enough to support ground-breaking innovations.

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1. Why alternative options for road and air transport?

An effective transportation system is essential to modern societies. Transportation has significant impacts on economic growth, social development and the environment. Mobility of persons and goods is an important component of the economic and social integration of the European Union and of the competitiveness of European industry and services. Many also consider individual mobility as an essential citizens' right. In September 2001, the Commission presented its White Paper "European transport policy for 2010: time to decide", defining the EU's main objectives on transport policy such as:

- "to achieve a better balance between road and other modes of transport and create conditions for a 'modal shift', away from road;
- to decouple transport growth from rising economic activity;
- to ensure the costs of different transports reflect their 'external costs' (including environmental damage, congestion, human casualties, etc.);
- to reduce casualties, particularly on roads."

The White Paper also proposes 60 measures to overhaul the EU's transport policy in order to make it more sustainable and avoid huge economic losses due to congestion, pollution and accidents. The measures focus to a large extent on the interactions between transport and economy and transport and environment. The White Paper only implicitly addresses the interdependence between transport and energy consumption, thus reflecting the global situation of the late nineties, with low oil prices and a continuous phase of geopolitical stability.

Over the last years, EU policy with regard to energy consumption in the transport sector was mainly determined by environmental policy goals. In the EU, transport is responsible for an estimated 21% of all greenhouse gas emissions that are contributing to global warming, and the percentage is rising. In order to meet sustainability goals, in particular the reduction of greenhouse gas emissions agreed under the Kyoto Protocol, the Commission initiated a number of actions. For example, in its Green Paper "Towards a European Strategy for the Security of Energy Supply" published in 2000, the Commission expressed its aim of a 20% substitution of traditional automotive fuels by alternative fuels by the year 2020. In November 2001, the Commission presented a communication on alternative fuels which identified three alternative fuel solutions that could jointly reach this substitution target:

- biofuels,
- natural gas,
- hydrogen.

It also pointed to one technology solution (hybrid cars), which could offer the degree of fuel saving comparable to what alternative fuels have to offer.

Since the beginning of this decade, the development has somewhat changed – issues of energy security, and especially security of oil supply, returned on the agendas of policy-makers in the European Union and its Member States. The general finiteness of fossil resources or the peaking of world oil resources are at the centre of many energy-related discussions. This is due to a number of current developments. The recently surging oil demand in large economies such as China, India or the USA has reduced spare capacity.

The instability in some key producer countries (Iraq, Iran, Venezuela, Nigeria) has continued and increased, especially after the events of September 11, 2001 and the following military actions. At the same time, the oil infrastructure has become a new target for – and more vulnerable to – terrorist attacks. As a result of these trends, oil prices rose from a historical low of around $10/bbl in 1999 to well above $70/bbl in 2006.

These developments may have significant implications for the transport sector in general and for EU transport policy. This can be illustrated by Commission and industry statistics:

- Recently, the transport sector in the EU has been 98% dependent on oil and accounted for 71% of all oil consumption and 30% of total energy consumption in the EU;
- 45% of EU oil imports originate from the Middle East; by 2030, 90% of EU oil consumption will have to be covered by imports;
- The ASSESS study projects a growth of overall freight transport of 50% and of overall passenger transport of 35% until 2020 (baseline: 2000) which will lead to a growing demand for transportation fuels. (ASSESS 2005)

It is obvious that strategic alternatives to replace oil in transport are urgently needed. The EU has started a number of research efforts such as technology platforms (on biofuels, hydrogen, etc.) to address the tremendous technological challenges that are linked to the development and diffusion of new alternative fuels and power train technologies. Together with the industry the Commission initiated the European Hydrogen and Fuel Cell Technology Platform (HFP) in order to push and coordinate research and development activities in this field.

The report on the mid-term review of the European Commission's 2001 Transport White Paper, presented on 22 June 2006, for the first time introduces a section on energy. It recommends actions to be taken on various fronts, such as increasing energy efficiency in transport by reducing fuel consumption, supporting research, and bringing mature new technologies to the market through standard setting and regulations.

But the communication also recognises that much is still to be agreed at EU level, in particular under the European energy policy which is currently in the early stages of definition. According to the work book published as Annex 1 of the communication, the Commission planned to present an action plan for energy efficiency and a roadmap for renewables in transport in autumn 2006; a strategic technology plan for energy in 2007 will be introduced in 2007. A major programme for green propulsion is due to be launched in 2009.

There is consensus among all interested parties that new strategies for reducing oil dependence of the transport sector are necessary. Among the measures proposed are policies to increase energy efficiency (reduce fuel consumption per vehicle-km travelled) and transport efficiency (reduce transport activity per unit GDP), but also measures to shift the balance between modes of transport or to foster technological innovation in the transport sector. Since the changes in the transport sector are affecting almost all spheres of economy and society, agreements on transport policies largely supported by all parties are usually difficult to be achieved. This is also true for recommendations regarding innovation strategies. A widely accepted long-term vision on which set of technologies is best suited to replace conventional oil-based fuels in the European Union is still missing.

Nowadays, at the beginning of the 21st century, several alternatives to oil-based fuels and propulsion technologies are visible, amongst them hydrogen, fuel cells, biomass, autogas or natural gas. However, it is currently impossible to predict which technologies will emerge as the front-runners for Europe.

In this context the present STOA-project aims at compiling a catalogue that offers a sound and concise but not too detailed overview of Alternative Technology Options for Road and Air Transport. Its objective is to contribute to improved transparency and governance of this highly complex and often controversial field. Relevant options are described technically and assessed with regard to their economic perspectives, their contribution to substitute fossil fuels in transport and their potential to reduce greenhouse gas emissions as well as other pollutants.

2. The idea behind this catalogue

By the end of 2005, the STOA panel initiated a project on “Alternative Technology Options for Road and Air Transport”. The decision was based on the diagnosis that over the years a number of alternative fuel and power train/propulsion options for road and air transport have been developed by public research institutions as well as by industry. Most of them have been extensively discussed in the scientific and popular literature, but a comprehensive comparison is still missing. This is especially true for an integrative perspective, since different fuels (gas, diesel, ethanol, methanol, natural gas, hydrogen, DME, autogas, kerosene, etc.) can be produced via different pathways from fossil, regenerative or nuclear sources of primary energy and can be used in different propulsion systems (conventional internal combustion engines, fuel cells or hybrids for road transport, turbojet engines, turbofans, gas turbine-powered propeller engines or conventional piston engines for air transport) that imply different designs for cars and aircraft and require different fuel supply infrastructures.

In addition, it is well-known that successful diffusion of a technology depends not only on its technical performance and economic competitiveness, but also on a set of non-technical factors such as customer attitudes, compatibility with other technologies, and infrastructures or individual behaviour.

In a first analysis, the ETAG group (European Technology Assessment Group) found that – although a variety of publications on this topic is already available – the information about future alternative transportation options is usually fragmented, either too scientific or simplistic in its presentation, more often than not biased because of commercial interests or political agendas, and generally not comparable. In other words, there is a need for a structured and reliable overview description of technical options in order to support political and practical decisions upon future alternative transportation solutions. The ETAG group therefore proposed – as a first step – to develop a product similar to the Danish Board of Technology’s Energy Catalogue (see STOA project “Overview of Sustainable Energy Sources”) that focuses on alternative options for road and air transport.

Our literature review has shown that because of the interdependence of primary energy sources, conversion technologies to produce alternative fuels, fuel storage technologies and modified or new power train technologies, a large number of options can be identified (more than 200, not counting any options for “technology mixes” like adding biofuels to conventional fuel or bi-fuel cars). This variety of pathways is illustrated in Figure 1 and in Annex 1. It is virtually impossible to discuss all these options in detail within the framework of this project.

Therefore, the project team carried out a selection of relevant technologies based on a set of criteria (see Chapter 3). On 11 July 2006, a scoping workshop was held with MEP and external experts in order to discuss and validate both the selection of relevant technology pathways and the criteria for selection (Del. No. 2). The workshop led to some modifications. In the next chapter, the criteria for selection as well as the selected pathways are listed. The pathways will then be described in the Chapters 4 and 5 with reference to the selection criteria. The descriptions of these pathways have been discussed with a wide range of stakeholders and independent experts (see list in the References section). A pre-final version of the catalogue was presented and discussed with MEP and Experts at a workshop in Brussels on the 30.01.2007. The final version of the catalogue was fine-tuned according to the comments received in contexts of this workshop.

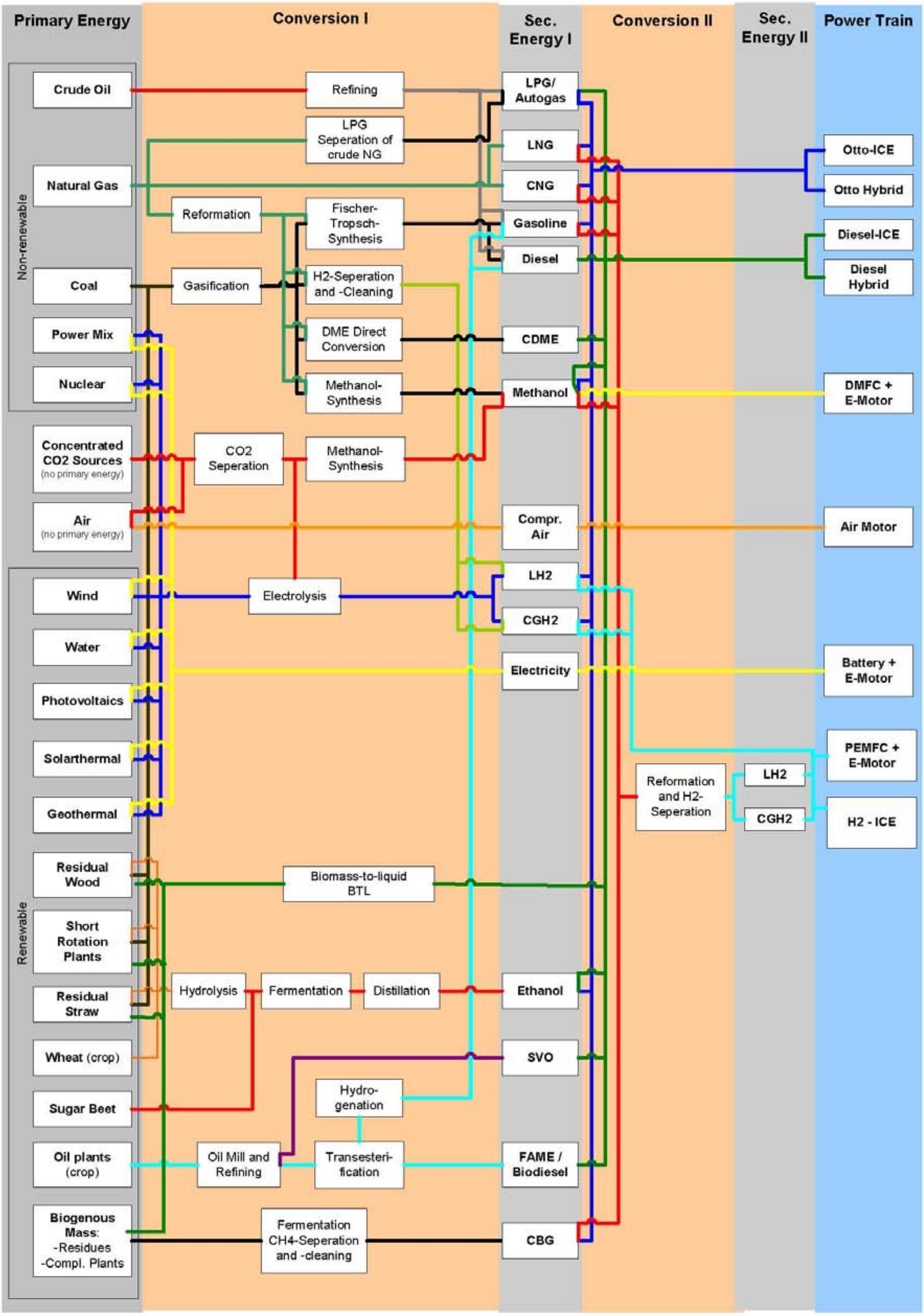

Figure 1: Variety of pathways

3. Selection of relevant technologies

As mentioned above, the ranges of technological possibilities that are discussed as alternative options for transportation are exceptionally wide. This illustrates that a variety of promising options for exploration and development in response to the strategic aims of the project (reduction of oil dependence and GHG emissions; competitive advantages) is theoretically available. On the other hand, the development of innovation strategies and policies as well as related research activities require some initial indication of the relevance of technological options to permit a more focused discussion and the identification of priorities.

A variety of approaches to identify criteria for an initial assessment and to select relevant research themes have been proposed. For this project (and paper), we adapted and modified a framework developed by the Imperial College Centre for Energy Policy and Technology (ICCEPT) in a 2001 report for the Carbon Trust (an independent company funded by the UK Government to help the UK move to a low carbon economy by helping business and the public sector to reduce carbon emissions and capture the commercial opportunities of low carbon technologies).

For the selection of pathways that should be included in the catalogue, the criteria listed in Figure 2 were taken into account.

A. **Strategic Impact** – a measure of the impact that a technology option could have on meeting the strategic aims of this project, as reflected by the following factors:

A.1. Environment and Human Health

- Enables "cleaner" mobility
- Reduces transport-related greenhouse gas emissions
- Is a key step on an evolving pathway to energy sustainability

A.2. Maintains or improves Europe's energy security by

- generally reducing oil dependence and/or
- substituting fossil primary energy sources by renewable sources

A.3. Competitiveness

- Broadens and deepens Europe's technological capabilities
- Improves competitive advantage with prospects of new business opportunities for Europe's industry and service sector

B. **Deliverability –** a measure that characterises a technology option in terms of maturity and potential rate of diffusion, as measured by factors such as

B.1. Development status, technology potential and steadiness of industrial activities

B.2. Cost competitiveness compared to established technologies

B.3. Number and/or severity of other (than B1 and B2) barriers to commercialisation, e.g.:

- Infrastructure
- Social acceptance

C. **Political Awareness** – a measure of the extent to which a technological option has attracted attention from policy-makers, media and the general public

Figure 2: Criteria for selection of relevant pathways

4. Alternative Options for Road Transport

Table 2 gives an overview of the selected pathways for road transport. These pathways will then be described in more detail.

Primary Energy	**Conversion I**	**Secondary Energy I**	**Conversion II**	**Secondary Energy II**	**Power Train**
Natural Gas	Reformation, H_2 Separation	H_2			PEMFC + E-motor
Coal	Gasification --> Reformation, H_2 Separation	H_2			PEMFC + E-motor
Wind	Electrolysis	H_2			PEMFC + E-motor
Wind	Electrolysis	H_2			Otto-ICE
Water	Electrolysis	H_2			PEMFC + E-motor
Water	Electrolysis	H_2			Otto-ICE
Photovoltaic	Electrolysis	H_2			PEMFC + E-motor
Photovoltaic	Electrolysis	H_2			Otto-ICE
Solarthermal	Electrolysis	H_2			PEMFC + E-motor
Solarthermal	Electrolysis	H_2			Otto-ICE
Nuclear Power	Electrolysis	H_2			PEMFC + E-motor
Nuclear Power	Electrolysis	H_2			Otto-ICE
Wet Biomass	Fermentation	Biogas	Reformation and H2 Separation	H2	PEMFC + E-motor
Wet Biomass	Fermentation	Biogas			Otto-ICE
Lignified Cellulose-containing Biomass	Gasification --> Fischer-Tropsch Synthesis	Gasoline / Diesel (BTL)			Otto- or Diesel-ICE
Lignified Cellulose-containing Biomass	Gasification --> H_2 Separation and Cleaning	H_2			PEMFC + E-motor

Primary Energy	Conversion I	Secondary Energy I	Conversion II	Secondary Energy II	Power Train
Lignified Cellulose-containing Biomass	Gasification --> Methanol Synthesis	Methanol			Otto-ICE
Lignified Cellulose-containing Biomass	Gasification --> Methanol Synthesis	Methanol	Reformation and H_2 Separation	H2	PEMFC + E-motor
Lignified Cellulose-containing Biomass	Gasification --> Methanol Synthesis	Methanol	Fischer-Tropsch Synthesis	BTL Fuel	Otto- or Diesel-ICE
Lignified Cellulose-containing Biomass	Gasification --> DME Direct Synthesis	CDME			Diesel-ICE
Sugar- and Starch-containing Biomass	Fermentation --> Distillation	Ethanol			Otto-ICE
Oil Plants	Oil Mill and Refining	Straight Vegetable Oil (SVO)			Diesel-ICE
Oil Plants	Oil Mill and Refining --> Transesterification	FAME / Biodiesel			Diesel-ICE
Natural Gas		Compressed Natural Gas (CNG)			Otto- or Diesel-ICE
Natural Gas		Liquefied Natural Gas (LNG)			Otto- or Diesel-ICE
Natural Gas		LPG / Autogas			Otto-ICE
Crude Oil		LPG / Autogas			Otto-Ice
Crude Oil	Refining	Gasoline			Otto-ICE
Crude Oil	Refining	Diesel			Diesel-ICE

Figure 3: Overview of selected pathways

Hydrogen: general overview

"Hydrogen is an energy carrier that can be produced from conventional fuels (in the transition to sustainable energy systems) or renewable energy. The increased diversity of primary energy sources will substantially enhance energy security leading to reduced oil or gas imports. Of particular importance is the use of hydrogen for transport as this application is virtually totally dependant on oil today." (Fuel Cell Europe 2006)

"Until 2030, hydrogen production from fossil fuels with carbon capture and sequestration (CCS) is expected to be the most important production source in Europe, with renewable hydrogen slowly being phased in." (Conclusion of the EU project HyWays; Phase I, Flyer)

Hydrogen (H_2) is being considered as a potential alternative fuel for future transport and stationary applications. Recently, many controversies are linked to hydrogen or to what is called the upcoming hydrogen age. When it comes to the potential relevance of hydrogen in the energy sector, it has to be clarified that hydrogen (H_2) is an energy carrier and not an energy source. The function of hydrogen is often compared with that of electricity; the important difference, however, is that hydrogen can be directly stored in large amounts – for electricity this is rather impossible. As the lightest of all gases hydrogen has a low energy density and therefore has to be stored either under pressure (compressed gaseous hydrogen: CGH_2) or as a liquid (liquid hydrogen: LH_2) by cooling it down to very low temperatures.

Hydrogen is not an environmentally clean technology in itself. Since it does not exist in nature in relevant amounts, it must be produced (just like electric power) – by processes that consume energy. In terms of emission of greenhouse gases and energy sustainability it is crucial where this energy is coming from. Today, the following two processes are seen as being most promising for generating larger amounts of hydrogen:

- In large scale via steam reformation of hydrocarbons, especially of natural gas. Other primary energy carriers might as well be of biogenous origin.
- Via electrolysis of water by use of electricity of any source (e.g. wind, water, solar, fossil, nuclear power).

Another option is the generation of hydrogen as a by-product of the crude oil refining process. It is one of the apparent merits of hydrogen that it can, in principle, be produced from nearly any primary energy source. However, in terms of CO_2 balance, it is decisive if this source is, for example, coal or renewable (wind, solar). H_2 can be the central link in a clean energy chain if it is derived from any renewable source. On the other hand, it can contribute to GHG emissions and global warming if derived from fossil sources.

In the transport sector, Hydrogen can be burned directly in slightly modified Otto-ICEs or it can be used to power fuel cells. In both cases, the exhaust gases do not consist of much more than water vapour. In comparison with direct combustion of hydrogen in conventional engines, the use of fuel cells leads to significant energy efficiency gains. ICE vehicles powered by hydrogen induce very low emissions including a little amount of NOx that can be removed by using an ordinary catalytic converter. This burning of hydrogen in conventional IC engines, as it is pushed forward especially by the BMW Group, is a relatively uncomplicated and cheap technique. However, compared to fuel cells the efficiency is considerably lower: accordingly, ICE vehicles using hydrogen consume much more primary resources than the same number of fuel cell vehicles. The important advantage of the H_2 ICE vehicles (BMW launched its first series production in November 2006) is that they are bivalent, which means that they can be driven by H_2 as well as by conventional gasoline.

This is a big advantage in terms of flexibility, especially in the light of the fact that the emergence of a significant European network of H_2 fuelling stations is not yet clearly visible.

Important challenges regarding the commercial use of hydrogen are not only related to its production but also to transport and storage. H_2 is usually stored at 300-700 bar or is kept liquid at a temperature of minus 253 °C in cryogenic tanks. The latter option is interesting because of its high energy density but not easily feasible, since a tank would be needed that is able to save that low temperature for longer periods of time. On-board storage in special tanks with 700 bar is not a technical problem in itself, but the costs for such tanks are not marginal and the range has not yet reached that of conventional cars. Innovative storage concepts, for example inside specifically designed adsorption materials, are conceivable but still in rather early stages of research at present.

Hydrogen can be distributed to refuelling stations either by pipeline in gaseous form or by truck under cryogenic conditions. It is also possible to install small-scale natural gas steam reformers or small-scale electrolysers for on-site hydrogen production at a hydrogen filling station (see STEPS 2005). In order to circumvent the difficulties of storing hydrogen, on-board generation from liquid fuels has been tested. This means that the vehicle is equipped with a small reformer which is able to generate hydrogen from methanol, gasoline, naphta or diesel. The hydrogen would then be used to power a fuel cell. However, in the meantime nearly all manufactures have abandoned this idea because of different reasons, amongst others the technical complexity which seems not to be compensated by the advantages (no hydrogen infrastructure needed).

At any rate, storage and transport of H_2 places considerable demands on tanks and material, which goes along with higher cost compared to those of conventional fuels. The first publicly accessible H_2 refuelling stations are emerging in Europe (e.g. Berlin, Munich, Tuscany/Livorno; see www.h2stations.org) but are still of rather tentative than of commercial character. From a technical point of view, the process of fuelling itself should not raise any problems. All in all, the technical problems mentioned above seem not to be insurmountable and there is still a large potential to decrease the costs.

Fuel cells: general overview

Fuel cells are often considered as one of the future leading technologies for mobile, portable and stationary applications. They offer high energy conversion efficiency compared to conventional engines. They do not emit any pollutants if they are fuelled by hydrogen (the generation of the hydrogen might led to significant emissions; see hydrogen chapter).

The basic principle is rather simple: fuel cells use an electrochemical process to convert chemical energy (in form of hydrogen, methanol or others) into electricity, heat and water. Fuel cells inverse the electrolysis process of hydrogen generation from electric power. They function in a similar way as ordinary batteries, having an anode and a cathode, although, unlike a battery, they do not store energy – they convert it from one form to another. So, fuel cells do not need to be recharged since they produce electricity as long as the required fuel (hydrogen, methanol or others) is supplied. A decisive part of a fuel cell is the electrolyte, the substance situated between the positive and the negative pole. It serves as the bridge for ion exchange which is the reason for the external electric current. A single fuel cell produces less than 1 or 2 volts. To increase the amount of electricity generated, single fuel cells are combined in series. Such series are called “stacks” and may consist of hundreds of fuel cells (STOA 2005).

Fuel cells differ in terms of fuel source, size, temperature at which they operate, and pressure at which the gases/fuels are supplied to the cell. Accordingly, various types of fuel cells do exist and are designed for different applications. For example, the Solid Oxide Fuel Cell (SOFC) is best suited for stationary applications. The system requires a high operating temperature of 500-1000°C.

The SOFC can be powered by different fuels, such as hydrogen, methanol or natural gas. Using natural gas, the SOFC shows efficiency up to 50 percent, which means (in a simplified way) that 50 percent of the energy input become electricity and 50 percent become heat. Low temperature fuel cells, such as the Proton Exchange Membrane Fuel Cell (PEMFC), work at operating temperatures below 100°C. Catalysts are needed to ensure sufficient reaction speed of the electrochemical reactions. The employed catalysts as well as electrolytes make it necessary to have a comparatively high degree of fuel/gas purity (Oertel/Fleischer 2003).

In the transport sector, up to now fuel cells are nearly exclusively of the PEMFC type, because of its adequate operating temperature (low temperature fuel cell, 50-80°C), its high power density and the solid electrolyte, avoiding difficulties with handling potentially corrosive liquid electrolytes (E4tech 2006). A proton exchange membrane is used as an electrolyte. This layer of solid polymer allows protons to be transmitted from one face to the other. In doing so, a PEMFC provides electric power in a vehicle. This energy is used to power an electric motor: fuel cell vehicles have an electric propulsion system. PEMFCs require pure hydrogen or hydrogen rich, nearly carbon monoxide-free gas as fuel; the oxidiser can be air.

A variant of the PEMFC is the DMFC (Direct Methanol Fuel Cell), which allows the direct use of methanol as fuel. DMFCs are generally designed to power smaller, portable applications such as laptops. The anode of the cell can be supplied with liquid methanol (80 to 90ºC) or with methanol vapour (120 to 130ºC) and the cathode with air. Thus, methanol does not have to be converted into hydrogen by an extra reformer. Basically, the DMFC might as well become interesting for the transport sector. For the moment, however, the DMFC has a relatively low performance compared to hydrogen-powered PEMFC. Further research and significant technical breakthroughs are needed, especially regarding stability, reliability, efficiency, and power density.

All in all, compared to conventional internal combustion engines PEM fuel cells have several essential advantages:

- The relatively high electrical efficiency of fuel cells around 50% or even higher – in hybrid combination up to 70% (STOA 2006, 65). They operate at maximum efficiency at part load – where most ICEs operate. On a well-to-wheel basis, a hydrogen fuel cell is generally more efficient and can be nearly twice as efficient as a gasoline or diesel fuelled internal combustion engine car (see JRC 2006, 50).
- Fuel cells applied to vehicles entail no tailpipe emissions at all if hydrogen is used as fuel. There is a realistic potential to reach low to zero GHG emissions for the overall process from "well to wheel". Several renewable and fossil feedstocks can be used for the generation of hydrogen (see next chapters). This high flexibility in terms of feedstock can be a crucial factor regarding energy security.
- Looking on the technology in a fuel cell car there are additional advantages: the far-reaching elimination of moving parts in the propulsion system leads to an uncomplicated mechanical system, to low vibration and noise levels, and to reduced need for maintenance (Oertel/Fleischer 2003). Moreover, the technology enables a high-performance on-board power supply as well as a wide range of vehicle design options. The modular design allows the fuel cells to be designed to match the specific output power requirements.

In spite of these clear advantages, commercialisation of fuel cells in the transport sector has not started yet. Important barriers to broad-scale commercialisation are:

- High costs for fuel cells
- Limited lifetime (operating hours) and reliability
- No infrastructure for production, supply and storage of hydrogen
- Limited on-board hydrogen storage density
- Global standardisation (harmonisation) of rules and regulation

The high costs of fuel cells are partly due to Platinum being an important component of PEM fuel cells. Platinum is relatively expensive and is limited in its availability. There is a potential to considerably reduce consumption of platinum by sophisticated recycling processes. Furthermore, the absolute amount of platinum needed per fuel cell is decreasing (see TIAX 2004).

Another severe problem has been low temperature starting: In the meantime, starting is still possible at -20°C and lower temperatures seem to be reachable. Technological progress is going on in different areas, there is still a large potential for improvements under many aspects and it appears not to be unlikely that – form a mid-term or long-term perspective – fuel cells could be able to go into series production and to compete on the market.

Only recently, the dynamic in this field was illustrated by a new development. In November 2006, the company Volkswagen announced on its UK website (Volkswagen 2006): “Volkswagen Research has developed a new and innovative type of high temperature fuel cell (HTFC) that means an affordable fuel cell-powered vehicle suitable for everyday use could be available as early as 2020.” This new PEMFC for automotive applications operates at 120°C and can tolerate a maximum temperature of 160°C. Honda goes as far to claim in a press release of September 2006 for the launch of its new fuel cell model FCX: (Honda 2006): “Limited marketing of a totally new fuel cell vehicle based on this concept model is to begin in 2008 in Japan and the U.S. [...] The vehicle is also highly efficient, with an energy efficiency of around 60 percent – approximately three times that of a gasoline-engine vehicle, twice that of a hybrid vehicle, and 10 percent better than the current FCX.” Figure 4 summarises the technical details of this vehicle. Figure 5 shows the new Mercedes-Benz B-Class “F-Cell” that offers an operating range of almost 400km and 100kw electric engine.

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	171l
Dimensions (L×W×H)		4,760 × 1,865 × 1,445mm
Max. Speed		160km/h
Energy Storage		Lithium-ion battery
Vehicle Range*		570km

Figure 4: Technical specifications of the Honda FCX. Source: Honda 2006 http://world.honda.com/news/2006/4060925FCXConcept/)

The European Hydrogen and Fuel Cell Platform (HFP) states in its draft implementation plan the goal to exceed an annual production of 400,000 hydrogen vehicles – fuel cell and internal combustion engines (ICE) drive trains – by 2020 (see Figure 6).

In the long-run, hydrogen combined with fuel cells seems to be a promising technology whereby decisive technological problems remain unsolved, amongst them for instance questions concerning the performance of fuel cells, or from where large amounts of "clean" hydrogen may be taken. It should be noted that, apart of many optimistic voices, there are as well highly sceptical observers who are not at all convinced of the practicability of hydrogen and fuel cells for transport (see for example: Bossel 2006). At any rate, fuel cells do not only have to compete with conventional technologies but as well with other technological developments which are illustrated in this report. In the next chapters some interesting routes that differ in relation to the generation of hydrogen are described in more detail.

Portable FCs

for handheld electronic devices Portable Generators & Early Markets Stationary FCs

Combined Heat and Power (CHP) Road Transport

EU H2/ FC units sold per year projection 2020 ~ 250 million ~ 100,000 per year

(~ 1 GWe) 100,000 to 200,000 per year

(2-4 GWe) 0.4 million to 1.8 million

EU cumulative sales projections until 2020 n.a. ~ 600,000

(~ 6 GWe) 400,000 to 800,000

(8-16 GWe) 1-5 million

EU Expected 2020 Market Status Established Established Growth
Mass market roll-out

Average power FC system 15 W 10 kW <100 kW (Micro HP)

>100 kW (industrial CHP) 80 kW

FC system cost target 1-2 €/ W 500 €/kW 2.000 €/kW (Micro)

1.000-1.500 €/kW (industrial CHP) < 100 €/kW

(for 150.000 units per year)

Figure 6: "*Snapshot 2020*"- Key assumptions on Hydrogen & Fuel Cell Applications for a 2020 Scenario. Source: HFP 2006, 8

Hydrogen from Natural Gas

Natural Gas → Reformation, H_2 Separation → H_2 → PEMFC + E-motor	
Motivations	• H_2 generation from natural gas is a mature and relatively inexpensive technology • Large-scale production is already feasible • This path is discussed as being a key step on the way to the "H_2 age" • If combined with carbon capture and storage (CCS) technology it could be a rather clean pathway
Challenges	• Natural gas is a finite resource • Natural gas is a fossil feedstock – without (still) expensive CCS technology it contributes to GHG emissions • When applying CCS technology, energy efficiency decreases
Central Controversies	• To what extent could a growing demand for CNG be covered by the suppliers? • Does this pathway foster the long-term reduction of GHG, since it paves the way to the "H_2 age"? • To what extent could the (growing) demand be covered by biogas (biomethane) • Is CCS technology a realistic option?

Source and characteristics

"Steam reforming of natural gas is an inexpensive method of producing hydrogen and is used for about half of the world's production. Steam, at a temperature of 700-1,100°C is mixed with methane gas in a reactor with a catalyser at 3-25 bar pressure. Thirty percent more natural gas is required for this process, but new processes are constantly being developed to increase the rate of production. It is possible to increase the efficiency to over 85% with an economic profit at higher thermal integration. A large steam reformer which produces 100,000 tons of hydrogen a year can supply roughly one million fuel cell cars with an annual average driving range of 16,000 km" (STEPS 2005, 116).

Regarding the transport of natural gas it should be noted that there are basically two possibilities:

- Via pipeline, in compressed form as so-called compressed natural gas (CNG). Transport in pipelines is getting to expensive from a certain point on, since transport costs are proportional to the length of the pipeline.
- In specialised "reefer vessels", in liquefied form at temperatures of -163°C. This is relatively costly but becomes more and more common for very long distances. Arriving at the destinations, the liquefied gas is gasified again and added to the CNG grid.

In Europe, there is a strong dependence on Russian pipeline gas; but it would be technically possible to import more expensive liquefied gas from any region in the world.

Deliverability, competitiveness and contribution to energy security

The significant point of this path is that already today it is feasible in large scales at moderate costs. Currently, natural gas is the most frequent feedstock for the production of hydrogen. Many experts say that only the reformation of natural gas offers a realistic short-time solution for large-scale production of hydrogen. The whole process is technically and commercially established. Natural gas is also used directly to fuel ICEs. However, in the long run it appears to be more efficient to convert it into hydrogen for use in fuel cells instead of burning it directly. Competitiveness strongly depends on the development of costs for infrastructure as well as for fuel cells.

The contribution to energy security is restricted by the fact that natural gas is a fossil resource which is not available in endless amounts. Only recently, it has been discussed to what extent shortages in Russian natural gas supply might be relevant for the EU. Even if it is not likely that serious supply problems will occur, this example has illustrated that capacities can only be increased up to a certain point (see DWV 2006, 12). Large-scale use of natural gas in the transport sector would lead to an overall increase in demand to be satisfied – at affordable prices (see chapter on CNG).

Energy balance, emissions and contribution to climate security

From a well-to-wheel (WTW) perspective, significant GHG emission savings can only be achieved if hydrogen (derived from CNG) is used in fuel cell vehicles: "Although hydrogen ICEs have a good fuel efficiency, their WTW balance is unfavourable compared to direct use of NG as CNG" (JRC 2006, 51). It is likely that hydrogen-powered ICEs will be available in a few years at considerably lower costs than fuel cells. However, according to a study (JRC 2006), such a pathway – from natural gas via H_2 to ICE – can even increase GHG emissions.

Considerable improvements are possible if already existing but not widespread and still expensive technologies of carbon capture and storage (CCS; another term is CO_2 sequestration) become more established. Even if CO_2 sequestration enables a favourable CO_2 balance, the use of such technologies itself needs energy and, thus, goes at the expanse of efficiency.

Additional applications and pathways

Recently, the use of a hydrogen and natural gas mixtures (HCNG) to power conventional engines in both transport and stationary applications has been tested as a transition solution to accelerate the development of a hydrogen infrastructure. HCNG vehicles offer the potential for immediate emissions benefits, such as a reduction in nitrogen oxides (NOx) emissions. At the same time, they can pave the way for a transition to fuel cell vehicles by building early demand for hydrogen infrastructure. Filling stations at Malmö and Stavanger put strong focus on testing H_2/CNG blends. In Malmö, buses and passenger vehicles are being tested with an 8 vol.% hydrogen/natural gas mixture, and similar projects are starting in France and Italy.

The EU project NATURALHY is looking at adapting the natural gas pipeline infrastructure to the transport of hydrogen. The aims of NATURALHY are to test all the critical components of a hydrogen system by adding hydrogen to natural gas in existing networks. This transitional approach will provide further experience with the transmission of mixtures of hydrogen and natural gas and, by means of innovative separation technologies, the hydrogen utilisation in stationary end use applications.

Further, it is possible to mix natural gas with biogas (biomethane), which brings so-called biomass-to-hydrogen technologies into the game (see biomass chapter). The crucial point is the availability of biomass as well as the overall efficiency of the process, since it includes several steps of conversion/upgrading.

Prospects

The generation of hydrogen from natural gas is feasible. From a mid-term perspective, it might support the market penetration of hydrogen and of fuel cells. The crucial point is that, in this case, hydrogen is derived from a fossil source. CCS technology could improve the GHG balance but downgrades the energy balance. This limits its potential contribution to energy and climate security. On the other hand, this path might serve as a bridging technology which accelerates the commercialisation of hydrogen in the energy sector and, thus, encourages the development of cleaner technologies to produce H_2. However, it is not clear to what extent a fast growing demand for natural gas could be satisfied by the suppliers and to what extent biogas (bio-methane) might be able to enlarge the feedstock basis.

Hydrogen from Coal

Coal → Gasification → Reformation, H_2 Separation → H_2 → PEMFC + E-motor

Motivations	• Technology is feasible for large-scale applications • EU can use its own coal resources • This path is regarded as a key step on the way to the “H_2 age” • If combined with CCS technology it could be a rather clean pathway
Challenges	• WTW efficiency is not good • H_2 is generated on a fossil basis • Without CCS technology it contributes to GHG emissions • When applying CCS technology, energy efficiency decreases
Central Controversies	• To what extent could a growing demand for coal be covered by domestic resources? • Does this pathway foster the long-term reduction of GHG, since it paves the way to the “H_2 age”? • Is CCS technology a realistic option?

Source and characteristics

Coal can be gasified at high temperatures (1300-1400°C) and pressures to synthesis gas. After cooling down and separation of soot and solid particles, synthesis gas is fed into a CO shift reactor and a H_2S/CO_2 removal stage. Then either a methanisation stage or pressure swing absorption follows in order to clean up the hydrogen for use in internal combustion engines (ICEs) or fuel cells (STEPS 2005). This rather complicated and expensive technology is only suitable for large-scale applications.

Deliverability, competitiveness and contribution to energy security

The gasification of coal is a mature technology and often viewed as an important route of hydrogen production in the short- to mid-term future. Due to rich coal resources, especially in the United States the "coal route" is understood as a suitable option for producing large amounts of H_2 (NRC 2005).

In Europe, this pathway would allow the use of "domestic" coal resources to produce hydrogen. However, H_2 production will have to compete with the use of coal for the generation of electric power and heat.

Energy balance, emissions and contribution to climate security

There are two central problems: the overall efficiency of this route is not good compared to the direct use of coal for the generation of electricity and heat. The other central problems of this pathway are the GHG missions, as long as no carbon capture technology (sequestration and storage) is used. The specific CO_2 emissions are much higher for coal than for oil, petrol or natural gas (in Europe in gCO_2/kWh: natural gas 203, petrol/diesel 264, black coal 346, lignite 414; DWV 2006, 13).

The United States are running a programme on the sequestration of CO_2 with first steps of commercialisation expected for 2012. In Europe, research programmes are undertaken as well. A major problem is the reliable storage of the captured CO_2. But even if CO_2 sequestration enables a favourable CO_2 balance, the use of such technologies itself needs energy and, thus, goes at the expense of efficiency. Efficient use of resources is a key element of sustainable development.

Prospects

In terms climate security the coal route is only suitable if it is combined with CCS-technologies. In term of energy security the advantage is that Europe would be able to bring in domestic resources up to a certain point. The coal route might be used as a sort of bridging technology. The pathway might support the breakthrough of hydrogen/fuel cell technology. However, the generation of hydrogen would be in fierce competition with other applications for coal.

Hydrogen from Renewable Sources

Wind → Electrolysis → H_2 → PEMFC or Otto-ICE
Water → Electrolysis → H_2 → PEMFC or Otto-ICE
Photovoltaic → Electrolysis → H_2 → PEMFC or Otto-ICE
Solarthermal → Electrolysis → H_2 → PEMFC or Otto-ICE
(Biomass → H_2: see chapter on natural gas and chapter on biomass)

Motivations	• Low to zero emissions possible on a well-to-wheel basis • High flexibility in terms of domestic feedstock • Large potential for innovation and competitive advantages • Broad acceptance in politics and society
Challenges	• Overall efficiency should be improved • Generation of hydrogen has to compete with other applications of renewable electricity • Large-scale production is still (very) expensive
Central Controversies	• Efficiency of these pathways is a point of discussion • It is not clear if there could be enough renewable potential to supply a hydrogen-based transport sector in Europe • Regarding photovoltaic electricity it is discussed if large-scale production at affordable costs will ever be possible

Source and characteristics

The process of splitting water molecules with electricity is called electrolysis. The electrolysis of water by using electrical energy from renewable sources is a promising route to producing "clean" hydrogen. The process of electrolysis is well-established, and the production of large amounts of H_2 is technically possible. There is still a potential to improve efficiency and costs. One particularly promising development route is high pressure electrolysis – higher production pressure means less compression energy for storage (JRC 2006, 48).

This sample of pathways is not only interesting for its good emission ratio but also for offering a high degree of flexibility regarding the primary energy source which can well be wind, water, photovoltaics or of solarthermal origin. In principle, hydrogen can be derived from any feedstock that is able to produce electric power.

Deliverability, competitiveness and contribution to energy security

The variability in terms of feedstock is very promising regarding potential contributions to energy security. The production of electricity from water, wind or photovoltaics is commercialised and widespread. The possibility to store hydrogen offers interesting options for such fluctuating sources as wind and photovoltaics. It could help to balance disadvantages of these technologies by offering a possibility to store energy.

The production of hydrogen from renewable resources might stimulate the use of more renewable energy, since excess renewable energy could be stored in hydrogen and used in clean transport applications.

Further, the renewable pathways are highly promising since they would allow mobility based on domestic resources and could contribute to energy security in a very clean way. However, a considerable contribution to energy security can only be realised if production on a larger scale is possible at reasonable costs. Controversial opinions do exist when it comes to the questions to what extent the generation of H_2 from wind and/or water will be commercially viable on a larger scale. The path via electrolysis is technically feasible but does not seem to be economically reasonable for large-scale production from a short- or mid-term perspective. The competitiveness strongly depends on the future development of oil prices and on future cost reductions of renewable power. So, it is not impossible that renewable hydrogen would become competitive relatively quickly if considerable increases in oil prices and decreases in costs for renewable power would occur.

Especially wind energy could become an interesting source, whereas photovoltaic electricity is not expected to be viable at very large scale in the short- or mid-term. However, both wind and photovoltaics are highly dynamic sectors in terms of technological and economic progress, which makes reliable predictions pretty difficult and leaves room for controversies. "The global market for traditional photovoltaics (PV) has in the last 5 years seen an annual rate of growth about 40%" (STOA 2006, 55). The EU goal of reaching 3 GW installed PV capacity in 2010 is expected to be exceeded, as 4,5-5 GW installed capacity is regarded as realistic by 2010. Still, this capacity is far from being enough to supply electricity for large-scale hydrogen production. For comparison, by the end of 2005, about 41 GW of wind power was installed in Europe; for the year 2010, 88 GW are expected (STOA 2006, 21). A study of the German Hydrogen and Fuel Cell Association and LBST quantitatively illustrates that the energy demand of the EU-25 transport sector could well be covered by hydrogen derived from renewable electric power (DWV 2006, 25). Offshore wind energy plays a crucial role in this scenario.

<u>Energy balance, emissions and contribution to climate security</u>

The energy efficiency of these pathways is limited by the fact that much energy is needed for electrolysis, for transport, transfer and packing of hydrogen. These renewable pathways entail that, first, electric energy is converted into hydrogen and, then, in the fuel cell, hydrogen is converted into electric energy again. This goes along with energy losses. Therefore it is not surprising that the generation of H_2 from renewable sources provokes many critical comments. In this context, it is generally discussed, from a more global perspective, if the use of H_2 in transportation makes sense in terms of the overall efficiency of the entire energy system. It is argued, that, in the short- and mid-term, oil and natural gas should rather be used as fuels, since it is more efficient to use the potential of renewable sources such as wind, water and photovoltaics to directly generate electric power. A confrontation of the most efficient use of renewable energy in relation to the production and use of hydrogen will also depend on the local situation.

At any rate, these pathways are amongst the cleanest that are currently visible, since they enable low to zero emission from a well-to-wheel perspective. This is especially true for wind, hydropower, photovoltaic and solarthermal energy. When it comes to biomass, the GHG balances appear much more complex and are not always clearly positive (see chapter on biofuels).

Additional applications and pathways

H_2 can also be generated form biomass via steam reformation or electrolysis. While the electrolysis path is not very likely (bad energy efficiency), the path via steam reformation could be a serious alternative (see chapter on natural gas and chapter on biomass).

Solar energy can not only be used via electrolysis but as well by thermal splitting of water. The latter process is still in an early stage but also promising in terms of efficiency. Splitting of water into hydrogen and oxygen needs high temperatures above 1700°C; such temperatures can be achieved for example in solar furnaces.

Besides that, various ideas are being developed and tested. For example, the US-based company SHEC investigates an interesting approach which is described on its website (www.shec-labs.com): "SHEC has constructed and demonstrated a Dry Fuel Reformation (DFR) system to produce hydrogen using methane that is powered primarily by sunlight-focusing mirrors. The system comprises a solar mirror array, an advanced solar concentrator, a shutter system to control the amount of radiant energy entering the reactor, and two thermo-catalytic reactors that will convert methane, carbon dioxide and water into hydrogen. Methane from sources such as biogas, landfill gas, flare gas, stranded gas and coal-bed methane is recovered through a collection system consisting of a series of pipes in the ground."

It should be mentioned here, that geothermal energy could also be used for the generation of hydrogen via electrolysis. It is not clear yet to what extent this path will be applied in praxis.

Prospects

These pathways are regarded as a kind of silver bullet by many observers, since they offer close to zero GHG emissions and are based on a variety of renewable energy sources. But it is not clear if, at which time, and in which regions the production of hydrogen from renewable sources will be feasible at larger scales and at reasonable costs. It is clear, however, that technological progress is fast in this field and that the growing need for clean, post-fossil energy sources will further increase the incentives to invest in new technologies.

Hydrogen from Nuclear Power

Nuclear Power → Electrolysis → H_2 → PEMFC or Otto-IEC

Motivations	• Large-scale production of hydrogen is technical feasible • Very low emission possible; contribution to climate security • Basic potential to contribute to energy security
Challenges	• Risks and dangers of nuclear technology • Long-term radioactivity of nuclear waste • Costs and availability of uranium
Central Controversies	• Is nuclear power a "safe" technology? • To what extent is the generation of nuclear hydrogen limited by finite uranium resources?

Source and characteristics

Nuclear power is a widespread and mature technology. It can be used to power the H_2 production via electrolysis.

Deliverability, competitiveness and contribution to energy security

Technically, the production of hydrogen from nuclear power via electrolysis is viable at larger scales. This could entail to take the electricity from the overall mix of the existing grid. Hydrogen can be produced economically in off-peak periods (at night times).

However, the potential contribution to energy security in general and to the production of hydrogen is rather controversial. The International Energy Agency points out in the World Energy Outlook 2006 that nuclear power could perform a major contribution related to both energy security and curbing CO_2 emissions in a cost-effective way. The International Atomic Energy Agency (IAEA) reports in its 2006 nuclear technology review referring to a conference that was organised by the IAEA in Paris in March 2005:

"*The vast majority of participants affirmed that nuclear power can make a major contribution to meeting energy needs and sustaining the world's development in the 21st century for a large number of both developed and developing countries. Rising expectations are driven by nuclear power's performance record, by growing energy needs around the world coupled with rising oil and natural gas prices, by environmental constraints, by concerns about energy supply security in a number of countries, and by ambitious expansion plans in several countries.*"

On the other hand, it is a fact that uranium production has been well below consumption for about 15 years and that uranium resources are finite. Many observers express doubts regarding a significant global extension of nuclear power, mainly because they see uranium resources as a strongly limiting factor. For example, the Energy Watch Group concludes in its paper on Uranium Resources and Nuclear Energy (EWG 2006, 6):

"This assessment results in the conclusion that in the short term, until about 2015, the long lead times of new and the decommissioning of aging reactors perform the barrier for fast extension, and after about 2020 severe uranium supply shortages become likely which, again will limit the extension of nuclear energy."

In terms of energy security, it appears to be rather clear that an extension of nuclear power would be crucial to achieve a significant nuclear production of hydrogen. It is not clear if, to what extent and when this extension will take place and how long the demand for uranium can be satisfied. Furthermore, it is not clear if and when advanced technologies, which are less dependent on uranium, will become a realistic alternative.

Energy balance, emissions and contribution to climate security

This route enables mobility nearly without GHG emissions. The nuclear power route clearly has the potential to contribute to climate security.

Alternative pathways

In future, an interesting option might be the direct use of heat from nuclear energy, using a chemical process enabled by future high-temperature reactors. First analyses indicate that this might be a rather efficient process, also for large-scale production, but further research and development activities are needed.

Prospects

The technology is feasible; hydrogen could be produced in a relatively clean and efficient way and might foster a breakthrough of hydrogen and fuel cell technologies. The controversy is related to the risks of nuclear power in general, to unsolved problems of radioactive waste, as well as in relation to nuclear weapons and terrorist attacks. Furthermore, uranium resources are definitely finite. Projecting uranium production and demand into the future is highly uncertain.

Battery Electric Vehicle (BEV)

Primary Energy →Electrical Power → Battery→ Electric Motor

Motivations	• High potential to contribute to energy and climate security as long as energy is derived form renewable sources • Electric engines offer promising performance • Electricity could be easily taken from the grid
Challenges	• Batteries are still the weak point > still unsatisfying performance of electric vehicles in terms of range and recharging time
Central Controversies	• Will it be possible to develop a battery that fulfils the requirements in terms of range and duration of recharging? • Is there potential enough to provide relevant amounts of "clean" electricity?

Source and characteristics

A battery electric vehicle (BEV) is an electric vehicle that utilises chemical energy stored in a rechargeable battery to power an electric engine. As it is the case for hydrogen, BEVs are only as clean as the electric power that is used to drive them.

In principle, electric engines are a rather old and established technology. The crucial link in this chain is definitely the battery. Presently, in most cases lead or nickel-cadmium batteries are in use. Their low capacity and high weight limit the range and the speed of electric cars. Commercialised electric series compact cars, e.g. the Citroën Saxo electrique or Peugeot 106 electric, have a range of 75-100 km and their maximum speed is around 90 km/h. Together with other aspects, e.g. long recharging times of around 6 hours, this is the reason for their current niche existence. Modern batteries, especially lithium-ion or nickel-metal hydride batteries, have about 3 times higher energy densities than lead batteries and allow a range of up to 300-400 km (depending on the layout). Especially lithium-ion batteries are getting more and more widespread in mobile applications, since they offer a good energy-to-weight ratio. Drawbacks are related to lifetime, reliability and recharging time.

Specially designed prototypes reach much higher speeds and larger ranges – but are generally not developed for commercialisation. For example, in 2006 the UK company PML Flightlink presented a new electric car ("Mini") equipped with an electric motor at each wheel. The 4 engines together provide more than 640 bhp and a top speed over 200 kph. The vehicle is built in an ultra-light way and is equipped with an on-board generator, in the form of a conventional petrol-fuelled engine that "only" generates electric power but does not drive the wheels directly (see www.pmlflightlink.com).

In view of the limited range of current battery technology, the weight is a crucial factor. Prototypes built of light material, such as the Flightlink Mini, prove that the range could be considerably enlarged if cars were built lighter. The disadvantage is that this generally goes at the expense of security and of interior space.

Deliverability, competitiveness and contribution to energy security

The future of electric cars mostly depends on technical progress in battery development. Research is going on and new developments have promising qualities. For example, in 2005 the US company Altair NanoTechnology announced a nano-sized titanate electrode material for lithium-ion batteries to be tested in vehicles. Yet, the new products do not fulfil the requirements for large-scale commercialisation in vehicles.

"Although lithium-ion technology is believed to provide a significant improvement margin in terms of cost and performance, specific energy storage and corresponding vehicle range remain relatively limited compared with gasoline or diesel vehicles, and battery charging time is still high for most customer expectations, unless fast charging is used. The latter requires more complex and considerably more costly charging stations and would require very aggressive policies for infrastructure to be put in place." (E4tech 2006, ii)

Up to now, use and development of electric cars have been fostered by legal and tax regulations: BEVs are a common form of so-called zero emission vehicles (ZEV). The State of California had set a minimum quota for the use of ZEVs. In London, electrically powered vehicles are excluded from the congestion charge. In Italy, private ZEVs benefit form tax advantages. In spite of these incentives, the central weak points of batteries in terms of range, speed and recharging time basically still exist.

"Battery electric vehicles (BEVs) still face significant barriers which are likely to prevent mass production and major market diffusion in the medium term." (E4tech 2006, ii)

Even if there was a surprising breakthrough in battery technology, the potential contribution to energy security would still depend on the source from which electricity is derived. Market penetration of BEVs would require a major increase in overall electricity generation capacities. In terms of energy security the crucial question is to what extent the overall demand for electric power could be satisfied by domestic resources. Most common sources in the EU are coal, natural gas and nuclear power. Furthermore, there is a rising share of renewable sources. If BEVs drive on renewable electricity, a high contribution to energy security is possible.

Coal and natural gas face the characteristic problems of fossil fuels: they are finite and they go along with GHG emissions as long as no CO_2 capture and storage technology is used. However, it is not impossible that future power plants will produce relatively "clean" power on a fossil basis. Regarding electricity from nuclear power, the contribution to energy security appears to be limited by the uranium resources (see chapter on nuclear hydrogen).

Energy balance, emissions and contribution to climate security

Electric vehicles do not emit any pollutants during use. Similar to hydrogen, the critical point in terms of emissions is where the primary energy is taken from. It can be a rather clean pathway if the energy is taken from renewable sources, such as wind or photovoltaics. As mentioned above, crucial factors are the potential extension of renewable sources as well as technological progress in CCS technologies. The latter might enable a relatively clean use of fossil resources, of which in particular coal and natural gas are interesting for the generation of electricity in Europe.

Additional applications and pathways

There is a general tendency to electrify at least parts of the propulsion system, since both hybrids and fuel cells use an electric engine.

Prospects

The commercialisation of electric cars strongly depends on the development of suitable batteries. In spite of decades of research and development activities, decisive technological breakthroughs regarding batteries are not in sight. Yet, a surprising breakthrough in battery technology would probably entail radical changes to both the transport and the energy sector.

Hybrids

Primary Energy → Different Propulsion Systems + Electrical Power → Battery→ Electric Motor

Motivations	• Contribution to energy and climate security by reducing fuel consumption • Fuel savings can be obtained without changing infrastructure • Electric engines offer interesting performance • Can be combined with various fuel propulsion systems (such as diesel, petrol, natural gas, hydrogen, pure electric engine)
Challenges	• Higher costs can still be a barrier to commercialisation • Hybrids with conventional engines are still dependent on fossil resources
Central Controversies	• To what extent do high fuel prices accelerate the commercialisation of more expensive hybrids?

Source and characteristics

Hybrid concepts are a strong focus of research, development and mass production activities. While the term hybrid can in principle be connected with various concepts, it meanwhile mainly refers to a combination of an electric motor and a battery system with a conventional combustion engine (ICE). Combinations with natural gas, hydrogen and fuel cell technology are feasible as well. In other words: a fuel-burning engine is combined with an electric power train. “The purpose is to combine the range and rapid refuelling of conventional vehicles with the environmental benefits of an electric drive mode and/or with the high torque and acceleration performances of electric engines.” (E4tech 2006, 16)

The various hybrid models are structured by different criteria. According to the degree of hybridisation it is distinguished between full and mild hybrids. Sometimes so-called start-stop systems are named mini-hybrids. The latter consist of a reversible starter-alternator system and are, for example, implemented and commercialised in the Citroen (PSA) C3 (2004) and C2 (2005). Others do not speak of a hybrid system unless there is at least a recuperative breaking technology implemented.

Such mild hybrids are able to store in a battery kinetic energy which is recovered during deceleration or breaking. The energy can be used use to start the vehicle or to support the ICE.

The most extensive changes in the car concept have been done in full hybrid cars (strong hybrids). Here, it is possible to run the car a certain distance by using only the electric system. The full hybrid concepts are subdivided into series, parallel and mixed architectures. Series hybrids use the thermal engine for no other purpose than to produce electric power, i.e. such vehicles have their own generator on board. Only the electric engine is connected to the drive train. This arrangement allows the ICE to be much smaller than in conventional cars and to be operated in its most efficient range. On the other hand, efficiency is reduced by the relatively long energy conversion chain of this architecture (chemical > thermal > mechanical > electrical > mechanical).

Parallel and mixed architectures allow running the combustion engine at the optimal working point most of the time. When less energy is needed than supplied by the combustion engine, the excess energy is stored in the battery by operating the motor as a generator. When more energy is needed than available from the combustion engine, the electric motor is added to the drive train, supplied by the energy that was stored in the battery before. In parallel hybrids, both engines can be used directly for the propulsion. Combinations of both systems are possible and are called “mixed architectures”.

Further, it is possible to construct plug-in hybrid electric vehicles (PHEVs), which can be charged (overnight) by connecting them to the grid. Some authors argue that such plug-in hybrids will soon become standard in the automobile industry (Romm/Frank 2006, Romm 2005).

Deliverability, competitiveness and contribution to energy security

Hybrid technology has already been commercialised. Japanese automakers have been the pioneers with Toyota, Honda and Nissan, starting commercialisation of full hybrid technology several years ago. European automakers have been less enthusiastic about this combination of two engines, while PSA and Volkswagen in the meantime presented their demonstration activities.

“The new Citroën C4 and Peugeot 307 Hybride HDi demonstrators have not only achieved outstanding results in terms of fuel economy (3.4 litres per 100 kilometres) and CO_2 emissions (90 grams per kilometre), but they retain the recognised driving comfort associated with conventional diesel HDi powered cars. At the same time, they add new improvements due to the hybrid powertrain, such as the all-electric mode at low speeds.” (PSA 2006)

In general, hybrids are more costly than conventional vehicles. This competitive disadvantage can be balanced by the fuel savings and tax benefits if the payback period is not getting to long. Hybrid technology entails a significant reduction in fuel consumption and, thus, contributes to energy security. One popular example of a full hybrid car is the Toyota Prius that has been sold in Europe since 2004 but has been available on the Japanese marked since 1997.

“Toyota launched the Prius in 1997 in Japan and started selling it overseas, such as in North America and Europe, in 2000. The second-generation Prius, equipped with the Toyota Hybrid System II, was introduced in 2003 with an emphasis on delivering both eco-friendliness and driving performance. It has been enjoying good sales both in Japan and overseas, especially in North America.” (http://www.toyota.co.jp/en/news/06/0607.html)

In the meantime other carmakers strongly intensified research and development activities. In Troy, Michigan, a research alliance consisting of General Motors Corp., BMW AG and DaimlerChrysler AG was build to jointly develop a two-mode hybrid drive system that should reduce fuel consumption while not compromising vehicle capability. Volkswagen is expected to be on the market with a hybrid version for the model Touareg by 2008/2009.

Energy balance, emissions and contribution to climate security

The use of hybrid technology increases efficiency, reduces fuel consumption and, thus, reduces the emission of GHG gases. Further, they emit far less HC, NOx and CO compared to conventional combustion engines.

Prospects

Hybrid technology becomes more and more established and extends its market shares. Whatever fuel and propulsion technology will be dominant in 20-30 years, it seems to be highly likely that hybrid technology will be part of the propulsion system. It is an important component of most fuel cell concepts and there seems to be a high potential to further improve the efficiency of conventional fuels. This “hybridisation” at the same time means an “electrification” of the drive train technology and, thus, supports a more dominant role of the electric engine in general.

Biofuels: general overview

The following vision has been shaped by the European Biofuels Technology Platform (leaflet from November 06):

“By 2030, the European Union covers as much as one quarter of its road transport fuel needs by clean and CO_2-efficient biofuels. A substantial part is provided by a competitive European industry. This significantly decreases the EU fossil fuel import dependence. Biofuels are produced using sustainable and innovative technologies; these create opportunities for biomass providers, biofuel producers and the automotive industry.”

In general, biomass is the amount of all substances of biogenous origin, including plants or parts of plants, manure and dung. Biomass can also be the biodegradable parts of municipal waste or sewage sludge. An important difference among different types of biomass is whether they are especially grown for energetic use as “energy plants” or whether the substance is a residual of another process. In both cases, the potential of substituting a conventional fuel by a biogenous one primarily depends on the available acreage.

Biomass can be differentiated under many aspects. Looking at the content of water, wet biomass can be distinguished from dry biomass. Wet biomass contains considerable amounts of water and is fermented to biogas in a reactor under exclusion of oxygen. All biomass containing carbohydrates, proteins, fats, cellulose and hemicelluloses as a main component can be used as feed material. Commonly used is manure and dung of stock farming or biogenous residuals of other branches and households. Dry biomass can be lignified cellulose-containing biomass, sugar and starch containing biomass or oil plants.

In terms of fuel production, the most important differentiation has to be made between first and second generation biofuels. First generation fuels, mainly biodiesel and bioethanol, are already established, at least in some national markets. These fuels have in common that for their production only parts of the plants, in general the crop, are used. The process is comparatively uncomplicated, but large parts of the plant can not be included in the fuel production. Such first generation biofuels are the only renewable transport fuel option that is commercially deployed toady.

Regarding the economic side of biodiesel and bioethanol the E4tech report (2006) concludes:

“There is some scope for reducing production costs through technical innovations in the processing plants. However, feedstock costs weigh heavily on the production costs in temperate climates.”

Second generation fuels are not yet established and still object of extensive research and development efforts. These fuels are produced by synthesis, in most cases from synthesis gas which is then treated in a so-called “biomass-to-liquid” process (BTL). A decisive benefit of these routes is the opportunity to define the properties of the fuels by setting the synthesis parameters as well. In doing so, engine and fuel can be very well adjusted to each other. This results in increased efficiency and reduced emissions, what explains the great interest of engine developers in these “synfuels” or “designer fuels”.

The following descriptions include both processes that are already established and those currently being demonstrated in prototype facilities. Routes and technologies are described separately in order to give an understandable overview. However, it should be kept in mind that especially in this field integrated concepts might be realised as well. For example, rape oil could be used as feedstock for biodiesel, the residues as feedstock for a BTL process. In this highly innovative field it is always possible that new developments make a new assessment of the situation necessary. Policy strategies should remain flexible and open enough to support ground-breaking innovations.

Biodiesel or bioethanol can be added to conventional fuels, at least in amounts of 5-10%, without requiring any modifications to the engines, which allows uncomplicated commercialisation from the technical perspective. The energy proposal of the EU Commission published on 10 January 2007 suggests an obligation for each member state to have 10% biofuels in their transport fuel mix by 2020.

Regarding the potential contribution of biofuels to the European fuel market the E4tech report (2006, 29) concludes: “We consider that the technical potential from EU27 resources, based on energy crops, agricultural and forestry residues, and the organic fraction of municipal solid waste, is roughly between 20% and 30% of EU27 road transport fuel in 2030 for bioethanol or biodiesel (including advanced biofuel routes; the lower end of the range depends on the fraction of synthetic diesel relative to other Fischer-Tropsch products [60% is assumed here]).” Accordingly, it is unlikely that biofuels will cover Europe’s fuel demand, even if enormous improvements in terms of efficiency would be realised. Biofuels are regarded as a “bridging technology” by many observers, which means that they will help to overcome the gap between mobility based on fossil fuels and “something else” that will come in future. In the European Commission’s biofuels report “A vision for 2030 and beyond” ambitious targets for the development of biofuels in the EU are mentioned (European Commission 2006b):

“The EU has a significant potential for the production of biofuels. Biofuel use has to increase from its present low usage – less than 2% of overall fuel – to a substantial fraction of the transportation fuel consumption in Europe (in line with this report’s vision of 25% in 2030). It is estimated that between 4 and 18% of the total agricultural land in the EU would be needed to produce the amount of biofuels to reach the level of liquid fossil fuel replacement required for the transport sector in the Directive 2003/30/EC.”

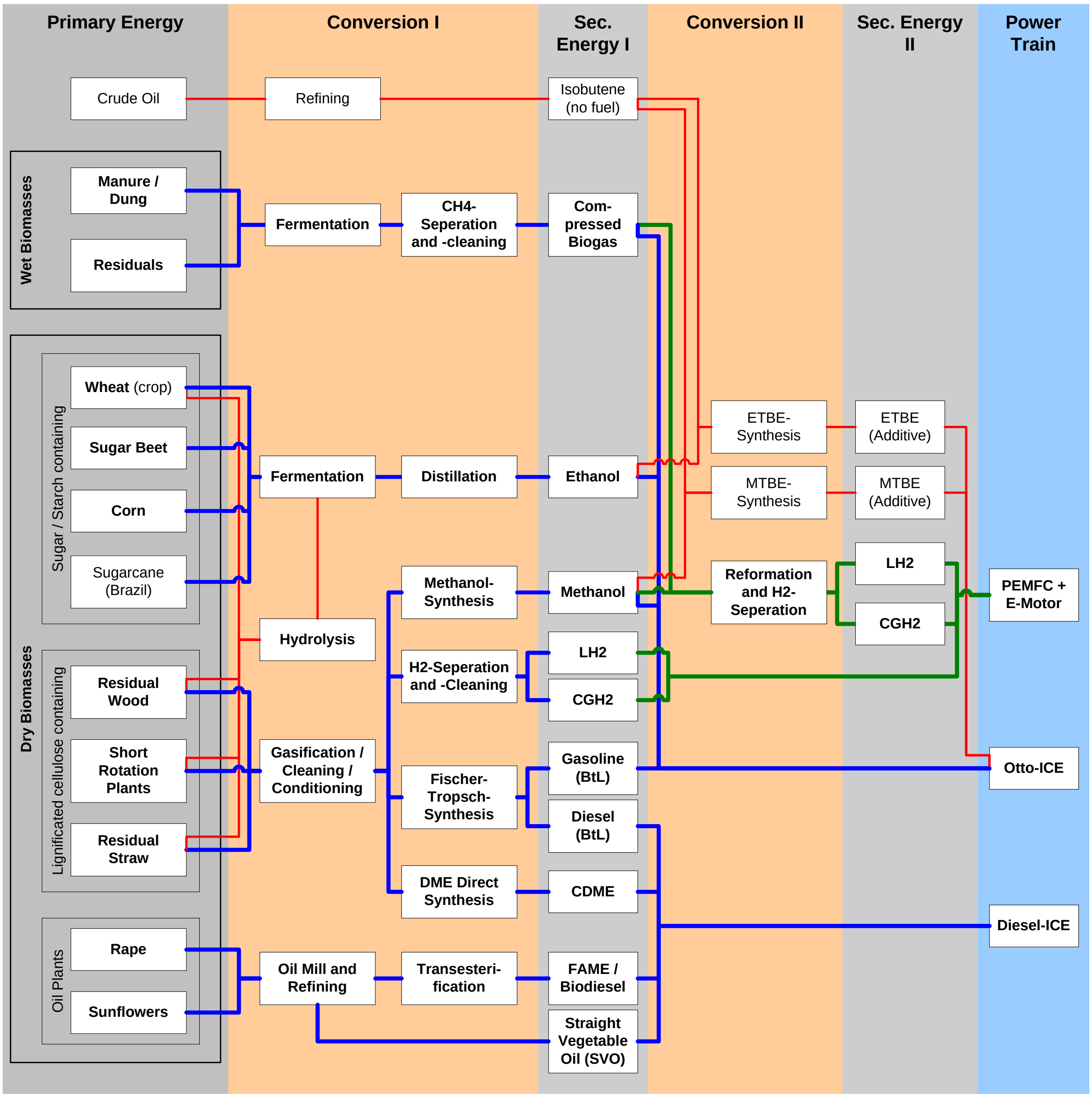

Figure 7: Biofuel pathways

Biodiesel (First Generation) and Straight Vegetable Oil (SVO)

Oil Plants → Oil Mill and Refining → Transesterification → **FAME / Biodiesel** → Diesel-ICE Oil Plants → Oil Mill and Refining → **SVO** → Diesel-ICE

Motivations	• Technology is already commercialised • Favourable CO_2 balance possible > contributes to climate security • Substitutes fossil fuels > contributes to energy security • Can be used as additive to conventional fuels without changes to the engine • Existing infrastructure can be used • Provides alternative sources of income in rural areas
Challenges	• Potential to substitute fossil fuels is limited by the available acreage • Cultivation and preparation of rape require considerable amounts of energy • Imports are critically discussed since they might go at the expense of ecological sensitive areas.
Central Controversies	• To what extent could the European diesel demand be satisfied by biodiesel derived from domestic resources? • To what extent would imports go at the expense of sensitive ecosystems (tropical rain forests)?

Source and characteristics

The conventional production of biodiesel is based on oil plants. The technology is well-established and commercialised in many European countries. Technically, the oil is extracted by milling the crop of the oil plants. Afterwards it is converted into a fatty acid methyl ester (FAME) through a chemical process called transesterification, whereby the glycerine is separated from the vegetable oil. The process leaves behind two products – methyl esters (the chemical name for biodiesel) and glycerine (to be used in soap and other products). Smaller amounts of (fossil) methanol are needed in the production process, while the substitution of fossil methanol by bioethanol seems to be possible. In Europe, especially in the centre and in the north, the most important form of biodiesel is so-called rapeseed methyl ester (RME, in Europe defined in DIN EN 14214) produced from rape seed and in the south of Europe, to a lesser extent, sunflower methyl ester (SME) produced from sunflower oils. Biodiesel is biodegradable, non-toxic and essentially free of sulphur and carcinogenic substances. Due to the chemical structure it generally burns cleaner than conventional diesel. With regard to storage and handling, biodiesel is the safest fuel since its flashpoint lies at around 150°C compared to 70°C for petroleum-based diesel.

Biodiesel is burned in diesel engines, either neat or mixed with fossil diesel. As a blend of 5%, biodiesel (B5) can be used in any diesel engine without technological changes.

Data for blends up to 20% (B20) are only available for the United States, where such blends are used in some public fleets. So-called flexible fuel vehicles (FFV's) are able to drive on different blends. B100 is basically usable as well in conventional diesel engines, but in many cases carmakers hesitate to give the corresponding vehicle and engine warranties or such warranties are given in an inhomogeneous way across Europe. In addition, B100 faces difficulties in fulfilling the Euro IV and Euro V norms (see below).

"Renault launched B30 biodiesel-compatible diesel versions of two of its commercial vehicles in December 2006. Trafic 2.0 dCi B30 and Master 2.5 dCi B30 are the first expressions of Renault's commitment to biofuels, made by the company as part of Renault Commitment 2009." (Renault 2006)

Another common way to make use of oil plants is to burn the oil directly, without transesterification, as so-called straight vegetable oil (SVO) in a retrofit diesel engine. Compared to FAME, this means fewer costs for the production of the oil but more adjustments concerning the vehicle. Regarding the use of pure SVO, one serious problem is that it is hardly possible to fulfil the Euro IV and V norms.

Deliverability, competitiveness and contribution to energy security

Biodiesel is considered as one possibility to achieve the aim of satisfying at least 5.75% of the European fuel demand by biogenous fuels in 2010, as determined in Directive 2003/30/EC of the European Parliament and the Council. Therefore, biodiesel is presently being established in Europe with great efforts. Europe has dominated the biodiesel industry to-date with 82% of global production. According to the European Biodiesel Board (EBB), biodiesel has been produced on an industrial scale in the European Union since 1992, largely in response to positive signals from the EU institutions. Today, there are approximately 120 production plants in the EU, mainly located in Germany, Italy, Austria, France and Sweden. Specific legislation to promote and regulate the use of biodiesel is in force in various countries, including Austria, France, Germany, Italy, and Sweden (EBB 2006). In Germany, for example, presently around 1,900 public gas stations offer pure biodiesel (Bockey 2006).

It is said that, currently, biodiesel is competitive at an oil price around 60 Euro (EU COM 2006/34). The costs vary depending on different factors such as geographical realities, tax structures and/or wage levels. In Germany, which is Europe's most important producer, biodiesel is only slightly cheaper on the market than conventional diesel. Dramatically rising oil prices might change the situation. The above-mentioned SVO is significantly cheaper but means higher costs for the modification of the vehicle. It is estimated that, in the mid-term, SVO might mainly be competitive in freight transport and in agriculture.

Due to the lower heating value, 1 litre of rape-based biodiesel substitutes 0.91 litre of conventional diesel. Today, from 1 hectare around 1,550 litres of rape diesel could be gained per year in Germany. However, it is estimated that this number could rise up to 1,820 l/ha until 2015 (FNR 2006). Referring to the 1,550 litres, this means for a 5 l/100 km conventional diesel car that it runs 28,210 km per hectare yearly.

As with all first generation biofuels, the contribution to oil security is first of all restricted by the availability of arable land. It is indisputable that biodiesel will not be able to substitute the total consumption of conventional diesel in Europe, which will be around 158.5 million tons in 2006. Because of the dependence on a set of highly changeable factors (oil price, tax system, priorities in food production, WTO agreements, technical innovations, etc.) it is rather difficult to agree on a realistic potential for the maximum amount of biodiesel made from plants grown in Europe. In order to give some orientation Germany is taken as an example again: In Germany, biodiesel made from rape holds a share of 5.5% of total diesel consumption.

It is sold mostly as a blend of up to 5%. From an economic perspective, it is said that the potential of arable land used for biodiesel is mostly tapped, since other countries are able to produce cheaper, what makes imports more attractive than increasing the acreage of presently around 700,000-900,000 hectares (FNR 2006, 36).

In the EU25, overall production of biodiesel was around 3 million tons in 2005, while the European Board of Biodiesel (EBB) estimated that in 2006, there was potential to produce around 6 million tons. Even if the 6 million tons could be realised, this would not be more than roughly 3.5% of the 158.5 million tons of diesel needed in the EU in 2005. Even if this number will rise in the next decades due to increased acreage, improved cultivation techniques and higher oil yields per ha, it seems to be rather difficult to come close to a number of 8-10%. However, a factor supporting biodiesel is that Europe is an importer of diesel fuel – whereas Otto fuel is exported. Since the market shares of diesel cars are constantly growing, the need for diesel fuel is growing as well. Biodiesel can be seen as a contribution to filling this gap.

Energy balance, emissions and contribution to climate security

The comprehensive JRC well-to-wheel analysis (2006, 2b, 36) concludes: "In the most favourable case RME (Rapeseed Methyl Ester) can save 64% of the fossil energy and 53% of the GHG emissions required for conventional diesel fuel." However, the energy balance of biodiesel is controversially discussed by the authors of this study and by other experts. Critical comments are generally based on the relatively high demand for fossil energy to cultivate the rape plants, especially to manure and treat the crops. The JRC (2006, 2b, 37) points out that the pathways from biomass to conventional biofuels (biodiesel and bioethanol) are principally inefficient in the way they use biomass. In this context, it is argued that the use of biomass for power generation or heating offers a better energy balance. However, most studies conclude that the use of biodiesel leads to substitution of fossil resources and, thus, contributes to energy security in Europe. Schindler and Weindorf (2006, 54) conclude that RME contains 58% of the energy that was stored in the rapeseed. A relevant factor for both energy balance and GHG emissions is the utilisation of the by-products (e.g. glyzerine, animal feed from residues) of the production process.

A reduction of GHG emissions can be assumed, but the amount of reduction is also discussed controversially. Emissions from the feedstock production are a major contributor to the CO_2 emissions in the overall GHG balance. Especially the N_2O emissions, which are induced by fertilisation, play a decisive role in the GHG balance and are mainly responsible for the many uncertainties in this area. Due to the strong greenhouse effect of this gas (300 times higher than CO_2), even relatively small emissions can have a significant impact on the GHG balance (JRC 2006, 2b, 34). According to a recent study, biodiesel from rapeseed reduces GHG emissions by 38-57% (E4tech 2006) on a well-to-wheel basis, while the exact amount depends on the energy consumption in the entire production chain. Schindler and Weindorf (2006, 56) calculate for RME 61 gCO_2-equivalent/km compared to 130 gCO_2-equivalent/km produced by a conventional diesel engine (well-to-wheel for a VW Golf).

Another aspect in the same context is that biodiesel has a relatively high content of oxygen. This is important because compared to petroleum-based diesel it improves the burning process and results in lower emissions of carbon hydrogens (HC), carbon monoxide and soot particles when using a standard engine. Cars approved for biodiesel comply with the EU emission standard EURO III. However, the introduction of stricter EU emission standards EURO IV (2005/2006) and EURO V (2008/2009) force car/truck manufacturers to develop engines that use different methods to comply with the emission standards depending on whether they are driven with biodiesel or petroleum-based diesel.

If a driver wants to switch between the fuel types, the engine needs to be equipped with a sensor that monitors whether the fuel contains more biodiesel than petroleum-based diesel or vice versa, so that the on-board computer can adjust the ignition timing the fuel flow or the time and course of injection (GAIN 2004). In standard versions, new cars with modern engines are often not equipped with such a sensor and therefore not approved for biodiesel use, since NOx emissions exceed the Euro IV and V norms. Costs for retrofitting are in the range of a few hundred Euros.

Additional applications and pathways

Biodiesel can also be derived form waste vegetable oil (WVO). The process is technically feasible, but not suitable for large-scale production. On an experimental level, there have been several efforts to use algae as a source for biodiesel production. In 1998, after nearly 20 years of field research, the final statement of the US "Aquatic Species Program" concluded that oil production from algae is rather expensive and complicated. Only recently, a company from New Zealand announced that it has produced a first sample of biodiesel from algae in sewage ponds. These examples indicate that there is still potential for innovation. However, a fundamental problem is to produce fuel in such quantities that it contributes to a significant substitution of oil-based fuels and, at the same time, at reasonable costs.

On a global scale, other plants are used as feedstock (soy, palm oil). Especially the use of palm oil is critically discussed: it is argued, that the cultivation of palm oil could go at the expense of tropical rain forest, which would be disastrous for the overall GHG balance.

Prospects

Conventional biodiesel is well established, relatively simple to produce and easy to handle. It can be used in conventional engines up to a concentration of 5 to 10%. The future role of biodiesel depends on developments in other areas, but it is likely that blends will be extended in the next years.

Bioethanol

Biomass Containing Sugar or Starch → Fermentation → Distillation → **Ethanol** → Otto-ICE

Motivations	• Technology is already commercialised • Favourable CO_2 balance possible > contributes to climate security • Substitutes fossil fuels > contributes to energy security • Can be used as additive to conventional fuels without changes to the engine • Existing infrastructure can be used • Provides alternative sources of income in rural areas
Challenges	• It is likely that an increasing demand will be satisfied by imported ethanol which is not based on European feedstock • In Brazil, the cultivation of sugar cane for ethanol might go at the expense of rain forests • GHG ratio depends on the whole production chain and can also be rather unfavourable
Central Controversies	• To what extent could the European demand for petrol be satisfied by ethanol derived from domestic resources? • To what extent would imports go at the expense of sensitive ecosystems (tropical rain forests)?

<u>Source and characteristics</u>

Ethanol is generally used to substitute gasoline; the substitution of diesel by ethanol is technically possible but practised only outside Europe (USA, Brazil). Ethanol which is produced from biomass is called bioethanol. Raw materials are sugar- and starch-containing substances. These plants, e.g. sugar beet, wheat or corn, are fermented in a reactor under exclusion of oxygen and afterwards distilled to ethanol. Ethanol can be burned purely or as an additive to gasoline in Otto engines. For example, E5 contains 5% of ethanol and 95% of conventional petrol.

Conventional engines are able to run on concentrations up to E10 without any changes, higher concentrations of ethanol require modifications. So-called flexible fuel vehicles (FFVs) are able to run on ethanol concentrations between 0 Vol.-% and 85 Vol.-% (E85). The engine and fuel system in a FFV must be slightly adapted to run on alcohol fuels because they are corrosive. There must also be a special sensor in the fuel line to analyse the fuel mixture and control the fuel injection and timing for adjustment to different fuel compositions. Conventional engines have to be modified only marginally for the use of E25, the use of E100 requires extra modifications. Bioethanol (FFV) cars are only several hundred Euros more expensive than conventional cars.

Ethanol has a lower heating value compared to gasoline, therefore 1 litre of ethanol substitutes 0.65 litre of gasoline. An advantage is the higher energy density, which means that power in kWh is rising when ethanol is used instead of petrol.

Deliverability, competitiveness and contribution to energy security

In this context, it should be referred to the leading ethanol countries, which are the USA and Brazil, where ethanol is already a rather widespread fuel that substitutes or is added to petrol. In Brazil, ethanol from sugar cane is well established and only gasoline containing a minimum of 23% ethanol (E23 or gasohol) or pure ethanol (E100) is available. Since 2003, FFVs have been successfully introduced to the Brazilian market: 70% of newly registered cars are FFVs and it is intended to power 80% of the transport fleet with ethanol derived mainly from sugar cane within five years. In the USA, ethanol is made almost exclusively from corn (maize) and provides the most important alternative to fossil fuels (diesel or rather biodiesel is not widespread in the USA). Among the European countries, ethanol is most established as a fuel in Sweden. About 400 fuel stations supply approx. 15,000 cars that can run on E85 as well as on conventional gasoline.

In terms of competitiveness, it is said that the lowest cost option is the ethanol derived form sugar cane in Brazil which can be competitive at oil prices around 60 US$/bbl (E4tech). Ethanol from corn in the USA is slightly more expensive, while in Europe, ethanol from wheat starts to be competitive at oil prices not below 70 US$/bbl (E4tech); other authors talk about 90 Euro/bbl in this context (EU 2006, Biokraftstoffe, 5). In Europe, the highest productivity per acreage is achieved with sugar beet. The disadvantage: sugar beet has high demands regarding soil quality, which considerably limits the potential acreage. As regards cereals, wheat has the highest efficiency per hectare, but yields are considerably lower than those of sugar beet. In consequence, large-scale ethanol production in Europe would rely mostly on wheat (JRC 2006, 32).

In 2004, world production of bioethanol for fuel use was around 30 billion litres (23.7 million tons). This represents around 2% of global petrol use. Production is set to increase by around 11% in 2005 (European Commission 2006a). In the EU, 9.7 million tons of ethanol would be needed in the year 2010 to substitute the envisaged 5.75% of the petrol only by ethanol (based on a petrol consumption of 113.6 million tons; see Bockey 2006). Seyfried (2006, 44) estimates that a far-reaching market penetration of 10 vol.% admixture in the EU25 would require production capacities around 13 million tons of ethanol per year; a number that can not be reached “overnight”.

The leading EU producers are Spain and Germany. The leading consumer was Sweden with large amounts of ethanol imported mostly from Brazil (EU 2006, Biokraftstoffe). Looking at Brazil again, it is said that the potential of arable land sets nearly no limits to local ethanol production (FNR 2006, 48), whereas less optimistic, critical voices refer to the problems of monoculture and the danger that ecological sensitive areas could be destroyed in order to extend ethanol production.

Energy balance, emissions and contribution to climate security

According to the JRC study (2006, 32), there are two essential elements that determine the final energy and GHG balances:

- the way the energy required for the production process is generated;
- the way the by-products are used.

A typical by-product derived from the residues is the animal feed distillers dried grains with solubles (DDGS) which is known for its high protein content. Residues could also be used to power a biogas plant.

Basically, ethanol plants offer good opportunities for combined heat and power generation. Depending on this fuel chain configuration, GHG emission savings could range between 7 and 77% for ethanol from wheat (E4tech). If the process energy for the ethanol production comes from lignite, the CO_2 balance can even be worse than that of gasoline or diesel.

If bioenergy (biogas) is used, good results can be obtained for total CO_2 emissions (Schindler/Weindorf 2006). The JRC (2006, 35) concludes: "Using by-products for energy production rather than animal feed has a very large impact. With pulp to heat, the sugar beet pathway can deliver savings of 73% for energy and 65% for GHG emissions. Similar reduction can be achieved with wheat DDGS. At the moment, and as long as the EU imports animal feed components such as soy meal, economics are, however, unlikely to favour use of these by-products as fuels."

However, the study also says that "conventional production of ethanol as it is practised in Europe gives modest fossil energy/GHG savings compared with gasoline" (JRC 2006, 35). According to Schmitz, GHG savings range between 0.5 kg CO_2 equivalent for wheat-based production and 2.24 kg for the production from sugar cane in Brazil. In Europe, savings are around 1.5 kg/litre if sugar beet serves as feedstock (Schmitz 2006). Some observers state that the GHG savings from Brazilian ethanol are even higher than those expected from the advanced biomass-to-liquid technology (see corresponding chapter).

In Europe, fertilisation of feedstock crops might lead to N_2O emissions, a gas that strongly contributes to uncertainties in terms of GHG balance, since already small amounts have a large impact on the greenhouse effect (JRC 2006, 34). It appears as if wheat and, to a smaller amount, sugar beet will remain the most important source for ethanol in Europe. It can be concluded that the typical European pathway from wheat to ethanol does not necessarily, but can contribute to energy and climate security. Sugar beet improves the balance but will hardly become widespread in Europe. As it is discussed for biodiesel (see chapter on biodiesel), from a more global perspective the question must be raised if this wheat-to-fuel pathway is maintainable in terms of energy efficiency.

Additional applications and pathways

Besides using ethanol directly as a fuel, it is also converted into the ethyl tertiary-butyl ether (ETBE) by adding isobutene. It can easily be admixed up to 15% without causing any problems (VDA 2005). ETBE is a common high-quality additive for gasoline that increases the octane rating and helps prevent engine knocking.

Since isobutene is a by-product of the mineral oil refinement, ETBE can only partly be of biogenous origin. When methanol is used instead of ethanol, methyl tertiary-butyl ether (MTBE) is generated by almost the same process. MTBE is used in the same application as ETBE. However, ETBE has generally replaced MTBE due to its environmental precariousness.

Until now, only the starch-containing corn itself is used for fuel production. Recently, new facilities have emerged which are designed to treat lignocellulose-containing materials for ethanol production, such as wood or straw (see Schmitz 2006, 20). The technology is still in an experimental stage and has not yet been commercialised, but it will surely become relevant in the next years, since it offers several advantages. Most important: much more ethanol can be produced per hectare at relatively lower costs. Savings of emissions and GHG gases are significantly higher than those for the wheat-to-ethanol pathway, while it is crucial that "these processes use part of the biomass intake as fuel and therefore involve little fossil energy" (JRC 2006, 36). The wood pathway is especially interesting for countries like Sweden or Canada with large forest areas, but also the use of straw could be an interesting fuel source in mid-European countries with a higher population density. Further, it is technically possible to use the biodegradable fraction of waste or sewage sludge as feedstock.

Other plants are discussed as feedstock, such as sweet sorghum (Kingsman 2006). The potential for innovations induced by biotechnology is still difficult to assess.

Prospects

The production of ethanol is a well-established technology in the USA and Brazil, but also in Europe, where domestic production is being extended by imports in order to satisfy the European demand. Significant contributions to climate and energy security are likely, but strongly depend on various factors in the production chain, where especially the contribution of fertilisers to GHG emissions is difficult to assess. In different countries different feedstocks have optimum potential: sugar cane in Brazil, maize in the USA, wood in Sweden or Canada, wheat and straw in Central Europe. This indicates that geographical conditions are also important for the potential energy efficiency and GHG savings. Further, it is possible that advanced technologies such as ethanol from straw and wood will become more dominant in future.

Biogas (Biomethane)

Wet Biomass → Fermentation → **Biogas** → Otto-ICE (CLEANING)

Wet Biomass → Fermentation → **Biogas** → Reformation, H_2 Separation → H_2 → PEMFC + E-motor

Motivations	• Of all biofuels it provides for the highest fuel substitution rate per hectare • Potential contribution to climate and energy security • In principle, biomethane can be added to the natural gas grid • Provides alternative sources of income in rural areas
Challenges	• Biogas must be upgraded to the quality of natural gas • Large-scale production for the transport sector has not yet been realised • Market penetration of gaseous fuels is still relatively low
Central Controversies	• To what extent could the European demand be satisfied by biomethane derived from domestic resources? • What is the future role of gaseous fuels?

Source and characteristics

Biogas is derived from wet biomass, which contains considerable amounts of water (at least more than 50%). It is fermented to biogas in a reactor under exclusion of oxygen. All biomass containing carbohydrates, proteins, fats, cellulose and hemicelluloses as a main component can be used as feedstock. Commonly used is manure and dung of stock farming or biogenous residuals of other branches and municipal waste. Not convertible in standard reactors is biomass that contains lignified cellulose, such as wood or straw.

The main components of biogas are methane with 50 to 60% and CO_2 with 40 to 50%. In addition, it contains several trace elements. By separating CO_2 and the trace elements, it can be cleaned to the quality of natural gas, which consists primarily of methane (CH_4). Thus, biogas can be mixed with natural gas, distributed with the same infrastructure and burned in Otto engines that run on natural gas.

In compressed form biogas is called CBG (compressed biogas).

Deliverability, competitiveness and contribution to energy security

The production of biogas is a well-established technology. But until now, for economic reasons, the gas is mainly used for power and heat generation and not as a fuel. Accordingly, there is little experience with biogas in the transport sector. Up to now, biogas production has mainly taken place on a small scale. Recently, and mainly in Scandinavia, concepts for large-scale plants have been developed that allow the production of automotive quality biogas (JRC 2006, 88). Only in Switzerland, small amounts of biogas for transport are already on the market.

When upgraded to the quality of natural gas, which is mainly methane, it can be used like methane: It can be sold in gas stations already selling natural gas and burned in advanced mono- or bivalent engines. It has the same advantages as natural gas.

Because of the relatively high heating value, 1 kg biomethane can substitute 1.5 litres of petrol and 1.08 litres of diesel. From one hectare, 3,560 kg biomethane can be gained, which allows to substitute around 5,000 litres of petrol. But biogas is significantly more expensive than natural gas.

Biogas could substitute considerable amounts of fossil fuels and thus contribute to energy security. The potential is limited by the availability of suitable biomass and also by the market penetration of gaseous fuels.

Energy balance, emissions and contribution to climate security

Biogas can contribute to climate security by substituting fossil fuels. The carbon in biogas was extracted before from the atmosphere by photosynthesis during the growth of the plants. Like natural gas, it has the advantage that it burns cleaner and releases less pollutants (see natural gas chapter).

Especially when produced from waste materials, biogas offers high and relatively low-cost GHG savings (JRC 2006, 4).

Additional applications and pathways

Biogas could also be converted into hydrogen through reformation. Recently, these so-called BTH (biomass-to-hydrogen) pathways are discussed frequently and first demonstration projects are conducted. From a well-to-wheel perspective this pathway is critically discussed in terms of efficiency, since several conversion processes are needed. Critics point out that biogas should be used more efficiently to produce electricity or heat. Furthermore, the BTH path faces the same problem as other biomass-based fuels: the amount of biomass is limited by several serious factors.

Prospects

In the transport sector, biogas is not yet on the market, However, it offers clear advantages in terms of both climate and oil security. It could play a significant role for future energy strategies. However, application in stationary energy production has clear advantages compared to its use in the transport area. Its chances for broader market penetration in the transport sector are strongly related to further developments of the fossil form of gaseous primary energy, which is natural gas.

"Of course, biogas could be used for many more applications than for vehicles. But we are convinced that the transport sector will play a key role as a driver of new technology, because the willingness to pay in this sector is high, and that there is a very real opportunity for consumers to individually contribute to a more sustainable society." (Anders Hedenstedt CEO Göteborg Energi AB, Gothenburg; http://www.euractiv.com/en/energy/biogas-goes-level/article-160306)

BTL: Biomass to Liquid

Lignified Cellulose-containing Biomass → Gasification → Fischer-Tropsch Synthesis → Diesel **(BTL)** → Diesel-ICE

Lignified Cellulose-containing Biomass → Gasification → Fischer-Tropsch Synthesis → Gasoline **(BTL)** → Otto-ICE

Motivations	• Large potential contribution to climate security • Considerable contribution to oil security possible • Specifications of the fuel can be fine-tuned to match the requirements of the engines • High flexibility in terms of feedstock • Admixtures to conventional diesel possible > no change to infrastructure needed • Provides alternative sources of income in rural areas
Challenges	• Not yet commercialised • Feasibility of large-scale production not yet proven • Still relatively high costs • Overall energy balance is critically discussed
Central Controversies	• To what extent can the complexity of these pathways be balanced by the benefits? • To what extent could the European fuel demand be satisfied by BTL fuels derived from domestic sources?

Source and characteristics

Biomass-to-liquid technology (BTL) encompasses several processes in the production line of the so-called second generation biofuels. The crucial point is that here the whole plant can be used to produce fuel, in contrast to the production of "first generation" biofuels where only parts of the plants (oil, sugar, starch) are used. Thus, for BTL products less land area is required per unit of energy produced compared with "conventional" biodiesel or bioethanol; the efficiency is significantly higher.

The second great benefit of the BTL route is the possibility to define the fuel properties by setting the reaction parameters. The specifications of the fuel can be fine-tuned to match the requirements of the engines by altering the form or length of the fuel molecules.

This fine-tuning is not possible in the currently used standard refining process for diesel or gasoline, what explains the great interest of engine developers in these “designer fuels”. Another often used synonym is “synfuel”. Engine and fuel can be perfectly adjusted to each other. This allows to increase efficiency and to reduce the emission of GHG gases and other pollutants. In principal, conventional engines do not have to be adapted to BTL, however, in order to guarantee an optimised burning process minor adjustments are useful.

The third advantage is that BTL fuel can be derived from substances that mainly consist of lignified cellulose. Thus, there is a wide range of suitable feedstock. The most common are residual woods, straw or short rotation plants such as willow as well as municipal or industrial waste.

The BTL production starts with grinding and drying of biomass which is then usually chopped into small pieces. By gasification these “pellets” are converted into synthesis gas (“syngas”), a mixture of hydrogen and carbon monoxide. Via a process called “Fischer-Tropsch synthesis” the synthesis gas is converted into diesel or gasoline. This combination of gasification and Fischer-Tropsch synthesis is called biomass-to-liquid process (BTL). By modifying temperature, pressure and catalyst material the specifications of the fuel can be fine-tuned to match the requirements of the engines. Around sixty percent of the distillate can be used directly as a diesel fuel, whilst the other fractions can be used in the chemical industry or be further processed into gasoline or kerosene.

Deliverability, competitiveness and contribution to energy security

Second generation fuels are not yet established on the market and still object of extensive research and development efforts. A number of pilot and demonstration schemes can be found in Europe. These are still complex engineering projects with several practical problems to be solved (see JRC 2006, 41).

Up to now, mainly (bio-)diesel is produced by BTL processes. A prominent example is the “SunDiesel” developed by Volkswagen. Supported by a consortium of carmakers (VW, Daimler-Chrysler) and oil companies (Shell), SunDiesel is currently being tested by the company Choren in Germany. First results are promising, but commercialisations will require further efforts. The launch of the first commercial facility is planned by Choren for 2007. The capacity will be approximately 16.5 million litres (approx. 12.705 tons) per year. New sites are in a planning stage, each with a capacity of around 225 million litres (approx. 173.25 tons). It is assessed that from one hectare 4,000 litres of BTL can be produced per year (FNR 2006, 52). On its webpage, Choren estimates that in Germany around 4 million tons of BTL fuels could be produced from residual straw alone, this amount would allow to substitute up to 14% of German diesel consumption (30.2 t in 2005). Choren also cites a study (Kaltschmitt/Vogel 2004) that calculates the biomass potential for the EU25 as large enough to produce up to 115 million tons of synthetic fuels per year. This would be enough to substitute around 70% of the EU25 diesel consumption in 2005 (158.5 Mio t). Production costs are still significantly higher than those for bioethanol or biodiesel, whereas considerable reductions are expected to be realised in future. It seems not to be impossible to produce fuel at a cost below 1 Euro per litre. It is expected that in a few years larger facilities will allow the production at a cost of 0.7-0.9 Euro per litre.

However, the numbers and calculations mentioned above may vary considerably due to the uncertainties regarding development and relevance of various factors. Large-scale production has not yet been commercialised. But it is obvious, that there is potential to substitute considerable parts of European fuel consumption by the BTL route.

And there is still a large potential for innovations: Many research activities can be observed in this field, for example at the Research Centre Karlsruhe, where the corresponding BTL process is licensed under the name Bioliq. The process is tailored to overcome the difficulty that biomass is usually widespread over the country and can hardly be collected and transported at reasonable costs. Straw, for example, has a rather low energy density, which makes long-distance transport unattractive. The Bioliq process is based on a two-step approach. In a first step, the raw biomass is converted in decentralised plants via "fast pyrolysis" into a liquid interim product (slurry) that can easily be transported to centralised facilities, where, in a second step, the production of diesel takes place.

Only recently, China has shown great interest in this process and seems to be working out plans for a demonstration site. China has large amounts of residual straw. In Sweden, the company Orbroram produces a synthetic diesel from biogas, which is called BioPar, and a synthetic diesel from natural gas called EcoPar.

Energy balance, emissions and contribution to climate security

Energy balance and GHG emissions are more favourable than those of first generation biofules. Especially in terms of climate security the potential benefits are promising. The JRC study (2006, 5) concludes that BTL processes have the potential to save substantially more GHG emissions than current biofuels at comparable costs. For the production of BTL only small amounts of external energy are required, because the synthesis processes can be fuelled by the biomass itself. This means that a neutral CO_2 balance is possible, since during combustion only the CO_2 contained in the biomass is released. The balance might only be disturbed by the energy needed for plant cultivation and transport. The emission of other GHG-relevant gases can be largely avoided. BTL fuel is free of sulphur and other impurities; the synthetic fuel only contains compounds that are really needed. Synthetic fuels can not only be adjusted to the engine requirements, but they can also be designed to produce minimum emissions, e.g. of NOx or soot.

Additional applications and pathways

The second part of the BTL process – the generation of diesel from syngas – is quite similar to the so-called gas-to-liquid (GTL) and coal-to-liquid (CTL) processes. Both routes result in high quality fuels that induce only few pollutants at the tailpipe.

Technologies for producing syngas and converting it into liquid fuels are rather old. For the CTL route, coal is gasified and than converted into liquid diesel using the Fischer-Tropsch process. Currently, only South Africa, which was cut off from oil supply by an embargo, intensively exploits its coal resources for fuel production. In the meantime, especially countries with large coal resources, such as the USA or China, show considerable interest in projects related to the CTL route. CTL produces considerably more GHG gases than conventional diesel. A combination of CTL with technologies for CO_2 capture and sequestration would lead to a much better CO_2 balance – but at the expense of efficiency.

In the gas-to-liquid route, natural gas is transformed into liquid gasoline. The procedure is technically well established but (in the past) commercially not attractive – this again depends on the availability of more economical options, which has been oil until now. In the meantime, a lot of new large-scale GTL plants are emerging, often nearby gas fields that are not well connected to the pipeline network. In such cases, GTL provides the possibility to bring the natural gas to the market. The JRC study (2006, 5) concludes that GHG emissions are slightly higher than those of conventional gasoline.

The pulp and paper industry might offer an efficient BTL route by using so-called "black liquor", a by-product of paper production that contains the lignin fractions of the processed wood. Syngas can be generated by gasification of black liquor, and this syngas can be used to produce synthetic fuels. Such combined approaches might have considerable potential with respect to the flexibility of BTL in terms of feedstock.

By separating the CO_2 directly from the synthesis gas, H_2 is generated. The H_2 is then converted in a proton exchange membrane fuel cell (PEMFC) to electricity that feeds an electric motor. The entire route looks like this: Lignified cellulose-containing biomass → gasification → H_2 separation and cleaning → H_2 → fuel cell + E-motor.

Prospects

BTL processes have the potential to save substantially more GHG emissions than current biofuel options at comparable cost and merit further study (see Leible et al. 2006). Issues such as land and biomass resources, material collection, plant size, efficiency, and costs will limit the application of these processes (JRC 2006, 5). However, a significant contribution to oil security can be expected.

Methanol and DME (from Lignocellulosic Materials)

Lignified Cellulose-containing Biomass → Gasification → Methanol Synthesis → **Methanol**→ Otto-ICE

Lignified Cellulose-containing Biomass → Gasification → Methanol Synthesis → **Methanol**→ Fischer-Tropsch Synthesis → BTL fuel → ICE (Otto or diesel)

Lignified Cellulose-containing Biomass → Gasification → Methanol Synthesis → **Methanol**→ Reformation and H_2 Separation → H_2 → PEMFC + E-motor

Lignified Cellulose-containing Biomass → Gasification → **DME** Direct Synthesis → CDME→ Diesel-ICE

Motivations	• A wide range of feedstocks can be used • Reduction of GHG emissions is possible • Synthetic fuels reduce emissions of NOx, SOx and soot
Challenges	• Fuel production is not yet commercialised • Feasibility of large-scale production is not yet proven • Methanol is needed in other industrial sectors as well • Methanol is known as being toxic
Central Controversies	• To what extent can the complexity of these pathways be balanced by the benefits? • Could these pathways provide a significant contribution to energy security?

In this chapter, a few routes based on methanol and DME will be addressed. The description and assessment is rather short, since there is not much practical experience with the single pathways.

However, it should be noted that especially the flexibility in producing and using methanol offers a rich platform for further innovations. Many experts can well imagine that especially methanol but also DME will play a more important role in the fuel sector in near future.

Source and characteristics

Methanol is the simplest alcohol; it is a light, flammable and toxic liquid. During the oil crises in the early 1970s, methanol was discussed as a cheap alternative to fossil fuels and, mainly in the USA, added to gasoline. Improper handling caused some difficulties and led to image problems in the public. The burning of methanol in conventional engines only requires small modifications.

Methanol is one of the safest fuels, because it is much less flammable than gasoline. A disadvantage is the fact that methanol is toxic. Another problem is its corrosivity to some metals. The decisive advantage is that it can be produced at relatively low costs from a wide range of feedstocks, among them natural gas, coal and very different sorts of biomass such as wood, straw, domestic and industrial waste.

The JRC study (2006, 76) critically states: “Methanol is an international commodity, large quantities of which are produced from coal and mostly natural gas, for use in the chemical industry. The technology is fully commercial and sourcing additional methanol for road applications is unlikely to be an issue especially for limited quantities.” However, recently there has been a tendency to use methanol as a flexible intermediate product rather than burning methanol directly. This is illustrated below by the different routes related to methanol.

Dimethyl ether (DME) is the simplest of all ethers. Its heating characteristics are similar to those of natural gas. Currently, DME is produced mainly from natural gas-derived methanol. DME can also be manufactured from methanol derived from coal or biomass; the production is similar to that of methanol and can be based on a broad variety of pathways. DME can be liquefied by low pressure and then used in diesel engines. Storage and distribution would be quite similar to that of LPG. “DME is to diesel what LPG is to gasoline. It is gaseous at ambient conditions but can be liquefied at moderate pressure” (JRC 2006, 42). As a fuel for compressed ignition engines it has very attractive characteristics such as clean burning and producing virtually no particulates. “A dedicated DME vehicle would probably not require a particulate filter but would need a purpose-designed fuel handling and injection system” (JRC 2006, 42).

Description of related pathways

The routes described above have in common that both methanol and DME are derived from lignified cellulose-containing biomass via synthesis gas. Once the methanol is produced, there are different ways to use it. Some of them are mentioned here:

- Methanol can be generated from synthesis gas and burned directly or as an additive to gasoline in an Otto engine. A programme to establish methanol-enriched gasoline (M85) as a fuel in California ended after 15 years duration in 2003 without the expected success. As a fuel for combustion engines, ethanol is presently the worldwide favoured alcohol. However, methanol has the advantages that it is cheaper than ethanol and that it can be made from a broader variety of biomass (as well as from coal or natural gas).
- Methanol is investigated as a feed material for the Fischer-Tropsch synthesis in order to produce BTL fuels. It is also possible to circumvent the Fischer-Tropsch synthesis by a procedure licensed under the name MTS (methanol-to-synfuels) by the company Lurgi from Switzerland. This detour via methanol is made to enable an economic treatment of biomass: In a decentralised way, methanol is manufactured as intermediate product which is easy to transport and store.

In a second and centralised step, the MTS process is carried out in larger facilities. The result could be either synthetic diesel or synthetic petrol of high quality.

- It is also possible to use methanol as a source of hydrogen for a PEM fuel cell. In this case, not hydrogen but methanol is stored in the car and is reformed into hydrogen on board. There exist a few demonstration cars using this technology (see chapter on hydrogen). Furthermore, methanol is discussed to fuel so-called direct methanol fuel cells. This technology is in the first stages of commercialisation for smaller, portable applications, such as laptops; but application in the transport sector is still linked to many unsolved problems (see chapter on fuel cells).
- Another application for synthesis gas and methanol is converting it to gaseous dimethyl ether (DME). The conversion is usually realised in a direct conversion reactor (Topsøe process). DME is discussed as an alternative fuel for customised diesel engines. For using the DME as a fuel it has to be stored in compressed form (CDME). It is plausible that DME would trade at a price corresponding to the methanol equivalent (JRC 2006, 60).

Natural Gas (CNG, LNG) and Autogas (LPG)

Natural Gas → CNG (Compressed Natural Gas) → Otto- or Diesel-ICE

Natural Gas → LNG (Liquefied Natural Gas) → Otto- or Diesel-ICE

Crude Oil → Refining → LPG (Liquefied Petroleum Gas) → Otto- or Diesel-ICE

Natural Gas (crude) → LPG Separation → LPG (Liquefied Petroleum Gas) → Otto- or Diesel-ICE

Motivations	Natural gas: • Comparatively clean burning process • Commercialisation of CNG could pave the way for other gaseous fuels such as biogas (biomethane) and/or hydrogen • CNG could be mixed with biogas (biomethane) LPG: • Comparatively clean burning process • Is easily available at low costs • Commercialisation could pave the way for other gaseous fuels (DME, hydrogen)
Challenges	• Natural gas and LPG are based on fossil feedstock • Availability of natural gas: transport sector might have to compete with other sectors; Europe might have to compete with other regions (China, India)
Central Controversies	• Could a gaseous infrastructure pave the way to a so-called "H_2-age"? • To what extend does CNG or LPG open the way for a market penetration of Biomethane or DME and, thus, serve as a key-step on the way to clean fuels.

Source and characteristics

The central difference between Natural Gas and Liquefied Petroleum Gas (LPG) is that Natural Gas can be found in nature whereas LPG is an artificial by-product from refining processes or can be extracted from natural gas. LPG, also called Autogas, is a mixture of butane, propane and low amounts of other gases. It commonly fuels Otto ICEs but can also be used in diesel engines.

Further, it is important to note that LPG, propane and butane are “automatically” generated during the extraction of natural gas and the processing of methane. So, there is some flexibility in terms of feedstock

Natural gas can often be found beneath oil basins. It is a gaseous fossil fuel consisting primarily of methane (CH_4). It nearly needs no processing for the use in automobiles which is a decisive advantage in terms of feasibility. The actual composition of Natural Gas may vary widely between countries, depending on the gas origin. Since the energy density of natural gas is low compared to diesel, the fuel has to be stored in compressed form as so called Compressed Natural Gas (CNG) or liquefied (LNG) at a very low temperature of -161°C. Accordingly, LNG offers a higher energy density than CNG, but CNG is much easier to handle. CNG can be transported in pipelines over long distances; the transport of LNG in specialised “reefer” vessels becomes more and more common but is comparatively costly. In terms of security the storage of both CNG and LPG is not dangerous.

Autogas can be compressed to a liquid at very low pressures. In this form it is used in conventional spark-ignition engines with only small alterations. The main modification required is the provision of an alternative fuel tank and supply to the engine (STEPS, 2005). Both Natural gas and LPG offer high octane ratings.

Figure 8: Filling Station with Natural Gas (In Countries painted brown natural gas is not available)

Source: ACE (www.ACE_2006-bestand_erdgastankstellen_in_europa.pdf)

<u>Deliverability, competitiveness and contribution to energy security</u>

The natural gas and LPG pathways are already commercialised and compete with each other as well as with conventional gasoline engines – even if market shares in the EU are (still) marginal. Especially bivalent CNG-cars which can be powered by conventional fuels as well as by CNG have the potential to increase market shares quickly. For example the Opel Combo CNG has a 200 bar CNG-tank which allows a range of about 360 km. If CNG runs empty the vehicles switches automatically to gasoline which is stored in a 15 litre tank and provides for another 150 -170 km. Driving performance of both fuels is equal. “There are more than 4.7 million natural gas vehicles (NGVs) in operation around the world today; nearly 557,000 in Europe alone. These include passenger cars, light vans, delivery trucks, garbage trucks and urban buses” (ENGVA 2006; http://engva.org/Content.aspx?PageID=63).

Concerning the market diffusion of CNG and LPG, the situation in Europe is not homogeneous. A crucial factor is the number of existing filling stations. In order to enable a successful transition to a mass-market product CNG and LPG need a dense network of filling stations. Whilst LPG is rather widespread in several European countries, CNG filling stations might be hard to find in many regions. In addition, stations are often situated in larger cities or in industrial areas but not along the highway network. On the other hand, there are countries such as Portugal, Italy and Germany where a relative dense network of CNG-fuelling stations is currently emerging (see figure 8). For example in Germany the energy supplier E.ON announced in autumn 2006 that it will build 150 CNG pumps at filling stations along German Highways.

Many observers see natural gas as the next dominant fossil fuel on a global scale. From the supply side, a coverage of, for example, 10% of general fuel demand by CNG would not add too much to the overall consumption of natural gas in Europe. On the other hand CNG-contribution to the energy security is clearly restricted by the fact that natural gas is a fossil resource which is not available endlessly (see DWV 2006, 12). Natural Gas and also LPG are imported to a large extent in the EU from politically sensitive regions which significantly reduce their potential contribution to Europe's mid-term energy security. A large scale use of natural gas in the transport sector would lead to an overall increase in demand which has to be satisfied – at affordable prices. Furthermore, if you consider the phasing out of coal and nuclear power, the overall demand for natural gas is expected to grow strongly. Transport has to compete with the generation of electricity and heating.

Regarding LPG the JRC study points out: "The net effect of an increase in the use of LPG for automotive purpose would be to increase imports." (JRC, 2006, 30). Of course, the same is true for natural gas. LPG is popular because of its usually low costs. Currently several automakers (Citroen, Daewoo, Fiat, Ford, Peugeot, Renault, Saab, Volvo and others) sell models equipped with bi-fuel models that run equally well on both LPG and gasoline. It is comparatively simple to retrofit a vehicle with LPG equipment. In most cases LPG vehicles are bivalent which allows them to drive on both, petrol and LPG. Figure 9 illustrates that LPG filling stations are rather widespread in Europe and that around 4.4 million vehicles are fuelled with LPG. However, as the STEPS report states, "the penetration on the total vehicle fleet of LPG has limited chances, given the nature of the resource itself, which may be seen either as a "surplus" in upstream oil production or as a by product of refining." (STEPS, 2005)

An important detail: Both LPG and natural gas vehicles are exempt from the London congestions charge. The mid-term effect of such regulations should not be underestimated. If similar regulations are applied to other European cities, market penetration of those fuels might become intensified.

Energy balance, emissions and contribution to climate security

As a fossil fuel, CNG and LPG face similar problems as oil: they are finite resources and contribute to global warming. The advantages of natural gas as a fuel are the comparatively clean burning process and the low content of carbon. Significant reductions of particulate matters, NOx and CO emission are possible. Related to GHG emissions, balancing is not easy and depends on various factors. The JRC (2006, 4) comments: "The WTW GHG emissions for CNG lie between gasoline and diesel, approaching diesel in the best case". The same study estimates that beyond 2010 GHG-emissions become lower than those of diesel since greater engine efficiency gains are predicted for vehicles equipped with engines that are optimised for the use of CNG. The STEPS report points out (2005, 51): "Natural Gas has nearly zero sulphur level and, thus, negligible sulphate emissions, while causing low particulate emissions because of its low carbon to hydrogen ratio. Evaporative emissions are low too, requiring little control.

Due to its low carbon-to-hydrogen ratio, it produces less carbon dioxide per GJ of fuel than either gasoline or diesel. However, exhaust emissions of methane, which is a greenhouse gas, are relatively high. It has low cold start emissions due to its gaseous state and a superior anti-knock behaviour due to its high octane factor, thus allowing higher compression ratios, favouring engine efficiency and operation under turbocharged conditions".

Primarily because of the lower carbon content LPG induces less exhaust emissions than petrol. Also on a WTW-basis, CO_2 benefits of LPG are significant compared to those of petrol. LPG's well-to-wheel energy consumption falls below that of gasoline but above that of diesel (STEPS 2005). Regarding WTW energy and GHG emissions balance, the JRC study concludes for LPG coming from the Middle East: "LPG's GHG emissions lie between diesel and CNG and energy between gasoline and diesel. Although not explicitly shown in the graph, transport distance has a significant impact, representing about 25% of the WTT energy in this case" (JRC, 2006, 30).

Additional Applications and pathways

Both, CNG and LPG, can be mixed with biomass derived gases (Biogas and DME; see Biofuels section)

Blends of hydrogen and natural gas are discussed and tested (see hydrogen chapter).

Prospects

CNG technology is feasible in the transport sector and has the potential to bring at least mid term improvements in terms of energy security and GHG emissions – whereby it is crucial that real "gas-engines" are being developed. But in particular its possible contribution to energy security strongly depends on the overall demand on natural gas. It is likely, that CNG vehicles will become at least established for niche applications (e.g. in larger fleets, in inner cities). LPG is a relatively uncomplicated technology. It offers environmental benefits at relatively low costs. It is becoming rather popular in several European countries. Since both, CNG and LPG, are based on fossil feedstock they must be considered as bridging technologies. They might help to pave the way for "cleaner" gaseous fuels such as hydrogen, biomethane or DME.

"The paradigm shift from liquid to gaseous fuels will create enormous new business opportunities—initially mainly for methane-powered vehicles, but eventually also for hydrogen fuel cell vehicles" Peter Boisen, former Volvo executive and chairman of ENGV Europe; quoted in ENGV 2006.

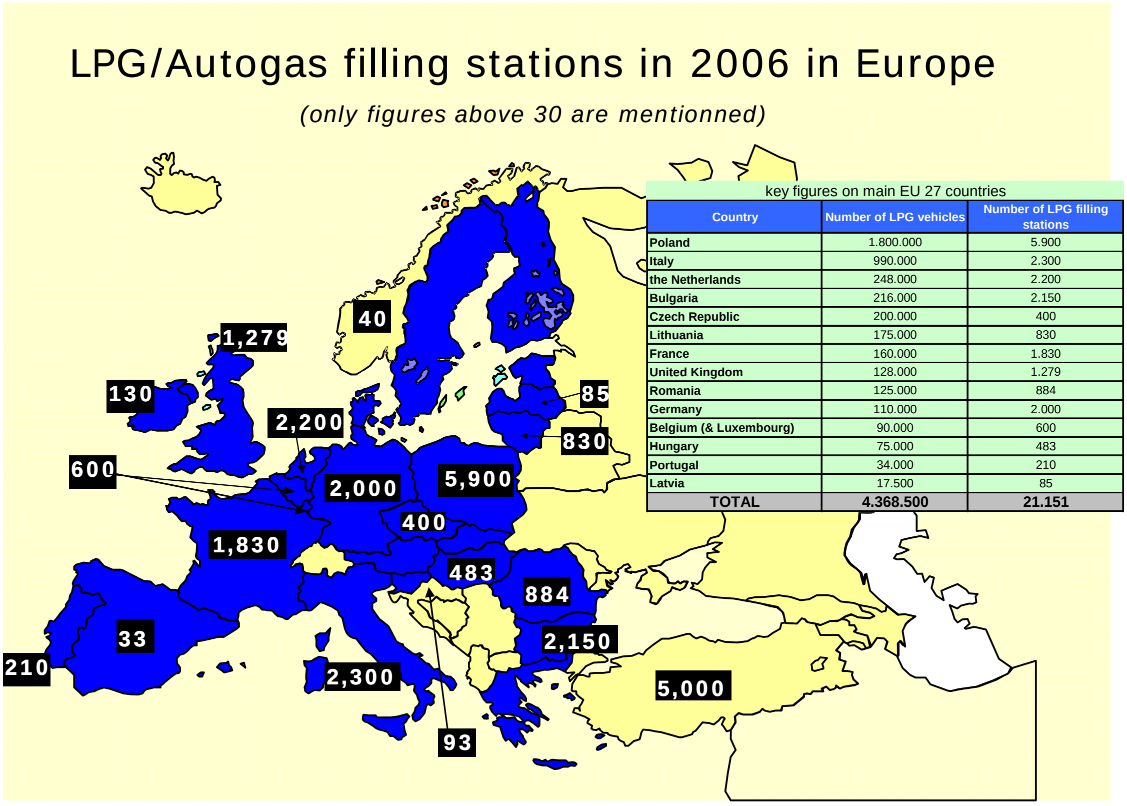

Figure 9: LPG/Autogas filling stations in 2006 in Europe

Source: AEGPL (European Liquefied Petroleum Gas Association) 2007.

Improved efficiency of conventional technologies

Motivations	• Technology is highly mature and established • Technology is available at relatively low specific costs • Potential to reduce fuel consumption and GHG-emissions is still large
Challenges	• Conventional technologies are in general oil-based
Central Controversies	• To what extent can the efficiency of conventional technologies be improved?

Source and characteristics (technological background)

The alternative technologies mentioned above have to compete with the conventional Internal Combustion Engine (ICE) which was developed and improved step by step; pushed by the dynamics and pressure of hard international competition during a time span of more than a hundred years.

Today, the ICE has the advantages of being a highly mature, well established technology which is available at relatively low specific costs. It offers a good handling and performance. It is undisputed that developments in engine and vehicle technologies will continue to contribute significantly to the reduction of energy use and GHG emission.

Deliverability, competitiveness and contribution to energy security

Two different types of ICE are established: diesel- and Otto-engines. For thermo-dynamic reasons, diesel engines are more efficient than petrol driven Otto-engines. In the last decades, the share of diesel vehicles rose remarkably in the EU. 15% of efficiency gains in Europe (STEPS 2005) have been a direct result of an increasing share of diesel vehicles. This might lead to problems in terms of energy supply as it calls for more diesel and less gasoline than can be produced in European refineries, as these usually have been built for a production focused on petrol. Furthermore, the production of diesel goes along with higher costs and CO_2 impacts at the refineries.

Energy balance, emissions and contribution to climate security

For the development of advanced combustion engines the European (Euro norm) but also US exhaust standards (SULEV: Super Low Emission Vehicle) are decisive. The emission standards of the successor to the current European standard Euro4 are presently discussed as Euro5 and Euro 6 in the European administration and will enter into force in the course of 2009 and 2014 respectively.

Proposed are further reductions of 25% HC-emissions for gasoline-cars and a reduction of 80% particulate matter- and 20% NOx-emissions of diesel-cars relating to the limiting values of Euro4. Concerning the emission of CO_2 the voluntary self-commitment of the European Automotive Manufacturers Association (ACEA) defines a target value of 140 g CO_2/km as the fleet average for all newly admitted passenger cars in 2008. For the Japanese and Korean Automotive Manufacturers Associations (JAMA and KAMA), a similar target applies for 2009.

An achievement of these values requires for both types of engine developments more efficient and cleaner burning systems, an advanced after-treatment of exhaust-gases, but also a significant increase of efficiency of the engines in general.

In the past the introduction of the three-way catalytic converter combined with an electronic injection system that allows a stoichiometric combustion was a major step in the reduction of HC-, CO and NOx emissions in the Otto-engine. Even if this reduction was significant, there is still a high potential, especially in the combustion process. For example the lean combustion is one important object of development activities in this area. At present, the introduction of direct injection is the most important singular innovation for Otto-engine that allows fuel savings of up to 10% compared to the conventional port injection.

Traditionally, the diesel-engine already in the past had better HC-, CO-emission values and a lower fuel consumption than the Otto-engine because of its advantageous combustion technique. The major disadvantage still is the high emission of particulate soot and NOx. Even if the advancement of the engine already reduced this emission significantly especially by realising the common rail principle, the emission standards proposed for Euro5 are not reachable without the implementation of a particle filter in the exhaust pipe.

For both engine types the use of synthetic fuels is seen as another opportunity to further reduce the fuel consumption and the emission of pollutants. Other general strategies leading to these aims for example are downsizing the engines or reducing the weight of the car by using advanced materials.

There are as well basically new concepts investigated such as the promising "combined combustion systems" or the "diesotto" concept which combines the benefits of gasoline and diesel engines to improve fuel efficiency. These concepts are based on synthetic fuels (see biomass chapter).

Prospects

New legislation is discussed on EU level which might replace the voluntary commitment of carmakers to reach the 140g CO_2/km target. There is still a large potential to improve efficiency of conventional technologies and to further reduce emissions. Synthetic fuels derived from biomass might as well contribute to an improved efficiency of conventional ICE's (see biomass chapter).

5. Alternative Options for Air Transport

Currently, the dominant propulsion technology in commercial air transportation is the gas turbine (either as turbojet, turbofan or turboprop) that is fuelled by kerosene. The technology is now relatively mature. The air transport industry over the years has made impressive improvements to aircraft energy efficiency, but these were mainly limited to incremental steps within the same technology domains and accompanied by operational measures like air traffic management or ground traffic management at airports. Despite these developments, the growth of global air traffic (50% over the last decade) has led to an immense increase in oil consumption and greenhouse gas emissions (GHG) caused by air transport. According to the ASSESS study, air transport continues to be the transport mode with the highest growth rate over the next 15 years (ASSESS 2005).

Because there is presently no alternative propulsion system to the gas turbine in sight, research on alternative fuels and alternative fuel sources as well as on new propulsion technologies is at an early stage. Research activities on the one hand focus on alternative fuels for this system and on the other hand on the improvement of the combustion through advanced combustion chambers. Other projects research into opportunities to increase the efficiency by an advanced aerodynamic, reduction of weight and others. In all cases the aim is to reduce the emissions of greenhouse-gases and other pollutions while increasing the efficiency of the propulsion system in general.

A promising approach for increasing efficiency is related to the design of airplanes. It is said that with the new Airbus 380 conventional design of airplanes has reached its limits in terms of both capacity and aerodynamic performance. As a new concept for design the so-called "flying wing" or blended wing body (BWB) is discussed. Many researchers believe it will have better fuel efficiency because more of the plane contributes to the lift. It is expected that the BWB would weigh less, generate less noise emissions, and cost less to operate than an equally advanced conventional transport aircraft. The BWB shape allows unique interior designs. Cargo could be loaded or passengers could board from the front or rear of the aircraft. Several questions still have to be answered before the BWB could be safely introduced as a transport aircraft. One is how to build a lightweight structure that can be pressurized. It is easy to pressurize a tube, but not so easy to pressurize a non-cylindrical shape.

There is a general consensus among experts that kerosene-fuelled gas turbines will remain the relevant technology for air travel for the foreseeable future. However, several alternative solutions are discussed. Among them are biofuels and hydrogen, at which we will have a closer look in the following.

Biofuels for air transport

Motivations	• Potential to contribute to both climate and energy security
Challenges	• Tough security standards in air transport • Its potential is restricted by the absolute amount of available biomass as well as by the use of biomass in other sectors (road transport, power generation, heating)

Source and characteristics

Kerosene could well be derived from biomass. Biomass derived admixtures to kerosin would be possible. For more specifications see the biomass chapter in the road transport section.

Deliverability, competitiveness and contribution to energy security

Biofuels are investigated as alternative fuels for aviation. But besides the general restrictions, such as available acreage or energy efficiency, which were discussed before in road transport, for aviation operational and safety requirements are much tighter than for road transport. One aspect in this context is that the fuel still must be perfectly liquid at low temperatures in great heights. Presently, there are no biofuels established for aviation. Taken from the technical side it should be no problem to introduce them to the market as admixtures to fossil kerosene; similar to the road transport sector. However, deliverability is strongly restricted by the absolute amount of available biomass as well as by the use of biomass in other sectors, such as the road transport sector or the generations of heat and power. It looks as if there would be easier and more efficient ways of making use of the existing biomass potential. In spite of innovative technologies, such as so-called second generation biofuels (see biomass chapter), it is not likely that the amount of available biomass will be large enough to serve road transport and air transport simultaneously.

Energy balance, emissions and contribution to climate security

Energy and CO_2 balance of biofuels are mainly dependent on the processing energy that is needed for cultivating and/or treatment of the feedstock. Accordingly, figures are rather similar to those for road transport. Variations might be induced by the behaviour of emissions in high altitudes.

Prospects

Biofuels or Bio-Kerosene in the air transport sector are technically possible but not likely to come. Because of different reasons, among them high security standards, it is more likely that the potential of biomass will be fully tapped by its use for road transport and other applications (heating and power generation).

Hydrogen for air transport

Motivations	• Potential to contribute to both climate and energy security • Re-fuelling structure in the aviation sector could be a benefit due to large and localised demands at airports
Challenges	• Tough security standards in air transport • Immense amounts of hydrogen would be needed at airports
Central Controversies	• Does it make sense to use hydrogen in the air transport sector as long as kerosene is still available?

Source and characteristics

see chapter on hydrogen

Deliverability, competitiveness and contribution to energy security

In principle, conventional gas turbines only need to be slightly adapted for the combustion of hydrogen. The major problem is storing large amounts of hydrogen in the airplane. This has a major impact on the general design of the airplane there have been no prototypes constructed yet. Furthermore, from today's point of view it seems to be difficult to supply a large airport with the immense amounts of hydrogen that would be needed to serve the entire demand.

But compared to road transport, re-fuelling facilities are much more centralised at airports. The STEPS report states (2005, 64): "It is possible that long distance air transport is better suited to a hydrogen economy than ground based transport. Here, there are few carbon free alternatives, the energy to weight advantages of hydrogen can be advantageous for aircraft (although the energy volume density is low which partly negates this), and cheap hydrogen could be produced by economies of scale due the large high volume and localised demand at airports. The relatively complex technologies in fuelling and storage could also be more safely handled by the aerospace industry although the hydrogen would probably have to be used in cryogenic liquid form, so there would still be significant technological challenges in handling and storage."

Energy balance, emissions and contribution to climate security

When hydrogen is used in airplanes, the only emission is water. However, depending on the flight altitude the water vapour contributes slightly to the greenhouse effect. Hydrogen itself is an energy carrier and not an energy source. Consequences, hydrogen is only as clean as the energy that is used to generate it.

For more specifications see the hydrogen chapter in the road transport section.

Prospects

It is not likely that hydrogen will be used in air transport before it will have been established in the road transport sector.

It is hypothetical but it would be interesting to see to what extent new designs of aircrafts would offer chances to implement new propulsion technologies. For example, it is easier to install a cryonic hydrogen tank in a "flying wing" than in a conventional airplane.

6. Concluding remarks

This catalogue deals with *alternative* technology options for road and air transport, which means that the focus clearly is on new, "alternative" or innovative pathways – even if one chapter describes the potential of increasing the efficiency of conventional technologies. The latter is regarded by many observers as the most reasonable concept, at least in the short-term.

The catalogue was compiled on the basis of existing literature and validated and enriched by interviews with experts form the academic world, from industry and from stakeholder organisations. A pre-final version was discussed at the European Parliament together with MEPs and experts. One conclusion of this research is that virtually all experts agreed on three main factors that are responsible for the current discussion on alternative fuels:

- the prognosticated phase-out of oil;
- potential impacts of climate change;
- competitive advantages.

If there would not be a debate on the phase-out of oil and on the risks of climate change, alternative fuels and propulsion technologies would probably not be discussed in such an intensive and diversified way. According to interviews conducted in the course of this project there is a broad basis for the opinion that "something new" has to come sooner or later. Whilst the air transport sector does not seem to become the front-runner in this field, a wide range of technological pathways are being discussed for the road sector; some of them are now in the first stages of commercialisation, others are still in the stage of basic research. The technologies compiled in this catalogue are all promising but also have their clear weak points and bottlenecks. Some of the very central controversies and problems to be solved are summarised as follows:

- Hydrogen and fuel cells: There are many difficulties linked to these pathways, such as storage and distribution of hydrogen. But probably the most crucial point is the generation of large amounts of "clean" hydrogen. However, hydrogen and fuel cell technologies are promising and strongly promoted, in particular on the European level. Important controversies are related to the question whether there is (still) an alternative to what is called the upcoming "H_2 age" or whether we have to go this way.
- For a long time, battery electric vehicles were considered as the future alternative to conventional technologies. In this case, the battery is the weak point – in spite of decades of research. An important controversy revolves around the question of whether it still makes sense to invest intensively in battery technologies?
- Hybrid technology becomes more widespread. Hybrid technology combines an electric motor and a battery system with a fuel burning system. Overall efficiency strongly depends on the technology of the burning system which can be a conventional combustion engine but also hydrogen combined with fuel cell technology or natural gas. Since hybrids are generally more expensive than conventional vehicles, one central question is to what extent high fuel prices will facilitate market penetration?
- Biofuels and synfuels can be generated from a wide range of feedstock based on various processes. There are important controversies about whether there is enough "domestic" biomass to substitute a significant share of the fuel demand at affordable costs. In this context, the question is raised whether it will be possible to avoid biofuels derived from ecologically sensitive areas?
- Natural gas is a finite resource and, thus, can hardly be a long-term solution. A central question is whether natural gas might serve as a bridging technology that paves the way to, for example, hydrogen or biogas (biomethan).

The controversies and problems mentioned above are certainly not the only ones in the related technological fields but are considered here as central bottlenecks. A lot of research activities and technological breakthroughs are still needed to further improve these pathways. Rapid technological developments in other fields, especially the field of information and communication technologies (from telephone to mobile phone, from letter to e-mail; from compass and map to navigation systems), demonstrate how difficult it is to predict what new technologies will emerge and become established within a time span of only 10 or 20 years. For many of such developments in the ICT sector and in other fields of technology, competitive advantage has been the “only” driving force –not energy problems or the risks of climate change.

There are plenty of examples illustrating that also in the transport sector progress is taking place consistently. Some important trends related to “alternative technology options” are:

- Electric motors become more widespread in connection with hybrid technology. It is pretty likely that electric motors will become a component of future hybrid propulsion systems.
- Blends become widespread: admixtures of biofuels to conventional fuels have already been realised; blends of natural gas and biogas or blends of hydrogen and natural gas are discussed as well.
- Gaseous fuels gain small but noticeable market shares.
- In order to reduce CO_2 emissions many research projects concentrate on technologies for carbon capture and sequestration (CCS technology) – progress is to be expected in this field.
- Increasing diversification of technologies becomes apparent. This might as well take place on a geographical level: different regions might be dominated by different fuels (e.g. bioethanol in Brazil).

Further, there is the question to what extent the development of alternative fuels and propulsion technologies will be influenced by developments on a global scale. For example, the fast growing economies and growing population of the worlds largest countries (e.g. China and India) will lead to increasing demand for energy, foodstuff and water (quantitatively but also qualitatively) as well as mobility (in India there are currently about 7 vehicles per 1,000 inhabitants whilst in Germany the ratio is more than 500 per 1,000 inhabitants). This rather hypothetical notion illustrates that plenty of unpredictable factors (wildcards) are involved in this complex field.

Innovations will be needed to tackle the three central challenges in this field: climate change, energy security and competitive challenges. This is also true for the air transport sector. But it is likely that innovative technological developments will be implemented and established faster in the road sector, since tight security standards in the air sector make it much more difficult to introduce new technologies which always present a challenge in terms of security. However, in the long run the predicted phase-out of oil would make business-as-usual impossible for all oil-based technological contexts. A phase-out of oil would, at the same time, exert pressure on European innovation regimes – “something new” has to come. Policy strategies should remain flexible and open enough to support ground-breaking innovations.

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Interviews

Interviews related to single items / chapters / questions were conducted with

ACEA: The European Automobile Manufacturers Association	Mr Paul Greening
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DLR: German Aerospace Center (DLR) Institute of Propulsion Technology, Engine	Mr Andreas Döpelheuer
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Total	Mr Daniel Le Breton

8. Acronyms and Abbreviations

AFC	Alkaline fuel cell
BtL	Biomass-to-liquid
CBG	Compressed biogas
CCS	Carbon Sequestration and Storing
CDME	Compressed dimethyl ether
CGH2	Compressed gaseous hydrogen
CH4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO2	Carbon dioxide
DME	Dimethyl ether
DMFC	Direct methanol fuel cell
ETAG	European Technology Assessment Group
ETBE	Ethyl-tertiary-buthyl ether
FAME	Fatty acid methyl ester
FC	Fuel cell
FFV	Flexible fuel vehicle
GHG	Greenhouse gas
H2	Hydrogen
H2SO4	Sulphuric acid
H3PO4	Phosphoric acid
HC	Hydrocarbon
ICE	Internal combustion engine
K	Potassium
KOH	Potassium hydroxide
L_2O	Nitrous Oxide
LH2	Liquid hydrogen
Li	Lithium
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MCFC	Molden-carbonate fuel cell
MTBE	Methyl-tertiary-buthyl ether
Na	Sodium
NaNiCl	Sodium nickel chlorine
NiCd	Nickel cadmium

NiMH	Nickel metal hydride
NOx	Nitrogen oxides
PAFC	Phosphoric acid fuel cell
Pb	Lead
PEMFC	Proton exchange membrane fuel cell
SOFC	Solid oxide fuel cell
SVO	Straight Vegetable Oil
WTW	Well-to-Wheel; the complete life-cycle

Appendix 1: Variety of alternative technology options for road transportation

Primary Energy	Conversion I	Secondary Energy I	Conversion II	Secondary Energy II	Power Train
Coal	Gasification --> H2-Separation and Cleaning -->FT-Synthesis	**Gasoline (Naphtha)**			**Otto-ICE**
Coal	Gasification --> H2-Separation and Cleaning -->FT-Synthesis	**Gasoline (Naphtha)**			**Otto-Hybrid**
Coal	Gasification --> H2-Separation and Cleaning -->FT-Synthesis	**Gasoline (Naphtha)**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Coal	Gasification --> H2-Separation and Cleaning -->FT-Synthesis	**Gasoline (Naphtha)**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Coal	Gasification --> H2-Separation and Cleaning -->FT-Synthesis	**Diesel**			**Diesel-ICE**
Coal	Gasification --> H2-Separation and Cleaning -->FT-Synthesis	**Diesel**			**Diesel-Hybrid**
Coal	Gasification --> H2-Separation and Cleaning -->FT-Synthesis	**Diesel**			**PEMFC + E-Motor**
Coal	Gasification --> H2-Separation and Cleaning -->FT-Synthesis	**Diesel**			**PEMFC + E-Motor**
Coal	Gasification --> H2-Separation and Cleaning -->Methanol-Synthesis	**Methanol**			**DMFC + E-Motor**
Coal	Gasification --> H2-Separation and Cleaning -->Methanol-Synthesis	**Methanol**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Coal	Gasification --> H2-Separation and Cleaning -->Methanol-Synthesis	**Methanol**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Coal	Gasification --> H2-Separation and Cleaning	**CGH2**			**Otto-ICE**
Coal	Gasification --> H2-Separation and Cleaning	**CGH2**			**Otto-Hybrid**
Coal	Gasification --> H2-Separation and Cleaning	**LH2**			**Otto-ICE**
Coal	Gasification --> H2-Separation and Cleaning	**LH2**			**Otto-Hybrid**
Coal	Gasification --> H2-	**CGH2**			**PEMFC +**

	Separation and Cleaning				**E-Motor**
Coal	Gasification --> H2-Separation and Cleaning	**LH2**			**PEMFC + E-Motor**
Coal	Gasification --> DME Direct Conversion	**CDME**			**Diesel-ICE**
Coal	Gasification --> DME Direct Conversion	**CDME**			**Diesel-Hybrid**
Crude Oil	Refining	**Gasoline**			**Otto-ICE**
Crude Oil	Refining	**Gasoline**			**Otto-Hybrid**
Crude Oil	Refining	**Gasoline**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Crude Oil	Refining	**Gasoline**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Crude Oil	Refining	**Diesel**			**Diesel-ICE**
Crude Oil	Refining	**Diesel**			**Diesel-Hybrid**
Crude Oil	Refining	**Diesel**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Crude Oil	Refining	**Diesel**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Crude Oil	Refining	**LPG /Autogas (Mixture of Butan and Propan)**			**Otto-ICE**
Crude Oil	Refining	**LPG /Autogas (Mixture of Butan and Propan)**			**Otto-Hybrid**
Crude Oil	Refining	**LPG /Autogas (Mixture of Butan and Propan)**			**Diesel-ICE**
Crude Oil	Refining	**LPG /Autogas (Mixture of Butan and Propan)**			**Diesel-Hybrid**
Natural Gas		**LNG**			**Otto-ICE**
Natural Gas		**LNG**			**Otto-Hybrid**
Natural Gas		**CNG**			**Otto-ICE**
Natural Gas		**CNG**			**Otto-Hybrid**
Natural Gas		**LNG**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**

Natural Gas		**CNG**	Reforma-tion, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Natural Gas		**LNG**	Reforma-tion, H2-Separation	**LH2**	**PEMFC + E-Motor**
Natural Gas		**CNG**	Reforma-tion, H2-Separation	**LH2**	**PEMFC + E-Motor**
Natural Gas	Reformation --> FT-Synthesis	**Gasoline (Naphtha)**			**Otto-ICE**
Natural Gas	Reformation --> FT-Synthesis	**Gasoline (Naphtha)**			**Otto-Hybrid**
Natural Gas	Reformation --> FT-Synthesis	**Gasoline (Naphtha)**	Reforma-tion, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Natural Gas	Reformation --> FT-Synthesis	**Gasoline (Naphtha)**	Reforma-tion, H2-Separation	**LH2**	**PEMFC + E-Motor**
Natural Gas	Reformation --> FT-Synthesis	**Diesel**			**Diesel-ICE**
Natural Gas	Reformation --> FT-Synthesis	**Diesel**			**Diesel-Hybrid**
Natural Gas	Reformation --> FT-Synthesis	**Diesel**	Reforma-tion, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Natural Gas	Reformation --> FT-Synthesis	**Diesel**	Reforma-tion, H2-Separation	**LH2**	**PEMFC + E-Motor**
Natural Gas (crude)	LPG Separation	**LPG /Autogas (Mixture of Butan and Propan)**			**Otto-ICE**
Natural Gas (crude)	LPG Separation	**LPG /Autogas (Mixture of Butan and Propan)**			**Otto-Hybrid**
Natural Gas (crude)	LPG Separation	**LPG /Autogas (Mixture of Butan and Propan)**			**Diesel-ICE**
Natural Gas (crude)	LPG Separation	**LPG /Autogas (Mixture of Butan and Propan)**			**Diesel-Hybrid**
Natural Gas	Reformation --> Metha-nol-Synthesis	**Methanol**			**DMFC + E-Motor**
Natural Gas	Reformation --> Metha-nol-Synthesis	**Methanol**	Reforma-tion, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Natural Gas	Reformation --> Metha-nol-Synthesis	**Methanol**	Reforma-tion, H2-	**LH2**	**PEMFC + E-Motor**

			Separation		
Natural Gas	Reformation --> Metha-nol-Synthesis	**Methanol**			**Otto-ICE**
Natural Gas	Reformation --> Metha-nol-Synthesis	**Methanol**			**Otto-Hybrid**
Natural Gas	Reformation --> Metha-nol-Synthesis	**Methanol**			**Diesel-ICE**
Natural Gas	Reformation --> Metha-nol-Synthesis	**Methanol**			**Diesel-Hybrid**
Natural Gas	Reformation --> H2-Separation	**CGH2**			**Otto-ICE**
Natural Gas	Reformation --> H2-Separation	**CGH2**			**Otto-Hybrid**
Natural Gas	Reformation --> H2-Separation	**LH2**			**Otto-ICE**
Natural Gas	Reformation --> H2-Separation	**LH2**			**Otto-Hybrid**
Natural Gas	Reformation --> H2-Separation	**CGH2**			**PEMFC + E-Motor**
Natural Gas	Reformation --> H2-Separation	**LH2**			**PEMFC + E-Motor**
Natural Gas	Reformation --> DME Direct Conversion	**CDME**			**Diesel-ICE**
Natural Gas	Reformation --> DME Direct Conversion	**CDME**			**Diesel-Hybrid**
Power Mix		**Electricity**			**Battery + E-Motor**
Power Mix	Electrolysis	**CGH2**			**Otto-ICE**
Power Mix	Electrolysis	**CGH2**			**Otto-Hybrid**
Power Mix	Electrolysis	**LH2**			**Otto-ICE**
Power Mix	Electrolysis	**LH2**			**Otto-Hybrid**
Power Mix	Electrolysis	**CGH2**			**PEMFC + E-Motor**
Power Mix	Electrolysis	**LH2**			**PEMFC + E-Motor**
Nuclear	Electrolysis	**CGH2**			**Otto-ICE**

Nuclear	Electrolysis	**CGH2**			**Otto-Hybrid**
Nuclear	Electrolysis	**LH2**			**Otto-ICE**
Nuclear	Electrolysis	**LH2**			**Otto-Hybrid**
Nuclear	Electrolysis	**CGH2**			**PEMFC + E-Motor**
Nuclear	Electrolysis	**LH2**			**PEMFC + E-Motor**
Residual Straw	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**			**Otto-ICE**
Residual Straw	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**			**Otto-Hybrid**
Residual Straw	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Residual Straw	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Residual Straw	Gasification --> FT-Synthesis	**Diesel**			**Diesel-ICE**
Residual Straw	Gasification --> FT-Synthesis	**Diesel**			**Diesel-Hybrid**
Residual Straw	Gasification --> FT-Synthesis	**Diesel**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Residual Straw	Gasification --> FT-Synthesis	**Diesel**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Residual Straw	Gasification --> Methanol-Synthesis	**Methanol**			**DMFC + E-Motor**
Residual Straw	Gasification --> Methanol-Synthesis	**Methanol**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Residual Straw	Gasification --> Methanol-Synthesis	**Methanol**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Residual Straw	Gasification --> Methanol-Synthesis	**Methanol**			**Otto-ICE**
Residual Straw	Gasification --> Methanol-Synthesis	**Methanol**			**Otto-Hybrid**

Residual Straw	Gasification --> Methanol-Synthesis	**Methanol**			**Diesel-ICE**
Residual Straw	Gasification --> Methanol-Synthesis	**Methanol**			**Diesel-Hybrid**
Residual Straw	Gasification --> H2-Separation and Cleaning	**CGH2**			**Otto-ICE**
Residual Straw	Gasification --> H2-Separation and Cleaning	**CGH2**			**Otto-Hybrid**
Residual Straw	Gasification --> H2-Separation and Cleaning	**LH2**			**Otto-ICE**
Residual Straw	Gasification --> H2-Separation and Cleaning	**LH2**			**Otto-Hybrid**
Residual Straw	Gasification --> H2-Separation and Cleaning	**CGH2**			**PEMFC + E-Motor**
Residual Straw	Gasification --> H2-Separation and Cleaning	**LH2**			**PEMFC + E-Motor**
Residual Straw	Gasification --> DME Direct Conversion	**CDME**			**Diesel-ICE**
Residual Straw	Gasification --> DME Direct Conversion	**CDME**			**Diesel-Hybrid**
Residual Straw	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Otto-ICE**
Residual Straw	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Otto-Hybrid**
Residual Straw	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Diesel-ICE**
Residual Straw	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Diesel-Hybrid**
Short Rotation Plants	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**			**Otto-ICE**
Short Rotation Plants	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**			**Otto-Hybrid**
Short Rotation Plants	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Short Rotation Plants	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Short Rotation Plants	Gasification --> FT-Synthesis	**Diesel**			**Diesel-ICE**
Short Rotation Plants	Gasification --> FT-Synthesis	**Diesel**			**Diesel-Hybrid**
Short Rotation Plants	Gasification --> FT-Synthesis	**Diesel**	Reformation, H2-	**CGH2**	**PEMFC + E-Motor**

			Separation		
Short Rotation Plants	Gasification --> FT-Synthesis	**Diesel**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Short Rotation Plants	Gasification --> Methanol-Synthesis	**Methanol**			**DMFC + E-Motor**
Short Rotation Plants	Gasification --> Methanol-Synthesis	**Methanol**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Short Rotation Plants	Gasification --> Methanol-Synthesis	**Methanol**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Short Rotation Plants	Gasification --> Methanol-Synthesis	**Methanol**			**Otto-ICE**
Short Rotation Plants	Gasification --> Methanol-Synthesis	**Methanol**			**Otto-Hybrid**
Short Rotation Plants	Gasification --> Methanol-Synthesis	**Methanol**			**Diesel-ICE**
Short Rotation Plants	Gasification --> Methanol-Synthesis	**Methanol**			**Diesel-Hybrid**
Short Rotation Plants	Gasification --> H2-Separation and Cleaning	**CGH2**			**Otto-ICE**
Short Rotation Plants	Gasification --> H2-Separation and Cleaning	**CGH2**			**Otto-Hybrid**
Short Rotation Plants	Gasification --> H2-Separation and Cleaning	**LH2**			**Otto-ICE**
Short Rotation Plants	Gasification --> H2-Separation and Cleaning	**LH2**			**Otto-Hybrid**
Short Rotation Plants	Gasification --> H2-Separation and Cleaning	**CGH2**			**PEMFC + E-Motor**
Short Rotation Plants	Gasification --> H2-Separation and Cleaning	**LH2**			**PEMFC + E-Motor**
Short Rotation Plants	Gasification --> DME Direct Conversion	**CDME**			**Diesel-ICE**
Short Rotation Plants	Gasification --> DME Direct Conversion	**CDME**			**Diesel-Hybrid**
Short Rotation Plants	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Otto-ICE**
Short Rotation Plants	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Otto-Hybrid**
Short Rotation Plants	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Diesel-ICE**
Short Rotation Plants	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Diesel-Hybrid**

Residual Wood	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**			**Otto-ICE**
Residual Wood	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**			**Otto-Hybrid**
Residual Wood	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Residual Wood	Gasification --> FT-Synthesis	**Gasoline (Naphtha)**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Residual Wood	Gasification --> FT-Synthesis	**Diesel**			**Diesel-ICE**
Residual Wood	Gasification --> FT-Synthesis	**Diesel**			**Diesel-Hybrid**
Residual Wood	Gasification --> FT-Synthesis	**Diesel**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Residual Wood	Gasification --> FT-Synthesis	**Diesel**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Residual Wood	Gasification --> Methanol-Synthesis	**Methanol**			**DMFC + E-Motor**
Residual Wood	Gasification --> Methanol-Synthesis	**Methanol**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Residual Wood	Gasification --> Methanol-Synthesis	**Methanol**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Residual Wood	Gasification --> Methanol-Synthesis	**Methanol**			**Otto-ICE**
Residual Wood	Gasification --> Methanol-Synthesis	**Methanol**			**Otto-Hybrid**
Residual Wood	Gasification --> Methanol-Synthesis	**Methanol**			**Diesel-ICE**
Residual Wood	Gasification --> Methanol-Synthesis	**Methanol**			**Diesel-Hybrid**
Residual Wood	Gasification --> H2-Separation and Cleaning	**CGH2**			**Otto-ICE**
Residual Wood	Gasification --> H2-Separation and Cleaning	**CGH2**			**Otto-Hybrid**
Residual Wood	Gasification --> H2-Separation and Cleaning	**LH2**			**Otto-ICE**
Residual Wood	Gasification --> H2-Separation and Cleaning	**LH2**			**Otto-Hybrid**
Residual	Gasification --> H2-	**CGH2**			**PEMFC +**

Wood	Separation and Cleaning				**E-Motor**
Residual Wood	Gasification --> H2-Separation and Cleaning	**LH2**			**PEMFC + E-Motor**
Residual Wood	Gasification --> DME Direct Conversion	**CDME**			**Diesel-ICE**
Residual Wood	Gasification --> DME Direct Conversion	**CDME**			**Diesel-Hybrid**
Residual Wood	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Otto-ICE**
Residual Wood	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Otto-Hybrid**
Residual Wood	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Diesel-ICE**
Residual Wood	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Diesel-Hybrid**
Wheat (crop)	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Otto-ICE**
Wheat (crop)	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Otto-Hybrid**
Wheat (crop)	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Diesel-ICE**
Wheat (crop)	Hydrolysis --> Fermentation --> Destillation	**Ethanol**			**Diesel-Hybrid**
Sugar beet	Fermentation(Ethanol) --> Destillation	**Ethanol**			**Otto-ICE**
Sugar beet	Fermentation(Ethanol) --> Destillation	**Ethanol**			**Otto-Hybrid**
Sugar beet	Fermentation(Ethanol) --> Destillation	**Ethanol**			**Diesel-ICE**
Sugar beet	Fermentation(Ethanol) --> Destillation	**Ethanol**			**Diesel-Hybrid**
Oil Plants (crop)	Oil Mill -->Refining --> Transesterification	**FAME / Biodiesel (e.g. RME)**			**Diesel-ICE**
Oil Plants (crop)	Oil Mill -->Refining --> Transesterification	**FAME / Biodiesel (e.g. RME)**			**Diesel-Hybrid**
Oil Plants (crop)	Oil Mill -->Refining --> Transesterification --> Hydrogenation	**Gasoline (Naphtha)**			**Otto-ICE**
Oil Plants (crop)	Oil Mill -->Refining --> Transesterification --> Hydrogenation	**Gasoline (Naphtha)**			**Otto-Hybrid**
Oil Plants (crop)	Oil Mill -->Refining --> Transesterification --> Hydrogenation	**Gasoline (Naphtha)**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**

Oil Plants (crop)	Oil Mill -->Refining --> Transesterification --> Hydrogenation	**Gasoline (Naphtha)**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Oil Plants (crop)	Oil Mill -->Refining --> Transesterification --> Hydrogenation	**Diesel**			**Diesel-ICE**
Oil Plants (crop)	Oil Mill -->Refining --> Transesterification --> Hydrogenation	**Diesel**			**Diesel-Hybrid**
Oil Plants (crop)	Oil Mill -->Refining --> Transesterification --> Hydrogenation	**Diesel**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Oil Plants (crop)	Oil Mill -->Refining --> Transesterification --> Hydrogenation	**Diesel**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Oil Plants (crop)	Oil Mill	**SVO (Straight Vegetable Oil)**			**Diesel-ICE**
Oil Plants (crop)	Oil Mill	**SVO (Straight Vegetable Oil)**			**Diesel-Hybrid**
Biogenous Mass: Residues, Compl. Plants	Fermentation --> CH4-Separation and -cleaning	**CBG (Compressed Biogas**			**Otto-ICE**
Biogenous Mass: Residues, Compl. Plants	Fermentation --> CH4-Separation and -cleaning	**CBG (Compressed Biogas**			**Otto-Hybrid**
Biogenous Mass: Residues, Compl. Plants	Fermentation --> CH4-Separation and -cleaning	**CBG (Compressed Biogas**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Wind	Electrolysis	**CGH2**			**Otto-ICE**
Wind	Electrolysis	**CGH2**			**Otto-Hybrid**
Wind	Electrolysis	**LH2**			**Otto-ICE**
Wind	Electrolysis	**LH2**			**Otto-Hybrid**
Wind	Electrolysis	**CGH2**			**PEMFC + E-Motor**
Wind	Electrolysis	**LH2**			**PEMFC + E-Motor**
Wind		**Electricity**			**Battery + E-Motor**

Water	Electrolysis	**CGH2**			**Otto-ICE**
Water	Electrolysis	**CGH2**			**Otto-Hybrid**
Water	Electrolysis	**LH2**			**Otto-ICE**
Water	Electrolysis	**LH2**			**Otto-Hybrid**
Water	Electrolysis	**CGH2**			**PEMFC + E-Motor**
Water	Electrolysis	**LH2**			**PEMFC + E-Motor**
Water		**Electricity**			**Battery + E-Motor**
Photovoltaics	Electrolysis	**CGH2**			**Otto-ICE**
Photovoltaics	Electrolysis	**CGH2**			**Otto-Hybrid**
Photovoltaics	Electrolysis	**LH2**			**Otto-ICE**
Photovoltaics	Electrolysis	**LH2**			**Otto-Hybrid**
Photovoltaics	Electrolysis	**CGH2**			**PEMFC + E-Motor**
Photovoltaics	Electrolysis	**LH2**			**PEMFC + E-Motor**
Photovoltaics		**Electricity**			**Battery + E-Motor**
Solarthermal	Electrolysis	**CGH2**			**Otto-ICE**
Solarthermal	Electrolysis	**CGH2**			**Otto-Hybrid**
Solarthermal	Electrolysis	**LH2**			**Otto-ICE**
Solarthermal	Electrolysis	**LH2**			**Otto-Hybrid**
Solarthermal	Electrolysis	**CGH2**			**PEMFC + E-Motor**
Solarthermal	Electrolysis	**LH2**			**PEMFC + E-Motor**
Solarthermal		**Electricity**			**Battery + E-Motor**
Geothermal	Electrolysis	**CGH2**			**Otto-ICE**
Geothermal	Electrolysis	**CGH2**			**Otto-Hybrid**
Geothermal	Electrolysis	**LH2**			**Otto-ICE**
Geothermal	Electrolysis	**LH2**			**Otto-Hybrid**

Geothermal	Electrolysis	**CGH2**			**PEMFC + E-Motor**
Geothermal	Electrolysis	**LH2**			**PEMFC + E-Motor**
Geothermal		**Electricity**			**Battery + E-Motor**
Concentrated CO2 Sources (no primary energy)	CO2 Separation + H2 by Electrolysis --> Methanol-Synthesis	**Methanol**			**DMFC + E-Motor**
Air (no primary energy)	CO2 Separation + H2 by Electrolysis --> Methanol-Synthesis	**Methanol**			**DMFC + E-Motor**
Air (no primary energy)	CO2 Separation + H2 by Electrolysis --> Methanol-Synthesis	**Methanol**	Reformation, H2-Separation	**CGH2**	**PEMFC + E-Motor**
Air (no primary energy)	CO2 Separation + H2 by Electrolysis --> Methanol-Synthesis	**Methanol**	Reformation, H2-Separation	**LH2**	**PEMFC + E-Motor**
Air (no primary energy)	CO2 Separation + H2 by Electrolysis --> Methanol-Synthesis	**Methanol**			**Otto-ICE**
Air (no primary energy)	CO2 Separation + H2 by Electrolysis --> Methanol-Synthesis	**Methanol**			**Otto-Hybrid**
Air (no primary energy)	CO2 Separation + H2 by Electrolysis --> Methanol-Synthesis	**Methanol**			**Diesel-ICE**
Air (no primary energy)	CO2 Separation + H2 by Electrolysis --> Methanol-Synthesis	**Methanol**			**Diesel-Hybrid**
Air (no primary energy)		**Compressed Air**			**Air Motor**