Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Analysis of Alternative Fuels in Automotive Powertrains

Examensarbete utfört i fordonssystem
vid Tekniska högskolan i Linköping
av

Andreas Gunnarsson

LiTH-ISY-EX--09/3840--SE

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Linköpings universitet
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Sammanfattning
Abstract

The awareness of the effect emissions have on the environment and climate has risen in the last decades. This has caused strict regulations of greenhouse gas emissions. Greenhouse gases cause global warming which may have devastating environmental effects. Most of the fuels commercially available today are fossil fuels. There are two major effects of using fuels with fossil origin; the source will eventually drain and the usage results in an increase of greenhouse gases in the atmosphere. Fuels that are created from a renewable feedstock are often referred to as alternative fuels and under ideal conditions they are greenhouse gas neutral, meaning that the same amount of greenhouse gases is released during combustion as the source of the fuel have absorbed during its growth period. This evaluation method is known as a well-to-wheel analysis which besides emissions also evaluates energy efficiencies during both the production and the combustion phases.

By evaluating results of well-to-wheel analyses along with fuel properties and engine concept characteristics, this report presents which driving scenario that is suitable for different powertrain configurations. For example, vehicles operating in high populated areas, as cities, have a driving scenario that includes low velocities and multiple stops while vehicles in low populated areas often travel long distances in higher speeds. This implies that different powertrains are suitable in different regions. By matching favorable properties of a certain powertrain to the properties important to the actual driving scenario this report evolves a fuel infrastructure that is suitable in Sweden.

Nyckelord
Keywords: well-to-wheel analysis, alternative fuel, gasoline, diesel, methanol, ethanol, natural gas, biomethane, synthesis gas, hydrogen, biogas, biodiesel, FT-diesel, DME.

Abstract

The awareness of the effect emissions have on the environment and climate has risen in the last decades. This has caused strict regulations of greenhouse gas emissions. Greenhouse gases cause global warming which may have devastating environmental effects. Most of the fuels commercially available today are fossil fuels. There are two major effects of using fuels with fossil origin; the source will eventually drain and the usage results in an increase of greenhouse gases in the atmosphere. Fuels that are created from a renewable feedstock are often referred to as alternative fuels and under ideal conditions they are greenhouse gas neutral, meaning that the same amount of greenhouse gases is released during combustion as the source of the fuel have absorbed during its growth period. This evaluation method is known as a well-to-wheel analysis which besides emissions also evaluates energy efficiencies during both the production and the combustion phases.

By evaluating results of well-to-wheel analyses along with fuel properties and engine concept characteristics, this report presents which driving scenario that is suitable for different powertrain configurations. For example, vehicles operating in high populated areas, as cities, have a driving scenario that includes low velocities and multiple stops while vehicles in low populated areas often travel long distances in higher speeds. This implies that different powertrains are suitable in different regions. By matching favorable properties of a certain powertrain to the properties important to the actual driving scenario this report evolves a fuel infrastructure that is suitable in Sweden.

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Contents

Chapter 1

Thesis Introduction

As the environmental effects of the increase of greenhouse gases in the atmosphere become more and more clear the interest of alternative energy sources increases. A result of this is that the automobile industry is facing tougher emission regulation as time goes. So far this has most often been achieved by more precise control of the engine together with refining of advanced technologies such as exhaust gas recirculation (EGR), variable valve timing (VVT), catalysts, particulate filters etc. But as long as the energy source is of fossil origin there will always be a net distribution of greenhouse gases to the atmosphere. Biomass based fuels, allow a far less distribution of greenhouse gases hence the carbon dioxide released during combustion has been absorbed by the feedstock from which they have been produced by. This creates a circulation of greenhouse gases and thereby the contribution to the greenhouse effect is minimized.

This thesis gives an overview of fuel properties and production of alternative, as well as fossil, fuels together with descriptions of combustion technologies. Based on that information, this thesis will present a discussion about an economical and efficient infrastructure for future fuel production and usage in Sweden.

Thesis Outline

Part I: This part introduces the sources used for fuel production.

Part II: Fuel properties and information about production processes for each fuel are found in this part.

Part III: A brief survey of basic engine knowledge and a closer presentation of interesting propulsion concepts are located in this part.

Part VI: This part includes a well-to-wheel analysis for interesting fuel-engine combinations.

Part V: A discussion regarding future fuel processing and usage of alternative fuels in Sweden is located in this part.

Part I

Sources

Chapter 2

Biomass

Almost any organic material is a potential energy source. Low value products such as sewage or other residues can be transformed to useful fuels. Biomass can be found all over the world and as the oil price rises, the interest for alternative energy sources increases. There are several benefits in using biomass as an energy source, such as reducing the amount of imported oil, improvement of air quality, reducing the greenhouse effect, and other economical benefits. A list of common biomass feedstock is as follows.

- Sewage
- Forestry wastes
- Agriculture residues
- Sugar
- Energy crops
- Vegetable oil
- Starch

2.1 Fuels

Numerous fuels can be generated from biomass using fermentation, gasification, or digestion. The evaluated fuels in this report are listed below.

- FT-diesel (Chapter 6)
- Biodiesel (Chapter 7)
- DME (Chapter 8)
- Methanol (Chapter 9)
- Ethanol (Chapter 10)
- Hydrogen (Chapter 11)
- Biomethane (Chapter 12)

Chapter 3

Natural Gas

Natural gas is a clean and highly useful energy source. The gas is generated in a similar way as oil. Because the gas is light, most of the gas oozes up through the ground and in to the atmosphere. If the gas travels through a porous rock and there are layers of hard rock above, the gas will get caught below the surface of the earth.

3.1 Composition

The composition of crude natural gas varies considerable depending on where in the world it is extracted. A typical composition is presented in table 3.1.

Composition of Crude Natural Gas		
Methane	CH_4	70-90%
Ethane	C_2H_6	0-20%
Propane	C_3H_8	
Butane	C_4H_{10}	
Carbon dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulphide	H_2S	0-5%
Rare gases	Ar, He, Ne, Xe	trace

Table 3.1. Typical composition of crude natural gas.[4, Natural Gas Supply Association, 2006]

3.2 Fuels

The high amount of hydrocarbons makes natural gas an excellent energy source. Some of the fuels that can be generated out of natural gas are listed below.

- Liquefied Natural Gas (LNG, Chapter 13)
- Compressed Natural Gas (CNG, Chapter 13)
- Dimethyl Ether (DME, Chapter 8)
- Hydrogen (Chapter 11)
- Methanol (Chapter 9)
- Liquefied Petroleum Gas (LPG)

Chapter 4

Oil

Oil is generated out of organic material which has been digested in an environment without oxygen during millions of years. For a long time oil has been the primary energy source in automobile propulsion systems. The top five producers of oil in 2004, according to [2, EIA, 2006], are presented in a decreasing order in the following list.

- Saudi Arabia
- Russia
- United States
- Iran
- Mexico

4.1 Fuels

Fuels which have its origin in oil are:

- Gasoline (Chapter 14)
- Diesel (Chapter 14)
- Liquefied Petroleum Gas (LPG)
- Jet fuel

Part II

Products

Chapter 5

Intermediate Products

The products presented in this chapter are not used in automotive powertrains. They are intermediate products in various production processes.

5.1 Synthesis Gas

5.1.1 Production

Synthesis gas contains primarily hydrogen and carbon monoxide. The ratio between the two gases differs, depending on which source the synthesis gas is produced from. The ratio between the gases is of high importance when the synthesis gas is further processed into a propulsion fuel.

Coal to Synthesis Gas

Synthesis gas production from coal can be summarized in the reaction (5.1) according to [13, Rosa, 2005].

$$C + H_2O \longrightarrow H_2 + CO \tag{5.1}$$

Natural Gas to Synthesis Gas

The production of synthesis gas from natural gas, presented in this subsection can be closer investigated in [9, Svenskt Gastekniskt Center, 2002]. The high amount of methane in natural gas leads to that the main part of the reaction can be described as follows.

- *Steam reformation*

  $$CH_4 + H_2O \longrightarrow 3H_2 + CO \tag{5.2}$$

  As can be seen in (5.2), the produced synthetic gas has a H_2:CO ratio of 3:1. The drawback of this method is that the reaction needs a high amount of energy to occur.

- *Carbon dioxide reformation*

  $$CH_4 + CO_2 \longrightarrow 2H_2 + 2CO \tag{5.3}$$

  This reforming process creates a low ratio between H_2 and CO_2 which in some cases is desirable. The process can be combined with the steam reforming process to control the ratio of the produced synthesis gas.

- *Partial oxidation*

  $$CH_4 + \frac{1}{2}O_2 \longrightarrow 2H_2 + CO \tag{5.4}$$

  Unlike the previous processes this reaction is exothermal, resulting in an energy efficient and simple process. The need for oxygen in the process makes it expensive. The outcome ratio is 2 and the emitted heat is 36 kJ/mol. A drawback of this method is that the mixture of hydrogen and oxygen is highly explosive. This technology has not yet been properly investigated which prevents it from making a commercial breakthrough.

- *Autothermal reforming*

  $$\begin{aligned} CH_4 + 2O_2 &\longrightarrow 2H_2O + CO_2 && (5.5)\\ CO + H_2O &\longrightarrow H_2 + CO_2 && (5.6) \end{aligned}$$

  In this process all the reactions (5.2) to (5.6) are active. The final two are exothermal with an emitted energy of respectively 802kJ/mol and 41 kJ/mol. This generates heat which helps the other transformations to occur. The process is often used as a pre- or aftertreatment to generate the desired H_2:CO ratio.

Oil to Synthesis Gas

The reaction which generates synthesis gas from oil can be summarized into (5.7) according to [9, Svenskt Gastekniskt Center, 2002]

$$-CH_2 - +H_2O \longrightarrow 2H_2 + CO \tag{5.7}$$

Biomass to Synthesis Gas

Facts presented in this section are collected from [25, Sörensen, 2004]. The content of synthesis gas produced from biomass depends on the feedstock, but also the amount of oxygen available for the reactions to occur. The ratio between the amount of available oxygen and the amount needed to allow a complete burning is called the "equivalence ratio". If the equivalence ratio is lower than 0.1 the process is called a pyrolysis. During pyrolysis the main energy content of the biomass is found in the char and oily residues and only a small amount is found in the gaseous product. In order to maximize the energy content of the produced gas the ratio should lie somewhere in between 0.2 and 0.4. To simplify the reaction chain only the path from cellulose to synthesis gas is considered. The reaction can be summarized into (5.8).

$$C_6H_{10}O_5 + \frac{1}{2}O_2 \longrightarrow 5H_2 + 6CO \tag{5.8}$$

There are many different gasifiers and three of them will be described to illustrate the principles of gasifying wood. The gasifiers not described here works in similarity to either of the three presented below. The interested reader can find detailed information about several gasifiers in [22, Olofsson Nordin Söderlind, 2005].

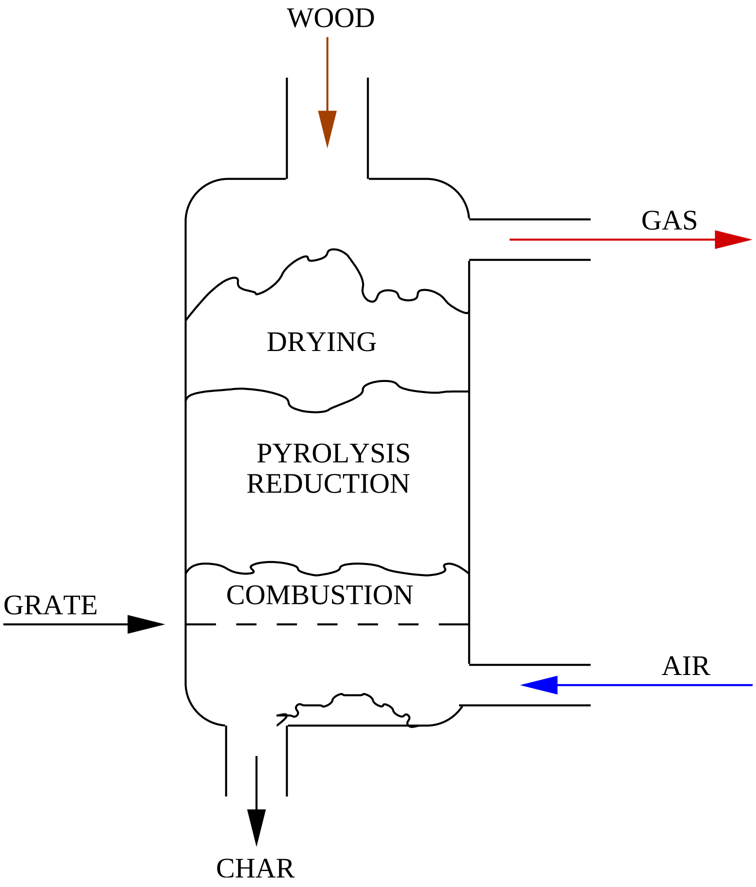

Figure 5.1. Schematic overview of an updraft gasifier.

- *Updraft gasifier*
  As can be seen in figure 5.1 wood is fed at the top sinking downwards and the air at the bottom rising through the container creating a counter-flow. Thereby the alias "counter-flow gasifier". At the bottom of the container combustion occurs, meaning that carbon reacts with oxygen creating heat and carbon dioxide. The carbon dioxide rises through the pile, once again reacting with carbon, creating carbon monoxide. At top of the pile water vapor leaves the feedstock and sinks until it reaches carbon, forming hydrogen and carbon monoxide. The water vapor can also react with carbon monoxide which generates hydrogen and carbon dioxide. This reaction is known as the shift reaction and can be performed in both directions in order to adjust the stoichiometric relation between hydrogen and carbon monoxide in the produced synthesis gas.

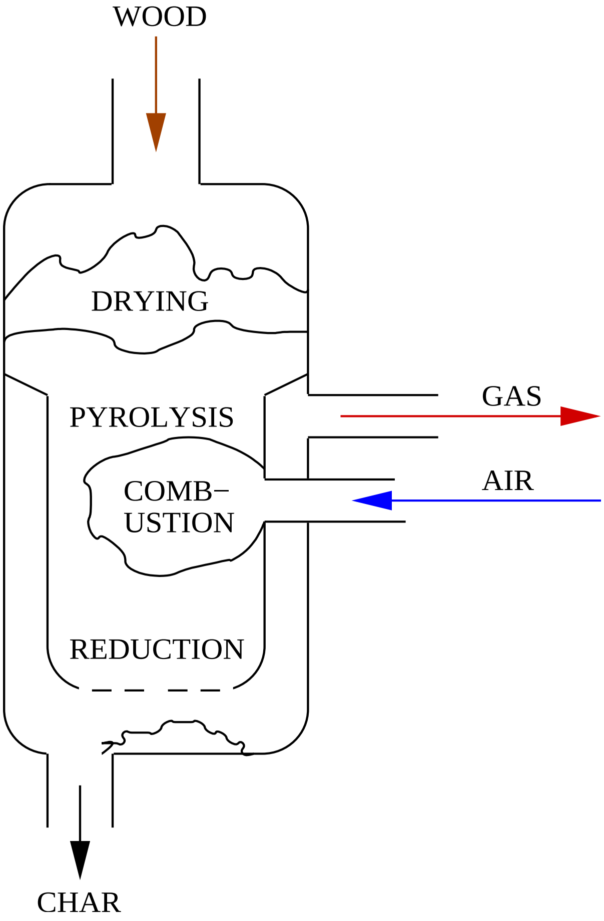

Figure 5.2. Schematic overview of a downdraft gasifier.

- *Downdraft gasifier*
  The downdraft gasifier follows the same concept as the updraft gasifier with the advantage of delivering a cleaner gas. Figure 5.2 presents a schematic view of the downdraft gasifier.

- *Fluidised bed gasifier*
  The reactions occur very similar to the updraft gasifier with the difference that fluidized sand is located in the reaction chamber. This shortens the process from hours down to minutes due to that the sand grazes the feedstock removing char etc. from the surface of the feedstock allowing a clean surface for further reactions to occur.

5.2 Biogas

5.2.1 Properties

Composition of Biogas			
Methane	CH_4	50-75	%
Carbon Dioxide	CO_2	25-45	%
Water	H_2O	2-7	%
Nitrogen	N_2	<2	%
Oxygen	O_2	<2	%
Hydrogen	H_2	<1	%
Hydrogen Sulphide	H_2S	20-20000	ppm

Table 5.1. Typical composition of biogas.[18, Svenskt Gastekniskt Center, 2002]

5.2.2 Production

Biogas is generated by anaerobic digestion of organic matter. It occurs naturally in swamps, rubbish dumps, septic tanks, and the arctic tundra. Concerning cellulose ($C_6H_{10}O_5$) as feedstock, the reaction can be summarized in equation (5.9) and can be divided into the reactions (5.10) to (5.13), according to [25, Sörensen, 2004]. The digestion process is highly complex and is not described in this thesis.

$$C_6H_{10}O_5 + H_2O \longrightarrow 3CO_2 + 3CH_4 \tag{5.9}$$
$$C_6H_{10}O_5 + H_2O \longrightarrow C_6H_{12}O_6 \tag{5.10}$$
$$C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2 \tag{5.11}$$
$$2C_2H_5OH + CO_2 \longrightarrow 2CH_3COOH + CH_4 \tag{5.12}$$
$$2CH_3COOH \longrightarrow 2CO_2 + 2CH_4 \tag{5.13}$$

5.2.3 Usage and Future Possibilities

Biogas facilities produce heat and electricity for nearby societies and cities. Further refining is necessary to produce useful fuels as biomethane, methanol etc. The low energy content of biogas, as well as its feedstock, hinders any extensive transportation. As a consequence facilities for refining biogas are often in direct contact with biogas production plants.

Chapter 6

FT-Diesel

6.1 Properties

FT-diesel			
Alias	GTL, BTL, CTL		
LHV	43.9	[MJ/kg]	[21, General Motors, 2002]
Density	$0.77\text{-}0.88 \cdot 10^3$	[kg/m^3]	[17, Kalakov Peteves, 2005]
Cetane	70-80	[-]	[17, Kalakov Peteves, 2005]

Table 6.1. Properties of FT-diesel.

6.2 Production

A description of the FT-synthesis is presented in [1, FramTidsbränslen AB, 2005]. Facts presented in this section are collected from that report. FT-diesel stands for Fisher-Tropsch-diesel after the two German chemists, Franz Fischer and Hans Tropsch, who patented a method of manufacturing long hydrocarbon chains (-CH_2-) from synthesis gas. The fuel is similar to petroleum diesel with the benefit of much lower content of noxious substances in the emissions. The ratio between hydrogen and carbon dioxide in synthesis gas is crucial for a high efficiency in the following FT-synthesis.

In a FT-synthesis from synthesis gas, 1 mole CO reacts under the presence of a catalyst, often iron or cobalt, with 2 mole H_2 creating mainly long chains of -CH_2- molecules (paraffins) and 1 mole H_2O per carbon unit as shown in (6.1). If the presence of hydrogen is to small a process called water gas shift reaction (WGS) can be used. WGS transforms carbon monoxide and water into carbon dioxide and hydrogen as shown in reaction (6.2).

$$\begin{aligned} CO + 2H_2 &\longrightarrow -CH_2 - +H_2O && (6.1) \\ CO + H_2O &\longrightarrow H_2 + CO_2 && (6.2) \end{aligned}$$

Several products are generated in the polymerization, such as hydrocarbons (C_1-C_4), gasoline (C_5-C_{11}), diesel (C_{12}-C_{20}), and waxes ($>C_{20}$). Before the synthesis gas is transported to the FT-reactor the combined sulphur and particle amount has to be less than 1 ppm and the combined presence of nitrogen, carbon dioxide, and methane needs to be below 10%. There are two technologies of FT-processes; low-temperature-Fischer-Tropsch, which is used to create greater polymer as diesel, and high-temperature-Fischer-Tropsch to achieve a high amount of lighter hydrocarbons.

The outcome of the process is controlled by the Anderson-Schultz-Flory distribution of hydrocarbons and is presented in equation (6.3), completed with a graphical presentation for some interesting chains in figure 6.1. The propagation and termination rates are depending on pressure, temperature, and how long the polymer chain has been in the process. By controlling these parameters the output of the desired product can be maximized. The amplitude of the curves presented in figure 6.1 represents the outcome weight fraction for each chain. The highest exchange is achieved for methane but the highest exchanged for a liquid fuel is diesel which motivates the production of diesel instead of gasoline.

$$\begin{aligned} W_n &= n(1-\alpha)^2\alpha^{n-1} && (6.3) \\ \alpha &= \frac{K_p}{K_p + K_t} && (6.4) \end{aligned}$$

where

W_n : Weight fraction of C_n.
n : Carbon number.
α : Probability of chain growth, decided by equation (6.4).
K_p : Propagation rate.
K_t : Termination rate.

The FT-process is exothermal and requires efficient cooling and temperature control in order to receive the desirable outcome. The gas which leaves the reactor is separated into methane, ethane, ethene, and unreacted synthesis gas. The unreacted gas can be reinserted in the reactor but it is more common that it is burned.

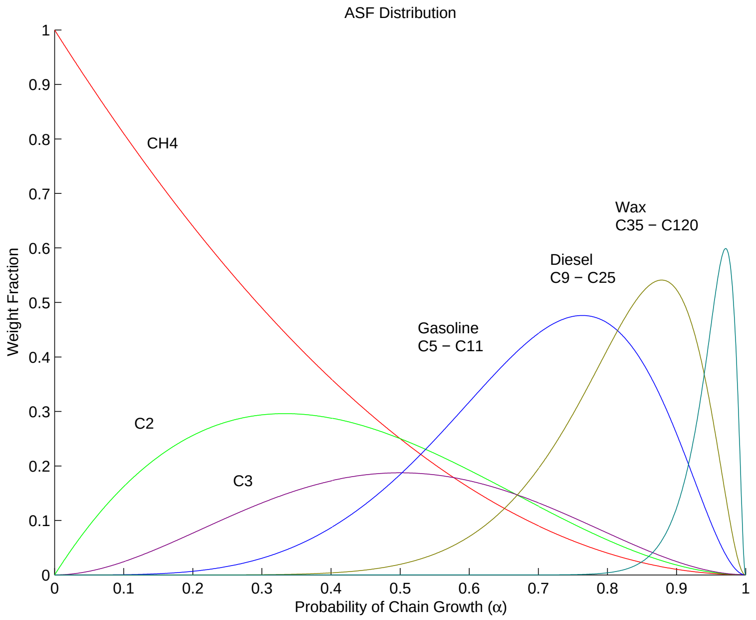

Figure 6.1. Anderson-Schultz-Flory distribution.

6.3 Usage and Future Possibilities

The production cost is higher than that of petro-diesel which is the industrial term for diesel produced from oil. Therefore FT-diesel requires economical assistance from the governments in order to make a commercial breakthrough. The similarity to petro-diesel is a great advantage because the vehicle fleet and infrastructure already exist. FT-diesel is fully compatible with ordinary diesel engines and there is no need for any modifications. As the product is sulphur free and only contains low amount of other impurities the emission is cleaner than that of petrodiesel. In 2001, Sweden carried out a test of FT-diesel and blends with petro-diesel propelling tractors, cars, buses, etc that lasted for 10 months. The emission results showed that all emissions decreased compared to petro-diesel, for example soot or PM (Particle Matter) decreased with 30% and nitrogen oxides (NO_x) with 8%. More information regarding this test is presented in [1, FramTidsbränslen AB, 2005].

Chapter 7

Biodiesel

7.1 Properties

Biodiesel				
Alias	FAME, RME, SME, B100			
Type	RME		SME	
LHV	37-38	[MJ/kg]	32	[MJ/kg]
Density	$0.88 \cdot 10^3$	[kg/m^3]	$0.87 \cdot 10^3$	[kg/m^3]
Cetane Number	51-58	[-]	46-67	[-]

Table 7.1. Properties of biodiesel. [26, Tse, 2004]

7.2 Production

Biodiesel can be produced out of vegetable oils or animal waste. The most common oils used in Europe to produce biodiesel are rapeseed oil and sunflower oil. Today the product is also known as FAME (Fatty Acid Methyl Ester) and can be divided into RME (Rape seed oil Methyl Ester) or SME (Sunflower oil Methyl Ester) which is done in table 7.1.

The following emphasized text is an extraction from [16, Tyson, Bozell, Wallace, Petersen, Moens, 2004].

Fatty acids methyl esters are one of two primary platform chemicals produced by the olechemical industry. Methyl esters from triglycerides are produced using inexpensive base catalysts (NaOH or KOH) methanol at low temperatures (60° C to 80° C) and pressures (1.4 atm) in both batch and continuous systems. The other major platform chemical, fatty acids, can also be used to produce methyl esters. Fats are hydrolyzed to free fatty acids and glycerol in one of two ways:

- *continuous, high pressure, counter current systems at 20 to 60 bars and 250°C with or without catalysts, which are typically zinc oxide, lime, or magnesium oxide added to water;*
- *counter current systems at atmospheric pressure with small amounts of sulfuric/sulfonic acids in steam.*

Methyl esters are produced from fatty acids using strong mineral acids, such as sulfuric acid or a sulfonated ion exchange resin, and methanol in counter current systems at 80°C to 85°C under mild pressures. If a feedstock contains both triglycerides and free fatty acids, acid esterification is performed on the entire feedstock first, followed by transesterification to convert the remaining triglycerides. Water management is a key to high yields and low processing problems. Yields of glycerides and fatty acids to esters for all processes generally exceed 97% and can reach 99% with careful management of equilibrium conditions. As temperatures and pressures increase, the transesterification reaction becomes autocatalyzed. Henkle used this process with crude soy oil in the 1970:s and at least one biodiesel technology provider (BDT) offers a variation of this technology for feedstocks containing FFA, the more the better. Conditions may not be supercritical for methanol but may employ high enough temperatures and pressures to autocatalyze the reaction.

7.3 Usage and Future Possibilities

The first industrial-size facility for producing Biodiesel opened in 1991 in Austria and by 1998 21 countries had commercial projects[14, Wikipedia, 2006]. A conventional diesel engine can run on biodiesel with only small modifications as gasket and filter changes. So a diesel vehicle owner, for a small amount of money, can convert the engine to run on biodiesel and contribute with the advantageous environmental factors that is associated with biomass based fuels. Biodiesel can also be used as a blender to petro-diesel and is then referred to as e.g. B80, where the number corresponds to the percentage of biodiesel present in the fuel.

Chapter 8

DME

8.1 Properties

DME		
Alias	Methoxymethane, Wood Ether, Dimethyl Ether	
Molecule	CH_3OCH_3	
LHV	27.6	[MJ/kg]
Density(liquid)	$0.66 \cdot 10^3$	[kg/m^3]
Cetane number	>55	[-]

Table 8.1. Properties of DME. [12, Bio-DME Consortium, 2002]

8.2 Production

A more detailed description of the production of DME is found in [9, Svenskt Gastekniskt Center, 2002]. DME is produced out of synthesis gas in the following reaction chain

$$3CO + 3H_2 \longrightarrow CH_3OCH_3 + CO_2 \tag{8.1}$$
$$2CO + 4H_2 \longrightarrow CH_3OCH_3 + H_2O \tag{8.2}$$
$$2CO + 4H_2 \longrightarrow 2CH_3OH \tag{8.3}$$
$$2CH_3OH \longrightarrow CH_3OCH_3 + H_2O \tag{8.4}$$
$$H_2O + CO \longrightarrow H_2 + CO_2 \tag{8.5}$$

The DME synthesis (8.1) can be separated into methanol synthesis (8.3) followed by the dehydration reaction (8.4) and the shift reaction (8.5). If the shift reaction is slow also the second DME synthesis (8.2) is active. Reaction (8.2) can be divided into (8.3) and (8.4).

8.3 Usage and Future Possibilities

The high cetane rating of DME makes it suitable for DICI-engines (see Chapter 16). In order to make the engine compatible with DME, mainly modifications of the fuel injector system is necessary. The highest interest of DME is found in Asia which is the market that has the highest growth in fuel usage. According to [31, Green Car Congress, 2006] there are several large-scale DME plant projects in Asia, with coal as feedstock. Estimates show a demand for 5 to 10 million tons of DME within 5 years, in China only. Sweden has also started a project to commercialize DME using biomass as the feedstock. Volvo is a part of that project and have developed a DME powered truck.

DME has exceptional emission properties, with very low levels of NO_x and soot. That is because there are no carbon-carbon bindings in the molecules and because it consists of 35% oxygen. The high amount of oxygen and its fairly low burning temperature is the main contributor to the low NO_x formation. The emissions can be reduced further by using conventional methods as for example EGR which is highly suitable for DME due to the lack of soot formation.

The relatively low energy density of DME and the fact that DME is a gas under normal conditions result in a bigger and pressurized fuel tank. This increases the retail price of the vehicle and causes trouble for vehicles where space is limited. DME liquefies under 5 bars pressure at 20°C according to [12, Bio-DME Consortium, 2002] which compared to other gaseous fuels is low and thereby a tank defined for DME is substantially cheaper and smaller than tanks defined for methane or hydrogen.

Chapter 9

Methanol

9.1 Properties

Methanol			
Alias	Hydroxymethane, Methyl Alcohol, Carbinol		
Molecule	CH_3OH		
LHV	19.9	[MJ/kg]	[21, General Motors, 2002]
Density	$0.79 \cdot 10^3$	[kg/m^3]	[17, Kalakov Peteves, 2005]
Octane Number	110-112	[-]	[17, Kalakov Peteves, 2005]

Table 9.1. Properties of methanol.

9.2 Production

This section contains material collected in [9, Svenskt Gastekniskt Center, 2002]. Methanol is produced from synthesis gas as presented in reactions (9.1) to (9.3).

$$2H_2 + CO \longrightarrow CH_3OH \qquad (9.1)$$
$$CO + H_2O \longrightarrow H_2 + CO_2 \qquad (9.2)$$
$$3H_2 + CO_2 \longrightarrow CH_3OH + H_2O \qquad (9.3)$$

At first the synthesis gas is compressed to help the upcoming reactions to occur. In the reaction chamber pellets of coppers is used as a catalyst causing the reactions shown in (9.1)-(9.3). After the reaction chamber the gas contains methanol, water and unreacted substances. The unreacted substances are separated by using a process known as methanol letdown, where the unreacted gases rise to the top and are guided back to the reaction chamber. The distillation is done in two phases, at first all the substances that have a boiling point lower than methanol are removed by heating the mixture to a temperature just below the boiling point of methanol. In the second stage the remaining mixture is heated just above the boiling point of methanol. Methanol is drawn off the top and the water which has the highest boiling temperature at the bottom. Byproducts are drained in the middle.

9.3 Usage and Future Possibilities

Methanol can directly be used in a fuel cell referred to as DMFC (Direct Methanol Fuel Cells). The technology is still in a developing phase but if it is successful, methanol usage is likely to increase drastically. The fuel can also be used in common combustion engines and is a strong candidate for replacing gasoline usage. This will be motivated later in this report.

Chapter 10

Ethanol

10.1 Properties

Ethanol			
Alias	Ethyl Alcohol, Grain Alcohol, Hydroxyethane		
Molecule	C_2H_5OH		
LHV	26.8	[MJ/kg]	[21, General Motors, 2002]
Density	$0.789 \cdot 10^{3}$	[kg/m^3]	[24, SImetric, 2006]
Octane	105-109	[-]	[8, Brusstar Bakenhus]

Table 10.1. Properties of ethanol.

10.2 Production

In this section only ethanol from cellulose (EFC) is considered. For more details about the production of ethanol out of cellulose, starch or sugar the reader is referred to [5, Badger, 2002]. The following emphasized texts are extractions from that report.

There are three basic types of EFC processes-acid hydrolysis, enzymatic hydrolysis, and thermochemical- with variations for each. The most common is acid hydrolysis. Virtually any acid can be used; however, sulfuric acid is most commonly used since it is usually the least expensive.

10.2.1 Acid Hydrolysis

There are two basic types of acid processes: dilute acid and concentrated acid, each with variations. Dilute acid processes are conducted under high temperature and pressure, and have reaction times in the range of seconds or minutes, which *facilitates continuous processing. ...*

... Most dilute acid processes are limited to a sugar recovery efficiency of around 50%. The reason for this is that at least two reactions are part of this process. The first reaction converts the cellulosic materials to sugar and the second reaction converts the sugars to other chemicals. Unfortunately, the conditions that cause the first reaction to occur also are the right conditions for the second to occur. Thus, once the cellulosic molecules are broken apart, the reaction proceeds rapidly to break down the sugars into other products-most notably furfural, a chemical used in the plastics industry. Not only does sugar degradation reduce sugar yield, but the furfural and other degradation products can be poisonous to the fermentation microorganisms. The biggest advantage of dilute acid processes is their fast rate of reaction, which facilitates continuous processing. Their biggest disadvantage is their low sugar yield. For rapid continuous processes, in order to allow adequate acid penetration, feedstocks must also be reduced in size so that the maximum particle dimension is in the range of a few millimeters....

... The concentrated acid process uses relatively mild temperatures and the only pressures involved are usually only those created by pumping materials from vessel to vessel. One concentrated acid process was first developed by USDA and further refined by Purdue University and the Tennessee Valley Authority. In the TVA concentrated acid process, corn stover is mixed with dilute (10%) sulfuric acid, and heated to 100°C for 2 to 6 hours in the first (or hemicellulose) hydrolysis reactor. The low temperatures and pressures minimize the degradation of sugars. To recover the sugars, the hydrolyzed material in the first reactor is soaked in water and drained several times. The solid residue from the first stage is then dewatered and soaked in a 30% to 40% concentration of sulfuric acid for 1 to 4 hr as a pre-cellulose hydrolysis step. This material is then dewatered and dried with the effect that the acid concentration in the material is increased to about 70%. After reacting in another vessel for 1 to 4 hr at 100°C, the reactor contents are filtered to remove solids and recover the sugar and acid. The sugar/acid solution from the second stage is recycled to the first stage to provide the acid for the first stage hydrolysis. The sugars from the second stage hydrolysis are thus recovered in the liquid from the first stage hydrolysis. The primary advantage of the concentrated process is the high sugar recovery efficiency, which can be on the order of over 90% of both hemicellulose and cellulose sugars. The low temperatures and pressures employed also allow the use of relatively low cost materials such as fiberglass tanks and piping. Unfortunately, it is a relatively slow process and cost effective acid recovery systems have been difficult to develop. Without acid recovery, large quantities of lime must be used to neutralize the acid in the sugar solution. This neutralization forms large quantities of calcium sulfate, which requires disposal and creates additional expense.

10.2.2 Enzymatic Hydrolysis

Another basic method of hydrolysis is enzymatic hydrolysis. Enzymes are naturally occurring plant proteins that cause certain chemical reactions to occur. However, for enzymes to work, they must obtain access to the molecules to be hydrolyzed. For enzymatic processes to be effective, some kind of pretreatment process is thus needed to break the crystalline structure of the lignocellulose and remove the lignin to expose the cellulose and hemicellulose molecules. Depending on the biomass material, either physical or chemical pretreatment methods may be used. Physical methods may use high temperature and pressure, milling, radiation, or freezing-all of which require high-energy consumption. The chemical method uses a solvent to break apart and dissolve the crystalline structure. ...
... Due to the tough crystalline structure, the enzymes currently available require several days to achieve good results. Since long process times tie up reactor vessels for long periods, these vessels have to either be quite large or many of them must be used. Either option is expensive. Currently the cost of enzymes is also too high and research is continuing to bring down the cost of enzymes. However, if less expensive enzymes can be developed enzymatic processes hold several advantages: (1) their efficiency is quite high and their byproduct production can be controlled; (2) their mild process conditions do not require expensive materials of construction; and (3) their process energy requirements are relatively low.

10.2.3 Thermochemical Processes

There are two ethanol production processes that currently employ thermochemical reactions in their processes. The first system is actually a hybrid thermochemical and biological system. An example is a process under development by Bioengineering Resources in Fayetteville, Arkansas. Biomass materials are first thermochemically gasified and the synthesis gas (a mixture of hydrogen and carbon oxides) bubbled through specially designed fermenters. A microorganism that is capable of converting the synthesis gas is introduced into the fermenters under specific process conditions to cause fermentation to ethanol. The second thermochemical ethanol production process does not use any microorganisms. In this process, biomass materials are first thermochemically gasified and the synthesis gas passed through a reactor containing catalysts, which cause the gas to be converted into ethanol. ...

... Ethanol yields up to 50% have been obtained using synthesis gas-to-ethanol processes. Some processes that first produce methanol and then use catalytic shifts to produce ethanol have obtained ethanol yields in the range of 80%. Unfortunately, like the other processes, finding a cost-effective all-thermochemical process has been difficult.

10.3 Usage and Future Possibilities

The first industrial use of ethanol was in 1876, when it was used in a combustion engine that worked in an Otto Cycle. The engine placed in Henry Ford's Model T in 1908 could use both gasoline and ethanol. The ethanol driven automobiles grew strong until after the second World War when fuels from petroleum and natural gas became available in large quantities and to a low cost. The profit in producing fuel out of agriculture crops sank and many of the former ethanol producing plants converted to the beverage alcohol industry. In the 1970s economical problems for Brazil caused a new interest in ethanol. Brazil is a big sugar producer which makes it suitable for the ethanol industry. Nowadays 40% of the gasoline demand in Brazil is replaced with ethanol.

Ethanol can be produced out of any biological feedstock that contains sugar or material that can be converted into sugar, such as starch or cellulose. Feedstock containing starch or sugar usually consists in the human food chain which causes a high market price. Using material containing cellulose, for example paper, cardboard, wood, and other fibrous plant material, could reduce the price of ethanol. These resources are in general very widespread which causes a worldwide interest.

Ethanol can be used as a blend in gasoline, e.g. 85% ethanol and 15% gasoline is referred to as E85 and E100 corresponds to pure ethanol. The blend of ethanol in gasoline is used to reduce emissions and increase the octane rating of the fuel. There are flexi-fuel vehicles that can use gasoline, ethanol or any blend of them. This has the drawback of efficiency losses in the engine when use of pure ethanol. The higher octane rating of ethanol compared to gasoline allows a higher compression ratio of the engine, with the result of a higher efficiency. If the engine is flexi-fueled the gasoline limits the compression ratio which leads to a higher fuel consumption when using ethanol compared to a vehicle only dedicated for ethanol usage.

Chapter 11

Hydrogen

11.1 Properties

Hydrogen			
Molecule	H_2		
LHV	120.0	[MJ/kg]	[21, General Motors, 2002]
Density	0.09	[kg/m^3]	[33, Krona, 2009]
Octane	106	[-]	[17, Kalakov Peteves, 2005]

Table 11.1. Properties of hydrogen.

11.2 Production

Although hydrogen is the most plentiful gas in the universe it does not exist naturally on earth. Due to its likeliness to react with other molecules hydrogen is almost always combined with other elements such as carbon or oxygen. Hydrogen can however be produced in multiple ways using fossil fuels, biomass, wind power etc. The source [19, National Renewable Energy Laboratory] contains numerous papers about production, storage and usage of hydrogen. This section contains a short summary of each production technology together with a list of recommendable papers for the interested reader to examine. Emphasized text is direct extractions from text presented in [19, National Renewable Energy Laboratory].

Biological Water Splitting

Certain photosynthetic microbes produce hydrogen from water in their metabolic activities using light energy.

- Algal Hydrogen Photoproduction,
  M. Ghirardi and M. Seibert, 2003.
- Molecular Engineering of Algal Hydrogen Production,
  M. Seibert, 2002.
- Cyclic Photobiological Algal Production,
  M Ghirardi, 2002.

Photoelectrochemical Water Splitting

Photovoltaic industry is being used for photoelectrochemical (PEC) light harvesting systems that generates sufficient voltage to split water and are stable in a water/electrolyte environment.

- Photoelectrichemical Water Splitting,
  J. Turner, 2003.
- Photoelectrichemical Systems for Hydrogen Production,
  K. Varner, 2002.

Reforming of Biomass and Wastes

Pyrolysis or gasification of biomass generates synthesis gas from which hydrogen is separated.

- Fluidizable Catalysts for Hydrogen Production from Biomass Pyrolysis/Steam Reforming,
  K. Magrini-Bair, 2003.
- Hydrogen from Post-Consumer Wastes,
  S. Czernik, 2002.

Solar Thermal Methane Splitting

Highly concentrated sun light generates the high temperature needed for splitting methane into hydrogen and carbon.

- High Temperature Solar Splitting of Methane to Hydrogen and Carbon,
  J. Dahl, 2003.
- Rapis Solar-thermal Dissociation of Natural Gas in an Aerosal Flow Reactor,
  J. Dahl, 2002.

11.3 Usage and Future Possibilities

Many believe hydrogen to be the fuel of the future due to the clean burning, the emission is only water. Why it is rarely seen in vehicles today depends on its volumetric low energy content at ambient pressure and temperatures. Besides the great emission properties hydrogen is interesting because it has the highest energy content per weight unit of any known fuel.

Due to the volumetric low energy content, hydrogen must be liquefied or compressed during transportation. This, together with and the explosiveness of the fuel sets high standard to the containers and tanks, both in vehicles and during transportation.

Chapter 12

Biomethane

12.1 Properties

Biomethane			
Alias	Biogas, CBM, CMG, SNG		
Molecule	CH_4		
LHV	45.4	[MJ/kg]	[21, General Motors, 2002]
Density	0.72	[kg/m^3]	[33, Krona, 2009]
Octane	>120		[3, Lampinen Pöyhönen Hänninen, 2004]

Table 12.1. Properties of biomethane.

12.2 Production

This section contains information collected in [27, WestStart-Calstart, 2005]. For a more detailed description of biomethane production, the reader is referred to that report. Biomethane is most often purified biogas and therefore it is commonly referred to as biogas but in order to distinguish them, purified biogas is consequently referred to as biomethane in this report. The primary task of the purification process is to extend its energy content. This is performed by decreasing the amount of carbon dioxide, which increases the ratio of methane in the gas. The content of methane typically extend 97% in the finished product. In order to make it compatible with engines, traces of other substances such as hydrogen sulphur, water vapor, nitrogen, oxygen, particles, halogenated hydrocarbons, ammonia, and organic silicon compounds, must be removed. Often biomethane is odorized as a safety measure to detect leaks in the systems in which it is being used. There is a way of producing biomethane with synthesis gas as an intermediate product. This process follows the same path as the production of FT-diesel which is described in Chapter 6.

12.2.1 Removal of Hydrogen Sulphide

Vehicle fuel standards require that the presence of hydrogen sulphide is less than 16 ppm. Biogas typically contains between 20 ppm and 20000 ppm of hydrogen sulphide, depending on which feedstock that is being used. The removal can be performed using one of the following technologies:

- Reduction of H_2S inside the digester vessel by adding metal ions to form on-soluble metal sulphides or creation of elementary sulphur through oxidation.
- Removal of H_2S with metal oxides such as SulfaTreat^{TM} and hydroxides
- Oxidation with air
- Adsorption of H_2S on activated carbon

If there is a high presence of hydrogen sulphide in the biogas the cost associated with adding metal ions will be considerable. The use of SulfaTreat^{TM} is an effective and cost-worthy method which is popular within the biogas industry. Removal of hydrogen sulphide without using chemical treatment and instead using oxidation with air is cheaper and often preferred by Danish biogas facilities. The drawback with this method is that aftertreatment often is necessary to obtain the desirable quality. The final technology, using activated carbon, requires regeneration or replacement of the carbon as it is depleted.

12.2.2 Removal of Carbon Dioxide

The methane content of the gas stands in direct proportional to its energy content. Because carbon dioxide occupies a large part of the biogas the removal of carbon dioxide is crucial in order to receive a high energy density. Methods used to remove carbon dioxide follow below, as well as a short description of each technology.

- Membrane Separation
- Pressure Swing Adsorption (PSA)
- Water Scrubbing
- Removal of CO_2 using Selexol^{TM}
- Removal of CO_2 using Low Pressure COOAB^{TM}

The *membrane separation technology* uses several, very thin membranes. The biogas is directed to the membrane which has a high diffusion of carbon dioxide and hydrogen sulphide in comparison to methane. This causes a separation of the methane and the other two gases. Some of the methane passes through all the membranes but there are ways of recirculating the gas in order to increase the overall efficiency.

In *pressure swing adsorption* the biogas is fed at the bottom of a vessel and as it rises, carbon dioxide, carbon monoxide, and nitrogen are adsorbed by the activated carbon or zeolites placed on the walls, which result in a pressure build-up. The gas is drained at the top of the vessel and has a methane content over 97%. Before the adsorbing material is completely saturated, the biogas is led to another vessel while the first is depressurized causing the absorbed gases to leave the adsorption material and is guided away. The use of multiple vessels makes it possible to have a continuous flow of biogas throughout the process.

The *water scrubbing method* uses a water flow through a pressurized pipe standing on its edge. The biogas is fed at the bottom and rises up through the pipe, while water is added at the top, flowing downwards. The pressure causes the carbon dioxide to dissolve in the water. The result is a high content of methane in the gas which is leaving the pipe at the top. The water could be recirculated if there is a decompressed chamber, also known as a flash tank, somewhere in the system. This allows the carbon dioxide to leave the water. In lack of a flash tank there must be a continuous stream of new water flowing through.

The *removal of carbon dioxide using Selexol*^{TM} works in the same way as recirculated water scrubbing. One advantage of using Selexol$^{\text{TM}}$ is that it, besides removing the carbon dioxide, also removes water vapor and hydrogen sulphide, giving the result that no additional removal is necessary. The Selexol$^{\text{TM}}$ can be purified of carbon dioxide and water vapor in a flash tank but to remove the hydrogen sulphide additional processing is necessary.

Low Pressure COOAB^{TM} is similar to both water scrubbing and Selexol$^{\text{TM}}$. Unlike Selexol$^{\text{TM}}$, COOAB$^{\text{TM}}$ only removes carbon dioxide from the biogas and additional processing is required. The advantages of using this method are that the pipe does not need to be pressurized and the biomethane contains over 99% pure methane. The COOAB$^{\text{TM}}$ is cleaned via steam heating. Heat exchangers are used in the process to minimize the energy requirements.

12.2.3 Removal of Other Contaminants

There are several effective ways to remove the other contaminants, including membranes, filters, and active carbon. The amounts of these components are directly connected to the biogas origin.

12.3 Usage and Future Possibilities

The usage of biomethane is yet small. Sweden had the biggest fleet, in 2006, with about 8000 vehicles propelled by biomethane. Often the vehicles are city buses or other local fleets. One reason for that gas propelled vehicles have not made a commercial breakthrough is the insufficiency of filling stations. This does not affect local vehicle fleets as they most often stays in certain regions, always having relatively close to a filling station. At present there are 64 filling stations providing biomethane and/or refined natural gas in Sweden but there are plans for over 100 additional filling stations. The Swedish government stands for 30% of the investment cost for these stations. [30, Fordonsgas, 2006]

The future potential of biomethane, regarding waste material as feedstock, is discussed in the Finnish study, [3, Lampinen Pöyhönen Hänninen, 2004]. The study states that 20% of all traffic energy consumption in Finland can be replaced by biomethane. By including sources like energy crop with the intermediate step of synthesis gas production, would generate an even higher potential.

Chapter 13

Refined Natural Gas

13.1 Properties

The methane content of refined natural gas is over 97%.

13.2 Production

Natural gas that is transported to a home or put in a car differs from the natural gas that comes up through the depths. The natural gas that is consumed consists almost entirely of methane. The raw gas has its source in oil wells, gas wells or condensate wells, each of them with its impurities. The facts presented below has its source in [4, Natural Gas Supply Association]. This web site gives detailed description of natural gas extraction, production, transportation, storage etc.

13.2.1 Oil and Condensate Removal

Natural gas is dissolved in oil mainly due to the high pressure and is separated automatically when the pressure is reduced. The most common way of separating oil and natural gas is simply to guide the gas into a closed tank and let gravity separate the different hydrocarbons. In some cases more complex technologies is necessary, for example the Low-temperature Separator (LTX). LTX is often used when light crude oil is mixed with high pressured gas. It uses rapidly changes in pressures in order to quickly change the temperature of the gas. This causes the oil and water to condensate and leaving the desired components in its gaseous form.

13.2.2 Water Removal

Water vapor removal of natural gas is usually done by using either an adsorption or absorption process. Absorption can be done using glycol that has the tendency to absorb water molecules. The glycol also absorbs some of the methane which can be recovered using a flashtank. If a large amount of natural gas should be refined there are advantages using a process called Solid-Desiccant dehydration. In this process the wet natural gas is fed at the top of a high tower which is filled with desiccants, e.g. alumina. As the gas travels down through the tower the water molecules adsorbs to the desiccants. In general there are two or more of these towers in the facilities that uses this dehydration technology due to that the desiccant will get saturated with water. If the facilities only had one tower the production of dry natural gas would stop during the dewatering of the desiccants.

13.2.3 Separation of Natural Gas Liquids

The additional hydrocarbons to methane found in natural gas have a higher value sold on its own than as a content of natural gas. There are basically two ways of separating Natural Gas Liquids (NGL) from natural gas; the absorption method and the cryogenic expander process. The absorption method works similar to the absorption method in the water removal process. Absorption oil is used to withdraw the NGL of the natural gas. To recover the NGL, the oil is heated to a temperature that lies between the boiling point for the NGL and the boiling point of the absorption oil, causing them to separate. This method can recover about 75% of the butane and 85% to 90% of the heavier molecules. One advantage of using this method is that it is able to target a particular hydrocarbon in order to maximize the outcome. Ethane is hard to extract from natural gas and in many cases it can not be motivated to do so regarding to the cost. The cryogenic expander process can recover the ethane and works similar to the LTX described earlier. The gas is chilled and then a rapid reduction of pressure allows the temperature to quickly decrease causing the ethane and other lighter hydrocarbons to condensate. This process has can recover about 90-95% of the ethane.

13.2.4 Sulphur and Carbon Dioxide Removal

The removal of sulphur is the most important cleaning of natural gas. Sulfur is highly corrosive and can do major damage to the machinery and it is also harmful to humans. The sulphur and carbon dioxide are removed using an amine solution that attracts sulphur or a solid desiccant much like the technologies described earlier.

13.3 Transport

Natural gas is often transported in an extensive network of pipelines. The network can be divided into three groups; the gathering system, the interstate pipeline, and the distribution system. The task of the gathering system is to transport the gas from the wellhead to the processing facilities. Due to the presence of carbon dioxide and sulphur, the raw gas can be highly corrosive which requires this transport to be done carefully. The interstate pipeline is the main transportation system which transfers the processed gas from the producing regions to the regions with a high requirement of natural gas. The distribution system distribute the refined natural gas to homes, industrial facilities, or filling stations.

13.4 Usage and Future Possibilities

The usage of natural gas is expected to increase in the future. Natural gas is mainly used for heating and electricity generation while only a minor part is used for propelling vehicles. United States has a well developed natural gas infrastructure where natural gas, in year 2000, accounted for 24% of the total energy usage and about 3% of the natural gas was used for propelling vehicles.

Chapter 14

Oil Based Fuels

14.1 Properties

Gasoline			
Alias	Petrol, Gas		
Molecule	C_4-C_{12}		[17, Kalakov Peteves, 2005]
LHV	43.2	[MJ/kg]	[21, General Motors, 2002]
Density	0.72-0.77	[kg/dm^3]	[17, Kalakov Peteves, 2005]
Octane	90-95	[-]	[17, Kalakov Peteves, 2005]

Table 14.1. Properties of gasoline.

Diesel			
Alias	-		
Molecule	C_{15}-C_{20}		[17, Kalakov Peteves, 2005]
LHV	43.4	[MJ/kg]	[21, General Motors, 2002]
Density	0.82-0.84	[kg/dm^3]	[17, Kalakov Peteves, 2005]
Cetane	45-53	[-]	[17, Kalakov Peteves, 2005]

Table 14.2. Properties of diesel.

14.2 Production

Oil refinery can be described in a simple and very direct way. Due to the high variety of boiling point of the components the raw oil is easy separated. The raw oil is heated in a furnace before it is transported to chamber within fractional distillation occurs. The chamber is separated horizontally in five cells with a

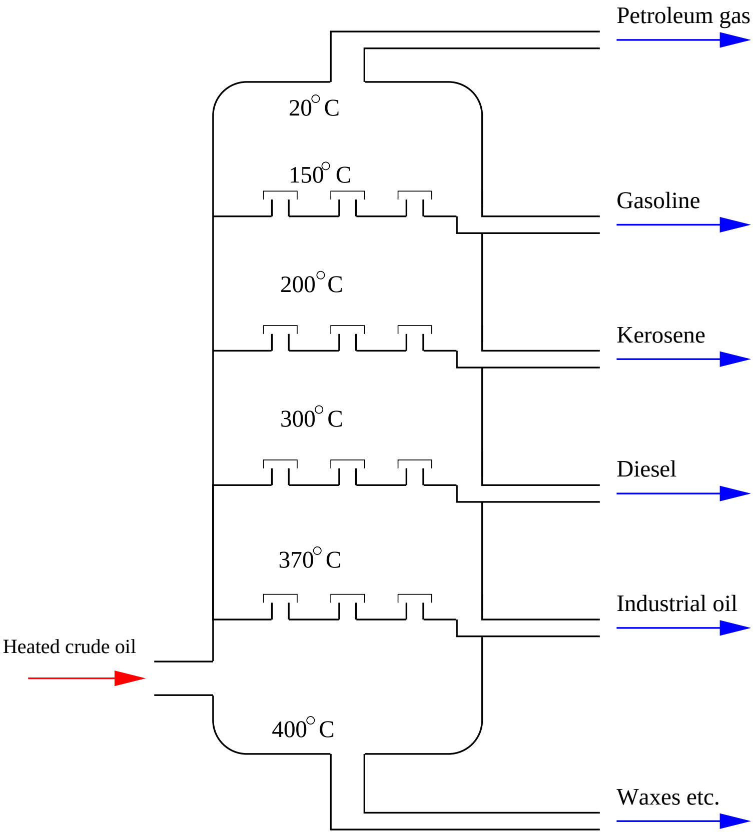

Figure 14.1. Schematic overview of an oil refinery container.

decreasing temperature in each cell. This causes the desired gas to liquefy in each cell and can be transported away. The cell placed at the bottom drains paraffin waxes followed by industrial oil, diesel, kerosene, gasoline and petroleum gas which is drained at the top of the chamber. The process is shown in figure 14.1. In order to optimize the outcomes several aftertreatments are used but this is not described in this report.

14.3 Usage and Future Possibilities

Gasoline and diesel has been the primary source of vehicle fuel for a long time and that will probably not change in close future. They are inexpensive to produce compared to alternative fuels but they suffer of heavy taxes which causes a market price the alternative fuels can match. Diesel propelled vehicles generally generate less greenhouse gases than a vehicle propelled by gasoline but the emissions are unhealthier to humans due to a high rate of particles and nitrogen oxide. Most of the alternative fuel propelled vehicle still support either gasoline or diesel because the insufficient infrastructure for alternative fuels.

Chapter 15

Batteries

15.1 Properties

Type	Energy Density [MJ/kg]
Nickel-Cadmium	0.162 - 0.288
Nickel-Metal-Hydride	0.216 - 0.432
Lead-Acid	0.108 - 0.180
Lithium-Ion (cobalt)	0.396 - 0.576
Lithium-Ion (manganese)	0.360 - 0.468
Lithium-Ion (phosphate)	0.324 - 0.432

Table 15.1. Properties of different types of batteries. [6, Battery University]

15.2 Usage and Future Possibilities

[6, Batteryuniversity] is a internet site that contains basic information, such as energy density, cycle life, maintenance advice etc, about all kinds of batteries. This chapter will not evaluate or discuss which battery should be used for propelling a vehicle, nor present any facts about the lifetime of batteries. This is because the lifetime of a battery highly depends on the maintenance of the battery which, if placed in a hybrid vehicle (Hybrids are presented in Chapter 18), depend on the vehicle control system. However, Toyota Prius which is the most sold hybrid considers the battery to be a lifetime component and gives a generous warranty on all hybrid parts. The reason why this chapter is included in this report is to illustrate the significant difference in energy density between batteries and other propulsion fuels presented in this report. The problem can be illustrated by calculating the required mass of Lithium-Ion (cobalt) battery in order to correspond in energy content to a 60 liters gasoline fuel tank, this result in a battery mass of over 3000 kg. The pure electric vehicle failed to enter the market due to the battery. Short distances between charging and its short lifetime, together with a high replacement cost are some of the reasons why the electric car never became an appreciated transportation vehicle. The emissions of an electric vehicle are not commonly discussed. A car driven by a battery does not generate any first-hand emissions. But the charging of a battery uses electricity, and the production of electricity causes greenhouse gases (Electricity is presented in Chapter 20.1). The hybrid vehicle has recently entered the market and uses a method that recharges the battery when braking. This has become a successive concept especially for urban vehicles.

Part III

Powertrains

Chapter 16

IC-Engine

Internal combustion engines (ICE) and how to control them is closely described in [15, Eriksson, Nielsen, 2006]. The thermodynamic laws limit the efficiency of internal combustion engines. Therefore it is of interest to study how the fuel should be combusted in order to achieve the highest possible efficiency. In general there are two different ways of combusting the fuel; the Otto-cycle and the Diesel-cycle. The difference between the two is that in the Otto-cycle the air/fuel-mixture is burnt while the volume remains constant, with the result of a high pressure peak. In the diesel-cycle the pressure is constant during the combustion and the volume increases. It is important to note that a diesel engine does not follow the diesel-cycle but rather the otto-cycle. Figure 16.1 is a pV-diagram for both the Diesel- and Otto-cycle. A pV-diagram presents a curve where pressure is plotted against volume.

According to the laws of thermodynamics, the area enclosed by the graph represents the released energy that is transformed into mechanical energy. As can be seen in figure 16.1 the Otto-cycle has a greater area which yields in a higher efficiency and can be theoretical decided by equation (16.1). The complete derivation is found in [15, Eriksson, Nielsen, 2006].

$$\eta_{\text{otto}} = 1 - \frac{1}{r_c^{\gamma-1}} \tag{16.1}$$

$$\gamma = \frac{c_p}{c_v} \tag{16.2}$$

$$r_c = \frac{V_{\max}}{V_{\min}} \tag{16.3}$$

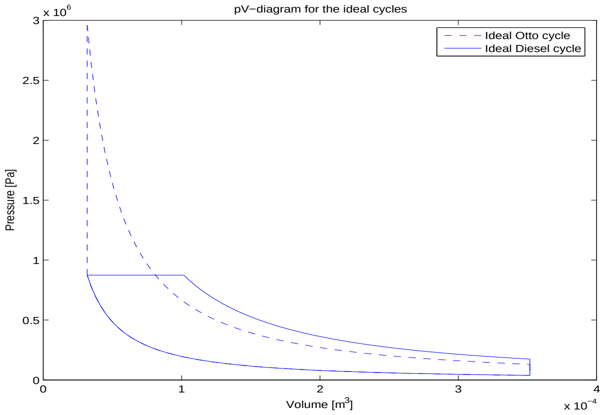

Figure 16.1. Ideal Internal Combustion Cycles. The enclosed area of the Otto-cycle is greater than the Diesel-cycle, this result in a more efficient combustion.

where

η_{otto} : Efficiency of an ideal Otto-cycle.
V_{min} : The minimum volume of the combustion chamber.
V_{max} : The maximum volume of the combustion chamber.
c_v : Specific heat capacity at constant volume.
c_p : Specific heat capacity at constant pressure.
γ : Definition of ratio of specific heats.
r_c : Compression ratio.

Modern IC-engines, both PISI and DICI, work in similarity to the Otto-cycle with some physical restraints that decrease the efficiency. Figure 16.2 presents a pV-diagram, based on measurements, for a port injected SI-engine. The lower enclosed area represents the induction stroke where the engine takes in air. This area corresponds to a negative output of energy known as pumping losses. The following list presents the physical restraints of a engine.

- All fuel is not burnt instantaneously
  This causes a decreasing of the enclosed area in figure 16.1 because the volume increases during the combustion.
- Friction
  The energy losses due to friction grow exponential regarding to the engine speed.
- Heat transfer
  During combustion, heat will travel through the combustion chamber walls. This effect is highest when a big amount of fuel remains in the cylinder for a long time which represent a high external load with a low engine speed.

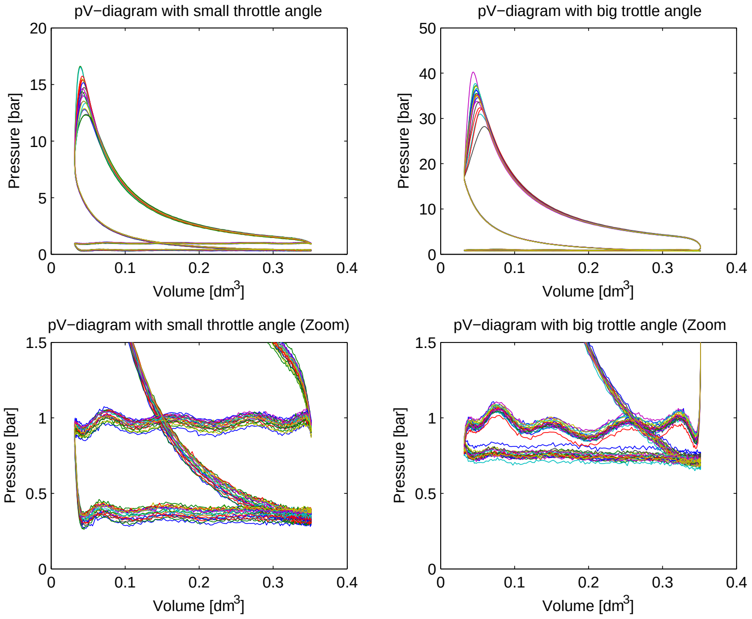

Figure 16.2. pV-diagrams for two different loads of an SI-engine powered by gasoline. The difference in pumping losses can be viewed in the two lower pictures.

- Knock
  The fuel can spontaneously and locally ignite which causes a rapid pressure rise and a following shock wave inside the combustion chamber. The shock wave reflects on the cylinder walls and is devastating to the engine. Knock occurs when pressure and temperature inside the cylinder reaches a certain level that is decided by the properties of the fuel. This limits the compression ratio which directly affect the efficiency according to equation (16.1). The phenomena is illustrated in figure 16.4.

The following abbreviations are often used in IC-engines:

- SI : Spark ignition
  The combustion mixture is ignited by a spark as shown is figure 16.3.
- CI : Compression ignition
  The combustion mixture auto ignites due to the high pressure and temperature that occurs when the mixture is compressed. A schematic overview of the ignition is presented in figure 16.5.
- PI : Port injection
  The fuel is fed to the air before the mixture enters the cylinder. A schematic overview of the configuration is illustrated in figure 16.3.
- DI : Direct injection
  Fuel is sprayed directly into the cylinder. An illustration of the assembly is shown in figure 16.5.

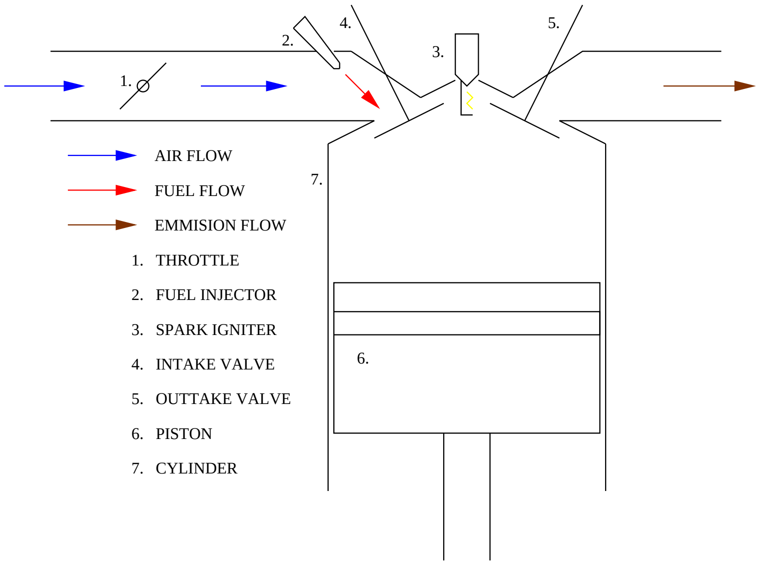

Figure 16.3. A schematic overview of a PISI-engine. Note that the fuel is injected at the port and that there is a spark plug present at the top of the cylinder.

16.1 PISI-Engine

The PISI-engine is the common engine concept used in gasoline vehicles and is developed to suit fuels with high octane rating. The output torque is decided by the amount of air fed to the engine controlled by the angle of the throttle. In modern cars a computer then calculates how much fuel that should be injected to achieve the correct mixture. In elderly cars this is done mechanical. The correct mixture, known as the stoichiometric air-fuel ratio, is decided so that all the fuel can react with oxygen. This is crucial in order to reduce the amount of undesirable emissions. The PISI-engine working according to the four-stroke cycle can be divided into the following steps.

- *The induction stroke.*
  The piston is at top dead center (TDC) moving downwards, while the inlet valve is open. The correct amount of fuel is fed to the air which is sucked into the cylinder.

- *The compression stroke.*
  The piston is at bottom dead center (BDC) and both the valves are closed compressing the gas mixture. As the piston approaches TDC the mixture is ignited by a spark.

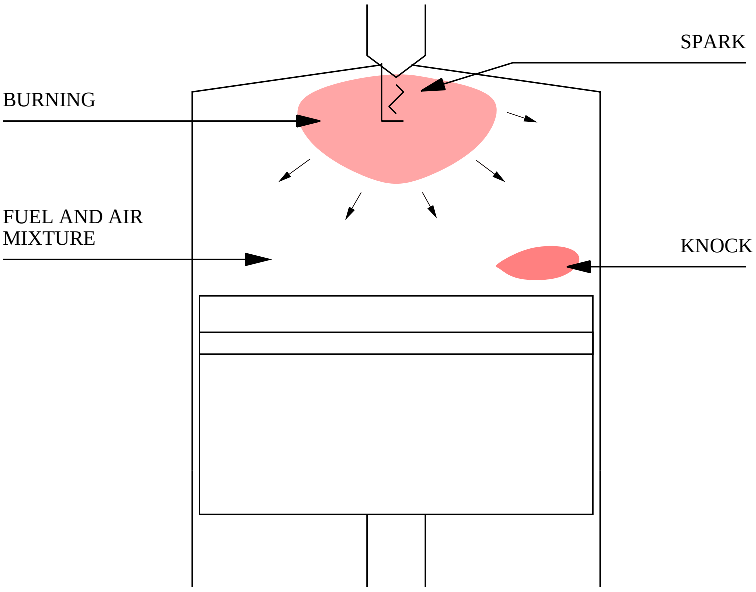

Figure 16.4. A schematic view of the flame front with knock presented in the lower right corner inside the cylinder.

- *The expansion stroke.*
  The piston is forced downwards generating a positive momentum on the crankshaft.

- *The exhaust stroke.*
  The piston is at BDC moving upwards as the output valve is open, emptying the cylinder of the emissions. When the piston is at TDC the cycle starts over.

PISI-engines are sensitive to knock because the cylinder contains the correct mixture during the compression phase. This can be controlled by modifying the time of ignition. The highest pressure caused only by the compression is constant and will always occur when the piston is at TDC. By igniting the mixture later than the optimum, the pressure build-up caused by the burning is postponed and the total pressure peak can be lowered so the engine do not knock. A graphical illustration of knock is presented in figure 16.4. PISI-engines have poor efficiency when throttle is closed. This is because in the first stroke of the cycle when the engine takes in air, a shut throttle hinders the piston from moving downwards. If the throttle is fully open the piston can move downwards without any restraints and only a small amount of energy goes to waste. The problem is illustrated in the lower plots of figure 16.2.

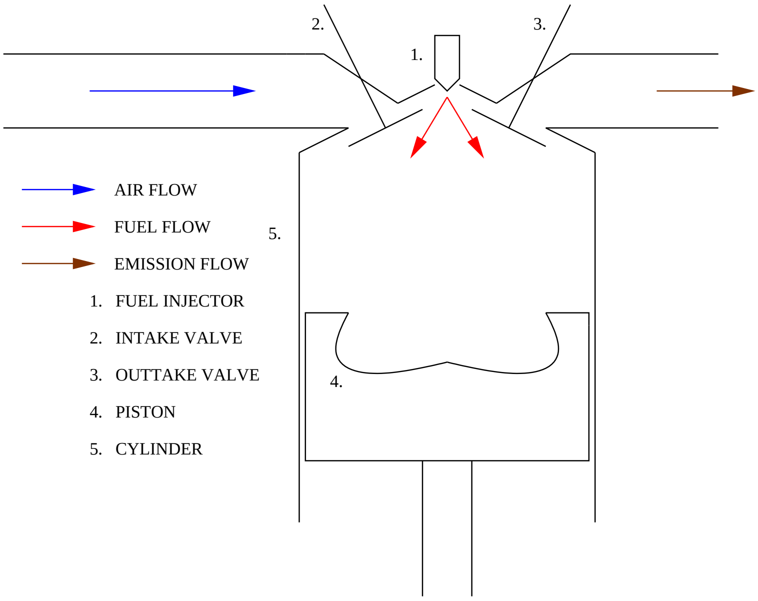

Figure 16.5. A schematic overview of the configuration of a DICI-engine. Note the lack of of a spark plug and that the fuel injector sprays the fuel directly into the cylinder.

16.2 DICI-Engine

DICI-engines are designed to be suitable for fuels with high cetane rating. Fuels with high cetane rating self-ignite easily. Because of this the DICI-engines work without the requirement of a spark in order to ignite the mixture. On the other hand the fuel must be injected during the compression phase, due to the mixture otherwise would ignite to early.

Unlike PISI-engines where the output torque is decided by the flow of air, DICI-engines control the torque by the amount of fuel fed to the engine. A description of the four stroke cycle for a CI-engine follows.

- *The induction stroke.*
  The piston is at TDC moving downwards as the inlet valve is open sucking air into the cylinder.

- *The compression stroke.*
  The piston is at BDC and both the valves are closed compressing the air. When it approaches TDC the fuel injector starts to spray fuel into the cylinder and the fuel self ignites due to the high pressure and temperature.

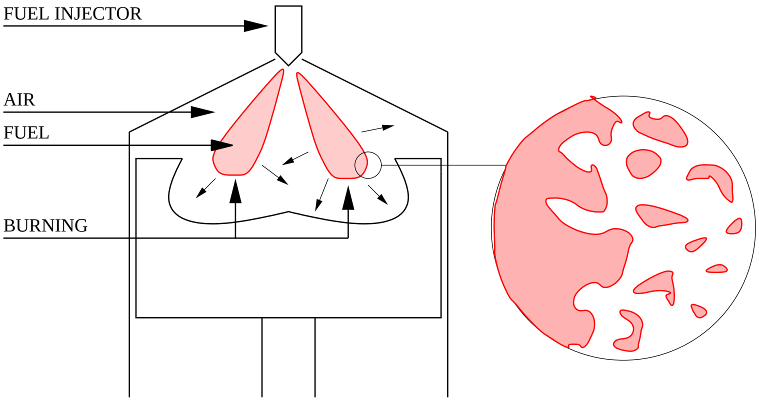

Figure 16.6. Basic view of the flame front for a DICI engine, note that the formation of the piston differs from a PISI engine piston.

- *The expansion stroke.*
  The fuel burns in the edge of the area where the fuel is injected. The pressure build-up forces the piston downwards generating a positive momentum on the crankshaft.
- *The exhaust stroke.*
  The piston is at BDC moving upwards as the output valve is open, emptying the cylinder of the residues. As the piston is at TDC the cycle starts over.

DICI-engines do not have the same knock problem as SI-engines because it is only air that is compressed. The compression ratio can therefore be higher with a result of an increased efficiency. It is important to note that DICI-engines can knock if there is a long ignition delay, allowing the fuel to mix with the air, forming a combustible mixture.

The lack of a homogeneous mixture of fuel and air in a DICI-engine results in that the only region where ignition can occur is on the surface of the fuel cones where the air/fuel ratio is in the ignition range. This set high demands on the nozzles of the fuel injectors to minimize the time for the fuel to fully combust. There are often multiple holes in the nozzle and each one is designed to generate droplets to further increase the reaction surface of the fuel. The time it takes for the fuel to combust is crucial for the engines performance since it limits the engine speed which is directly proportional to the power of the engine. To inject fuel directly into the cylinder, as it compresses the air, the injector system must be greatly pressurized, unlike PI-engines where injection occurs at more moderate pressure.

Disadvantages of this concept is the high level of NO_x and soot. Soot is also known as particle matter (PM) and is particles formed of unburnt hydrocarbons. The formation of NO_x is highly dependent of the flame temperature. Recirculating exhaust gases will slow the burning down and therefore reduce the temperature. This method has its highest efficiency for low engine speeds. When the engine is in high speed the burning must be fast in order to fully combust and therefore almost no exhaust gas can be recirculated. If there is not enough oxygen for the fuel to fully combust the hydrocarbons are dehydrated and cracked into soot. This occur just inside the edges of the fuel cones where the air/fuel ratio is lower than the stoichiometric value. Reduction of soot is often done by installing a particulate filter that adsorbs the particles before they leave the exhaust pipe.

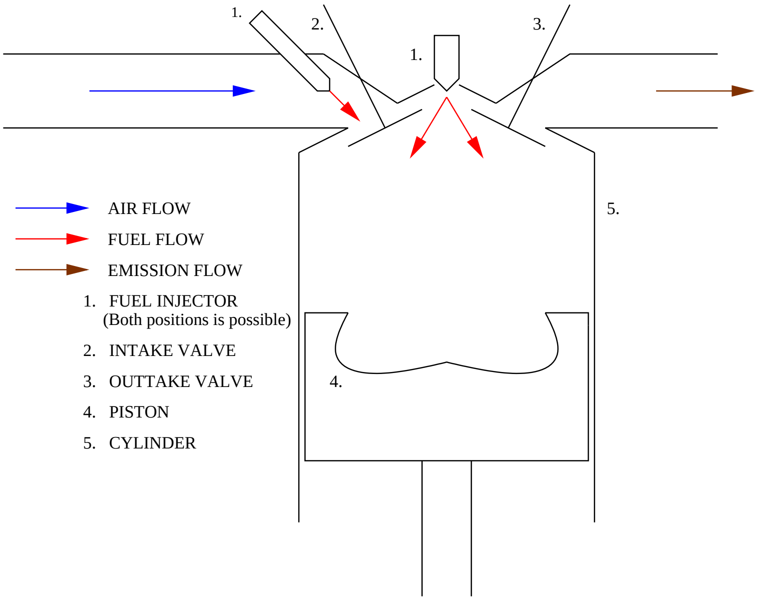

Figure 16.7. Schematic overview of a HCCI-engine. Note that the fuel injectors can be placed either at the port or inside the cylinder.

16.3 HCCI-Engine

HCCI is the abbreviation for Homogeneous Charge Compression Ignition and is an engine concept designed to use the advantages from both the SI and the CI concepts. The engine has a high compression ratio so the efficiency is similar to that of a CI-engine with the additional advantage of low emissions of NO_x and soot. Soot is generated in areas where the mixture is rich. The concept of the HCCI engine is a homogeneous lean mixture which results in no or low soot formation. The lean mixture also generates a low burning temperature that counteracts to NO_x formation.

A simple description of the four-stroke cycle for a HCCI-engine is presented below.

- *The induction stroke.*
  The piston is at TDC moving downwards as the inlet valve is open, taking in air into the cylinder.
- *The compression stroke.*
  The piston is at BDC and both the valves are closed. Early in the compression phase the fuel is injected. As the piston reaches TDC the fuel self ignites due to the high pressure and temperature.

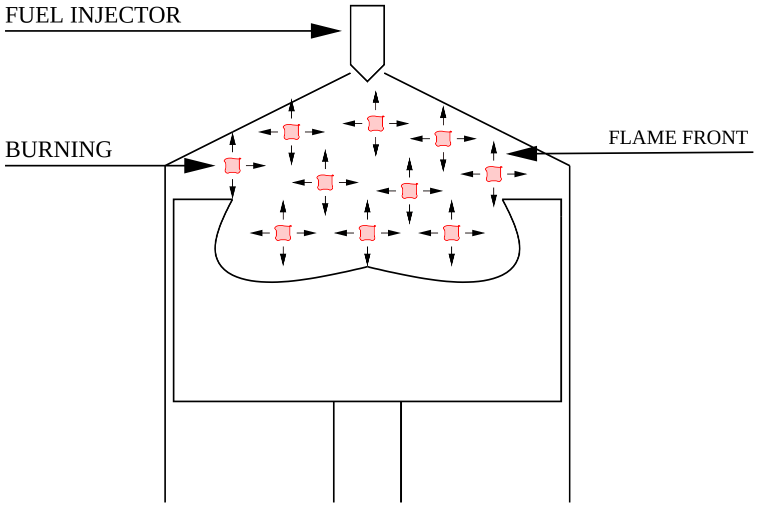

Figure 16.8. Basic structure of a flame in a HCCI-engine. Note that ignition occurs simultaneously at multiple places inside the cylinder.

- *The expansion stroke.*
  The pressure build-up, caused by the burning, forces the piston downwards and create a positive momentum on the crankshaft.

- *The exhaust stroke.*
  The piston is at BTC moving upwards as the output valve is open emptying the cylinder of the residues. When the piston is at TDC the cycle starts over.

The basic idea of HCCI-engines is that all the combustion mixture is self ignited simultaneously. Figure 16.8 shows the basic concept of the combustion. In order to prevent the devastating pressure wave, caused by local self ignition, it is crucial that the mixture is homogeneous. This sets high standard of the fuel injection. Fuel must be injected so that the air/fuel ratio is in the combustible region for the entire cylinder. The pistons and the nozzles are designed to create a swirl effect in order to achieve a homogeneous mixture.

Once the fuel is injected and the valves are closed the law of physics decides when ignition occurs. However, by controlling the initial conditions such as pressure, temperature etc. the time of ignition can be affected. This is known as combustion phasing. A list of different technologies follows:

- Variable Valve Timing
  VVT is a method that can affect both the temperature and the pressure. The temperature is controlled by varying the amount of hot residual gases left in the combustion chamber from prior cycles and the pressure is controlled by the amount of air fed to the cylinder.

- Variable Compression Engine
  VCE was originally designed to use the fuel consumption benefits of a smaller engine, on small loads, and the maximum output torque advantage of a bigger engine. By controlling the compression ratio, the cylinder pressure can be varied and the time of ignition is altered.
- Multi fuel engines
  By varying the blend of two fuels the auto ignition conditions are affected and therefore the time of ignition can be controlled.
- Split direct injection in the negative valve overlap
  With VVT it is possible to close the valves early in the exhaust stroke with the benefit of a second compression where a small amount of fuel can be injected. Tests performed at Chalmers University of Technology[23] shows heat releases during the compression which can be associated to combustion. The amount of pilot fuel alters the combustion phasing by affecting the initial temperature.
- Heating the intake air
  If there is a lack of combustion in one cycle, the following cycle also will lack combustion.This is due to the initial temperature for the next is lowered. By heating the intake air this issue is solved.

HCCI engines are yet to enter the industrial market. Research is performed in various location of the world with different control strategies. The concept has a relatively low operation range with the result that the engine must be hybrid that can use a different concept on higher loads in order to make it suitable for vehicle propulsion. However, there are stationary industrial applications where the operation range is sufficient. HCCI engines are higher in production cost than ordinary engines mainly due to the necessity of advanced mechanical controlling system, but also the durability to withstand the violent combustion. Fuels must have a relatively high octane rating to be compatible with this concept. The appealing benefits of a hybrid concept, where the HCCI concept is complemented with the DICI concept on higher loads, has led to the research of using fuels with low octane rating i.e. diesel. This hybrid concept demands a lowering of the compression ratio to prevent early ignition. Lowering the compression ratio directly affects the efficiency negatively, and leads to an increasing amount of unburned hydrocarbons in the emissions. In order to maintain a respectable efficiency there is a need for a low initial temperature which stands in direct conflict of using internal EGR for emission improvements.

Chapter 17

Fuel Cells

Facts presented in this chapter is based on [20, Larminie and Dicks, 2000]. Fuel cells are similar to a battery but have the advantage that the energy is not stored within. They are powered by an energy carrier stored in a tank, most often hydrogen. Fuel cells transform chemical energy into electric energy and are not limited by the Carnot cycle like the combustion engines are. The emission of a fuel cell charged by hydrogen is only water. Together with the high efficiency makes it an appealing propulsion system.

17.1 Technology

Fuel cells are most often driven by hydrogen which is fed to the anode where it is separated into H^+ and e^-, see (17.1). At the cathode O_2 is separated into O which reacts with the e^- and H^+ to form H_2O as presented in (17.2). These reactions sum up to the overall reaction shown in (17.3).[29, fctec, 2006]

$$\begin{aligned} 2\mathrm{H}_2 &\longrightarrow 4\mathrm{H}^+ + 4\mathrm{e}^- && (17.1)\\ \mathrm{O}_2 + 4\mathrm{H}^+ + 4\mathrm{e}^- &\longrightarrow 2\mathrm{H}_2\mathrm{O} && (17.2)\\ 2\mathrm{H}_2 + \mathrm{O}_2 &\longrightarrow 2\mathrm{H}_2\mathrm{O} && (17.3) \end{aligned}$$

The current is limited by the reaction rate of H_2. The reaction rate is affected by the probability of the H_2 to react and by the anode area. H_2 needs an activation energy to separate and release the energy bounded in the molecule. The probability of separation increases with the temperature and thereby the reaction rate rises. A bigger area also increases the reaction rate since the reaction occurs on the surface of the anode. This causes some problem due to the desire of a small fuel cell with a high current. The area of the anode and the reaction area can differ greatly. Modern fuel cell electrodes have a microstructure that results in a reaction area that can be up to a thousand times bigger than the normal height times width area. The voltage of a fuel cell is about 0.7 volts which generates the need for the fuel cells to be connected in series, known as a stack. This could be

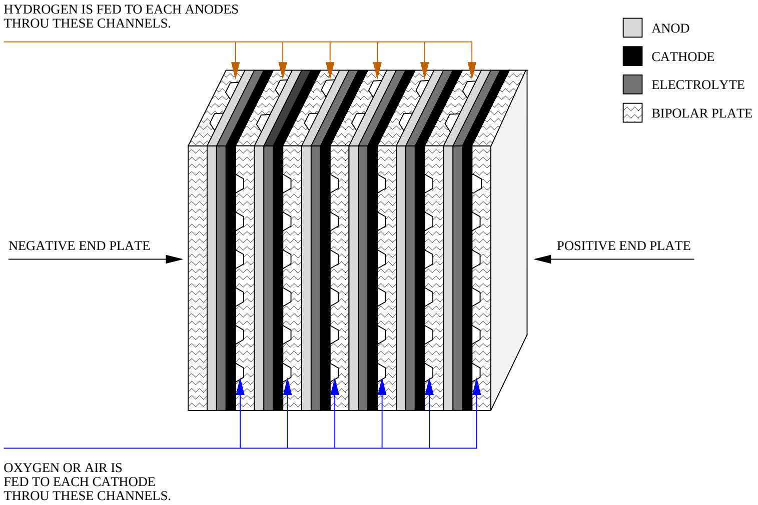

Figure 17.1. Schematic overview of a fuel cell stack.

done with just a small connection at each fuel cell. However, this is an ineffective way due to the fact that electrons then needs to travel across the entire surface to the connection point which can generate a pressure drop. A more effective way of manufacturing stacks is to connect the entire surfaces of the fuel cells to each other using a bipolar plate. This must be done without allowing the H_2 and O_2 to mix. The most common arrangement is shown in figure 17.1.

This method of creating stacks has two major drawbacks. The area in contact with the gas is decreased, causing a lower reaction rate, and it also restricts the gas-flow, especially when using air instead of oxygen. The advantages of using fuel cells are presented in the following list. For efficiency and emission comparisons between fuel cells and internal combustion engines the reader is referred to the well-to-wheel results presented in Chapter 22.

- *Efficiency*
  The fuel cells are generally more efficient than combustion engines hence it is not limited by the carnot-cycle. Figure 17.2 presents an efficiency map for the fuel cell used in the well-to-wheel analysis performed by [21, General Motors, 2002], which the tank-to-wheel analysis in this report is based on.

- *Simplicity*
  The lack of moving parts is likely to lead to a long life time.

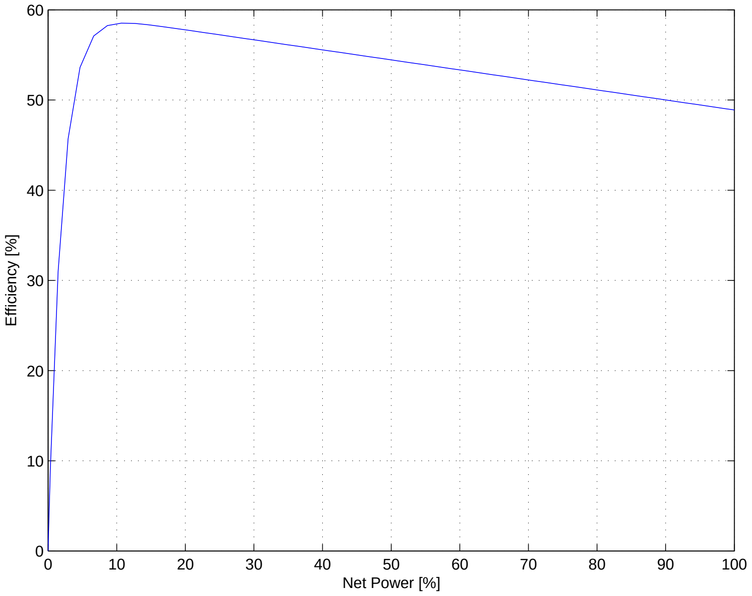

Figure 17.2. Efficiency map of a fuel cell. Note that the efficiency is above 50% for almost the entire operating range, which is higher than the maximum efficiency of a common combustion engine. [21, General Motors, 2002]

- *Emissions*
  The emission is only water when use of pure hydrogen. If other fuels are used, the emission is still low compared to combustion engines. However it should be noted that the process of manufacturing hydrogen often releases greenhouse gases.
- *Silence*
  The lack of combustion in fuel cells leads to low noise levels.

The fuel cell mentioned earlier in this report fueled with methanol is often referred to as DMFC (Direct Methanol Fuel Cell). According to [29, fctec, 2006], DMFC uses the reaction presented in (17.6) and can be divided into the anode reaction (17.4) and the cathode reaction (17.5). There are multiple fuel cells commercial available today but most of them are expensive compared to common ICE engines.

$$\mathrm{CH_3OH + H_2O} \longrightarrow \mathrm{CO_2 + 6H^+ + 6e^-} \tag{17.4}$$

$$\frac{3}{2}\mathrm{O_2 + 6H^+ + 6e^-} \longrightarrow \mathrm{3H_2O} \tag{17.5}$$

$$\mathrm{CH_3OH} + \frac{3}{2}\mathrm{O_2} \longrightarrow \mathrm{CO_2 + 2H_2O} \tag{17.6}$$

Chapter 18

Electric Hybrid Vehicle

[32, www.hybridcenter.org] contains a good overview of the basics of an electric hybrid vehicle. Hybrid vehicle is a collective name for vehicles combining two or more different engine technologies. The one presented in this report is an electric hybrid which combines a combustion engine with an electric motor. Basically there are three different electric hybrid configurations, series, parallel and a combination of the two, known as a series-parallel hybrid, or a full hybrid. The three following sections will present each configuration.

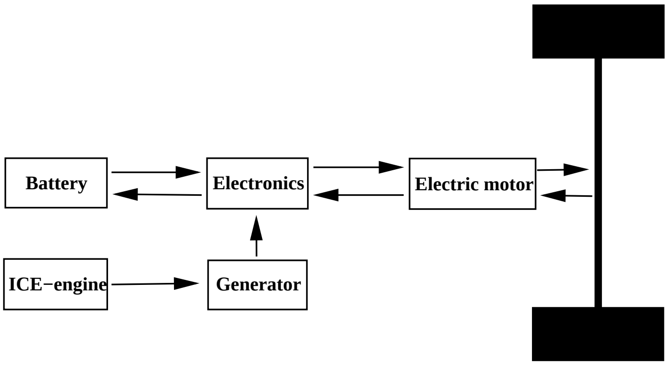

Figure 18.1. Schematic vverview of the series hybrid concept. The arrows represent possible energy flow routes.

18.1 Series Hybrid

In the series hybrid configuration only the electric motor can supply power to the wheels, as can be seen in the schematic overview presented in figure 18.1. This configuration allows a small ICE-engine hence its only task is to charge the battery. On the other hand the configuration requires a strong electric motor and a big battery. The series hybrid is most efficient in stop-and-go traffic, as often is the case in cities. This is because it then can recharge the battery without using the ICE engine and operate as a pure electric vehicle. The major benefit of this configuration is that the ICE engine can operate in its most efficient region during charging hence it is not connected to the wheels. A drawback by this configuration is that in higher engine loads, where all the power is supplied by the ICE engine, the powertrain is less efficient than a powertrain only containing an ICE engine. The reason for this is the non ideal efficiency of the generator through which the power must pass.

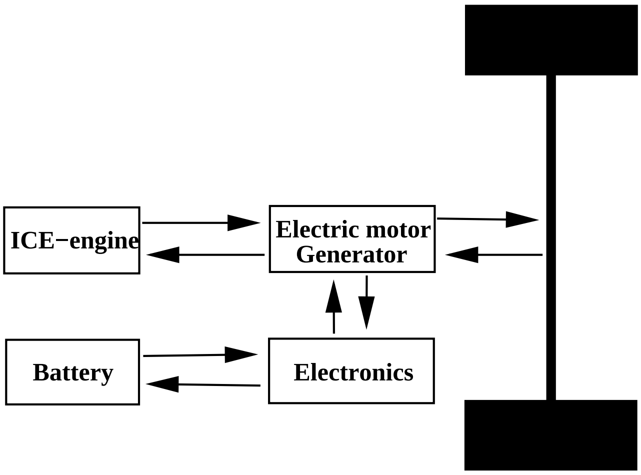

Figure 18.2. Schematic overview of the parallel hybrid concept. The arrows represent possible energy flow routes. The flow route to the ICE engine is active during start-up when the electric motor acts as a starter engine.

18.2 Parallel Hybrid

The combustion engine in a parallel hybrid configuration is in direct contact with the wheels, as in a common ICE powertrain. An electric motor, which also is used as a generator, is connected to the drive shaft to supply torque when needed, or to recharge the battery, the configuration is displayed in figure 18.2. The battery and the electric engine in this configuration can be significantly smaller than in the series hybrid due to the major part of the power is produced by the ICE engine. This configuration does not match the efficiency of the series hybrid in stop and go traffic but it does not suffer of the efficiency loss the series hybrid does in higher engine loads. The key feature of this configuration is that the torque can be provided from the ICE engine and the electric motor simultaneously, which increases the performance of the vehicle. A powertrain only containing an ICE engine must be designed to meet the required torque during acceleration, this torque demand is considerably higher than driving in constant speeds. The result is that the ICE engine must be large enough to supply the desired torque in an acceleration but most often it only uses a fraction of the maximum torque. Because a larger engine consumes more fuel than a smaller the powertrain becomes inefficient. The major benefit of the parallel hybrid configuration is that it allows additional torque supplied by the electric motor during acceleration. This permits downsizing of the ICE engine without decreasing the maximum output torque needed during accelerations.

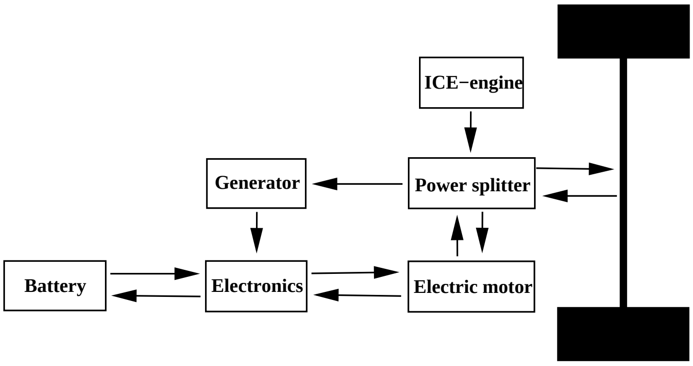

Figure 18.3. Schematic overview of the series-parallel hybrid concept. The arrows represent possible energy flow routes.

18.3 Series-Parallel Hybrid

The series-parallel hybrid configuration allows the powertrain to work both as a series hybrid as well as a parallel hybrid. The torque can be supplied by the electric motor and the ICE engine separately or simultaneously. The configuration combines the benefits of both the series and the parallel hybrids and reduces their individual drawbacks. This configuration is however more expensive than the other hybrid configurations. A schematic overview of the series-parallel hybrid concept is presented in figure 18.3.

Part IV

Well-to-Wheel Analysis

Chapter 19

Well-To-Wheel Analysis

A well-to-wheel analysis is used to thoroughly compare different fuels with regards to energy loss and emissions throughout the production chain from source to the end of the exhaust pipe, including extraction of feedstock, transportation, processing etc. This is a highly complex and difficult task and requires first hand information and measurement in order to receive a just result. Because of the limited time frame and unsatisfactory access to first hand information, the well-to-tank analysis in this report will be based on the analysis [21, General Motors, LBST, 2002], performed by General Motors and LBST in cooperation with the energy companies, BP, ExxonMobil, Shell and TotalFinalElf. The tank-to-wheel analysis is based on the recently published well-to-wheel analysis, [10, EUCAR, concawe, 2006], performed by concawe and EUCAR. In this well-to-wheel analysis the time frame is set to 2010 and the market is Europe. Why this is of importance will be discussed in the following section.

19.1 Reliability

Energy balances and emissions tend to differ from one WTW-analysis to another. This is the result of physical factors as well as the choice of calculation method. The physical factors are e.g. geographical location, size of production plants etc. If ethanol is produced and distributed in Brazil there will be less energy loss than if it is distributed to Europe. There are however more concealed factors. If an exact copy of the Brazilian plant is built in Europe, using the same feedstock, the energy loss will still be higher than the plant located in Brazil due to the difference in climate. The facilities in Europe require more heating and the rate of the feedstock growth is lower. Another factor is the source to the electricity used in the production chain. Electricity can be produced local with generators or supplied with a national power grid. Wind power causes no or very low energy loss and emissions while for example coal power generates a great amount of greenhouse gases. As sources to the power grid vary all over the world, this affects the result of the WTW-analysis. It is therefore important to initially decide which geographical region the WTW-analysis should be performed. The other

Source	Example
Geographical Location	Climate
Cultivation	Manure
Quality of Feedstock	Byproducts
Transportation	Distances
Plants	Size
Power Structure	Electricity
Boundaries	Feedstock

Table 19.1. Factors that affect the result of a WTW-analysis. [7, Börjesson, 2006]

initial decision is to set the time-frame for which the analysis should apply. The evolving of technologies improves the efficiencies and that has to be concerned in a WTW-analysis. However, the time-frame can not be set to far ahead because the further the time-frame is set the more uncertain the result will be. The biggest cause to the variations is the value assigned to the feedstock and the byproducts. Diesel are extracted from crude oil with an about 95% efficiency in case a high value of gasoline and other byproducts is set. If the byproducts are considered as waste material the efficiency of diesel extraction of crude oil will be considerable less, however gasoline, butane etc. are not waste material but rather very high value products and therefore energy inputs can be assigned to them. All factors that affect the result must be carefully defined and printed in the report. Often the WTW-reports completely lack these sections and even the background reports fail to include all factors. A list of variables that affect the WTW-analysis are presented in table 19.1.

19.2 Acknowledgment

There are some concerns regarding GM´s WTW-analysis ([21, General Motors, LBST, 2002]) that hinder this report to conclude diverse mathematical derivations in reproducing the results. Lack of information in the background report of such as reusing of heat and power networks inside the production chain has caused some trouble in duplicating the exact numbers presented in [21, General Motors, LBST, 2002]. There have been direct contacts with LBST in order to straight out some of the concerns. For example excessive heat in one part of the process can be used in a different part of the production chain. As the production chain is divided into several intermediate steps, each with corresponding energy input, it is crucial to get the information what the source of that energy input is in order to duplicate the overall input of external energy. In some cases this information is left out making the reproducing of the result very time consuming. This has led to the decision not to include any mathematical derivations and completely leave out the intermediate steps in the paths of biomass to fuel. The reader can find all intermediate steps in [21, General Motors, LBST, 2002]. In some of the tables numbers do not add up to the total at the bottom but differs in the last position. The presented values are rounded off causing the difference and it is thus not an error. A complete list of names used in the tables are located in Appendix A.

Energy loss is presented in [MJ/MJ_{fuel}] and represent energy loss in [MJ] of respective process per [MJ] of finished fuel at the end of the production chain, for example at a refueling station or in a vehicle tank. GHG stands for greenhouse gases and are calculated in a similar unit as the energy loss, [g/MJ_{fuel}], and correspond to the amount of emissions in [g] in respective process per [MJ] of finished fuel, according to formula (19.1) [21, General Motors, 2002]. Methane and nitrogen oxide are more severe greenhouse gases than carbon dioxide and therefore they have greater weighting factors. Consequently, the unit [g] in the GHG-emissions is not the ordinary physical unit but rather a fictional unit derived from that formula.

$$\text{"}CO_2 - \text{equivalent"} = CO_2 + 21CH_4 + 310N_2O \tag{19.1}$$

Chapter 20

Well-to-Tank Analysis

20.1 Electricity

In order to perform a WTW analysis the need for a proper analysis of the paths for electricity is unavoidable since electricity often is included in some of the processes along the chain. In the WTW analysis of the different fuels in this report the electricity used by depots, facilities, filling stations etc. is a mix of several different sources. The electricity mix is representative to the mean electricity consumption in Europe and will be referred to as the EU-mix of electricity. Table 20.1 presents the average European electricity sources in 1999.

	Input	Output		Market
	Primal Energy	El	GHG	Share
Source	[kWh/kWh$_{el}$]	[kWh]	g/kWh$_{El}$	[%]
Nuclear	1.169	-	?	40.7
Biomass	0.008	-	?	0.3
Brown Coal	0.201	-	?	7.0
NG	0.354	-	?	12.3
Mineral Oil	0.247	-	?	8.6
Geothermal	0.002	-	?	0.1
Waste	0.189	-	?	6.6
Hard Coal	0.567	-	?	19.8
Hydro Power	0.128	-	?	4.5
Wind Power	0.004	-	?	0.1
EU-mix	2.869	1.000	463	100

Table 20.1. Average source to electricity in Europe in the year 1999. [21, General Motors, 2005]

20.2 Oil Based Fuels

Gasoline, kerosene and diesel, among others, are produced simultaneously in the same process. To accomplish a good WTT-analysis it is crucial to decide the amount of input energy that is related to a certain product. The output of a refinery varies all over the world. For example, the refineries in the USA have a higher output of gasoline than refineries located in Europe, which instead have a high output of diesel. The most important parameter in deciding the output products is the market, and as there is an increasing use of diesel in the European market this will affect future output ratios.

Crude oil is extracted and shipped to a refinery and further transported to the depots, mainly by pipeline, train or barge. Pipeline and train transportation require electricity while barge transport needs heavy fuel, oil or diesel. The electricity used is euro-mix (see chapter 20.1) which also is needed at the depot. The final transportation from the depot to the refueling stations is carried out by heavy road vehicles meeting the exhaust limits according to EURO 4 and can be view in table C.5. The average distance is calculated to 150 km which represents a trip of 300 km because no gods can be loaded for the journey back to the depot. The last required energy input is at the refueling station that uses electricity. The overall result is presented in table 20.2. More detailed information regarding the intermediate steps is located in Appendix C.

	Gasoline	
	Energy Loss [MJ/MJ$_{\text{Gasoline}}$]	CO$_2$-eq [g/MJ$_{\text{Gasoline}}$]
Crude Oil Extraction	0.028	3.7
Crude Oil Transport	0.012	0.9
Refining	0.100	7.4
Distribution	0.020	1.1
Total	0.160	13.1

	Diesel	
	Energy Loss [MJ/MJ$_{\text{Diesel}}$]	CO$_2$-eq [g/MJ$_{\text{Diesel}}$]
Crude Oil Extraction	0.027	3.6
Crude Oil Transport	0.012	0.9
Refining	0.060	4.7
Distribution	0.020	1.1
Total	0.119	10.2

Table 20.2. Energy loss and GHG-emissions in gasoline and diesel production chain. [21, General Motors, 2005]

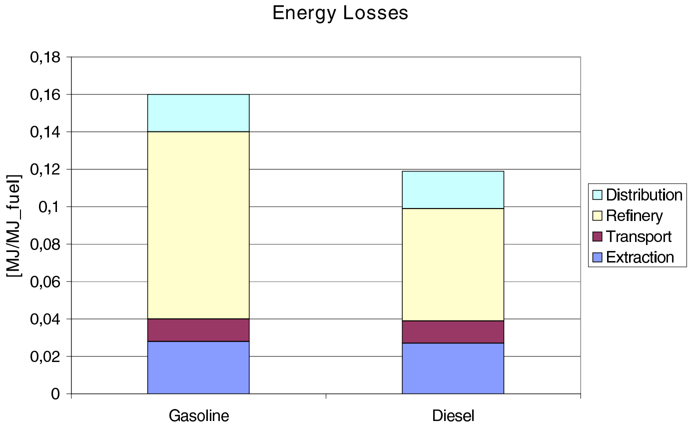

Figure 20.1. Energy loss connected to respective process in producing 1 MJ of gasoline or diesel.

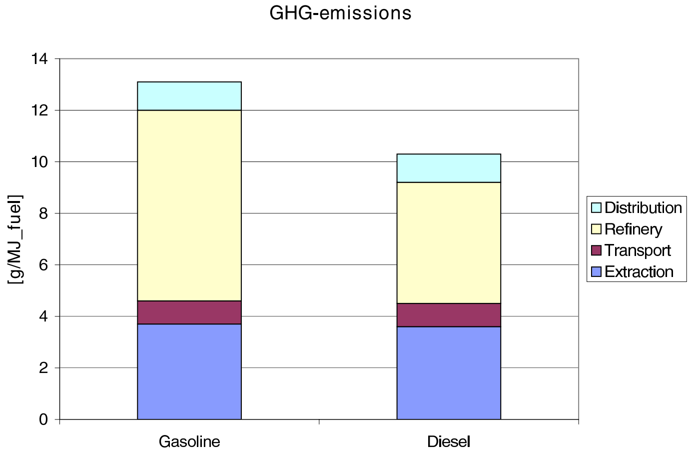

Figure 20.2. GHG-emissions connected to respective process in producing 1 MJ of gasoline or diesel.

	Market Share		LHV	Energy Loss	CO_2-eq
	True[%]	Assumed[%]	[MJ/Nm^3]	[MJ/MJ]	[g/MJ]
NL	18.6	22.0	31.5	0.021	2.1
NO	10.0	11.8	38.8	0.048	3.7
UK	25.6	30.4	38.8	0.015	1.8
CIS	18.1	21.4	35.9	0.314	21.3
AL	12.1	14.4	33.8	0.036	3.7
EU-mix	84.4	100	35.9	0.087	6.5

Table 20.3. Mix of European natural gas used in [21, General Motors, 2005]. The GHG-emissions connected to natural gas from CIS are significantly higher than the others due to the severe difference in transportation distance.

20.3 Natural Gas Based Fuels

The natural gas grid is extended in Europe and the future usage and processing are predicted to stay fairly constant. Therefore the European natural gas supply is considered to be the same in 2010 as it was in 2000. In this report there will be no separation of the natural gas according to its origin. The natural gas will be considered as a European mix (EU-mix) with multiple origins. This might cause some diffusion when comparing to other reports. For example, natural gas imported from Russia results in high emissions compared to natural gas from the UK due to severe difference in transportation distances. Most of the produced natural gas in the UK is consumed domestic while Russian gas is transported thousands of kilometers. The top five natural gas suppliers that together represent about 85% of the total European supply are, in a declining order, the Netherlands (NL), Norway (NO), United Kingdom (UK), former USSR (CIS) and Algeria (AL). Table 20.3 presents their true market share, the share assumed in this study, some of their properties, energy loss and GHG-emissions during extraction and transportation.

There are two different natural gas distribution grids in Europe. One has an absolute pressure of 0.1 MPa which most often distribute gas for households while the other has a absolute pressure of 4 MPa and delivers gas to industrial consumers or power stations. The energy consumption of the filling station varies according to which grid it is connected to, due to the pressure difference between the discharge pressure and the pressure in the gas grid. The pressure build-up is done using compressors running on the EU-mix of electricity which can be studied in Chapter 20.1. The primal transportation of natural gas is done using pipelines. However, there is another route that may be interesting in a close future and that is transportation via maritime vessel of liquefied natural gas (LNG). Today some of the gas imported from Algeria is LNG and other areas like Libya, Nigeria, and the Middle-East are possible future natural gas suppliers for Europe. Table 20.4 shows the energy loss and GHG emissions when producing the presented fuels from natural gas.

	Energy Loss [MJ]	CO_2-eq [g]	Table
CNG			
CNG_1	0.12	7.9	D.1
CNG_2	0.20	14.3	D.1
CNG_3	0.23	16.2	D.2
Methanol			
MeOH_1	0.62	25.2	D.3
MeOH_2	0.61	26.8	D.4
FT-diesel			
FT_1	0.74	29.8	D.5
FT_2	0.68	27.1	D.6
Hydrogen			
CGH2_1	0.57	88.2	D.8
CGH2_2	0.61	89.9	D.8
DME			
DME_1	0.62	28.1	D.9

Table 20.4. Comparison of energy loss and GHG emissions connected to the production of 1 MJ of respective fuel derived from natural gas. For more information about each fuel the reader is referred to the table specified in the last column or directly to [21, General Motors, 2005] and [11, concawe EUCAR, 2006].

A complete list of the abbreviations used for the different fuels with alternative paths are presented in Appendix A and the paths are defined in Appendix D. The basic abbreviations are as follow:

CNG : Compressed Natural Gas
MeOH : Methanol
FT : FT-diesel
CGH2 : Compressed Gaseous Hydrogen

20.4 Biomass Based Fuels

The energy loss in producing fuel from biomass are extended compared to the fossil fuels. Most of the loss can be assigned to the extraction of energy from the main feedstock as for example sugar beet pulp for ethanol. To discard a fuel by just examining the efficiency of the production is inadvisable. Other conditions should also be concerned. Ethanol production from sugar beet pulp requires an energy input of 3.6 MJ in order to produce 1 MJ ethanol. If the pulp is not used in any other way the poor efficiency is defensible. However, the sugar beet pulp is used as animal fodder which together with the low efficiency would make production of ethanol from sugar beet pulp too expensive.

Fuel derived of biomass stores greenhouse gases, which results in the negative values in table 20.5. For example, biomethane uses waste material that, if not processed, would generate and release methane gas into the atmosphere. During combustion of the fuel the bounded greenhouse gases will be released. More detailed information regarding energy loss and greenhouse gases when producing fuels from biomass can be found in Appendix E. Table 20.5 presents the energy loss and GHG emissions in the production of the corresponding fuel with biomass as a source. Appendix A include a complete list of evaluated fuels with its corresponding abbreviation used in these figures. A list of the basic abbreviations used in table 20.5 follows:

CGH2 : Compressed Gaseous Hydrogen
MeOH : Methanol
EtOH : Ethanol
FT : FT-diesel
CMG : Compressed Methane Gas (Biomethane)

	Energy Loss [MJ]	CO_2-eq [g]	Feedstock	Table
Hydrogen				
CGH2_3	0.85	6.9	Wood Residues	E.1
CGH2_4	0.88	7.1	Wood Residues	E.1
CGH2_5	0.88	21.4	Popular Wood	E.2
CGH2_6	0.92	21.9	Popular Wood	E.2
CGH2_7	1.24	0.4	Organic Waste	E.3
CGH2_8	1.25	0.4	Organic Waste	E.3
Methanol				
MeOH_3	0.87	-61.8	Wood Residues	E.4
MeOH_4	1.71	-59	Wood Residues	E.4
Ethanol				
EtOH_1	1.78	-55.7	Crop Residues	E.5
EtOH_2	3.60	-70.3	Sugar Beet Pulp	E.5
EtOH_3	1.98	-29.3	Popular Wood	E.5
EtOH_4	1.24	-32.4	Suger Beet	E.5
FT-diesel				
FT_3	1.23	-61.7	Wood Residues	E.6
Biodiesel				
Biodiesel_1	1.12	-21.4	Seed (Rape or Sunflower)	E.7
Biodiesel_2	0.75	-46.6	Seed (Rape or Sunflower)	E.7
Biomethane				
CMG_1	0.48	-56.7	Organic Waste	E.8

Table 20.5. Comparison of energy loss and GHG emissions connected to the production of 1 MJ of respective fuel derived from biomass. For more information about each fuel the reader is referred to the table specified in the last column or directly to [21, General Motors, 2005].

Chapter 21

Tank-to-Wheel Analysis

Different ways of combusting the fuels are considered in this chapter. All results consider a specific concept and fuel in the year 2010 and beyond. A list of evaluated combinations are presented in table 21.1.

	ICE						FC	
	PISI		DISI		DICI			
	C	H	C	H	C	H	C	H
Gasoline	**X**	**X**	**X**	**X**			**X(R)**	
Diesel					**X**	**X**	**X**(R)	
FT-Diesel					**X**	**X**		
Biodiesel					**X**	**X**		
CNG	**X**	**X**						
Methanol							**X**(R)	
Ethanol	**X**		**X**					
Hydrogen	**X**	**X**					**X**	**X**
DME					**X**	**X**		

Table 21.1. Evaluated propulsion systems in the well to wheel analysis present in this report. C corresponds to conventional and H for hybrid. When (R) is added to the **X** it means that a reformer is present.

All tests are performed according to NEDC (New European Drive Cycle) which is presented in figure 21.1 and the minimum vehicle performance criteria of each powertrain is listed in table 21.2. The comparison in the following section is based on a 1.6 liters PISI gasoline engine, a more detailed description of the engine is located in Appendix B. The result for the reference vehicle is presented in table 21.3.

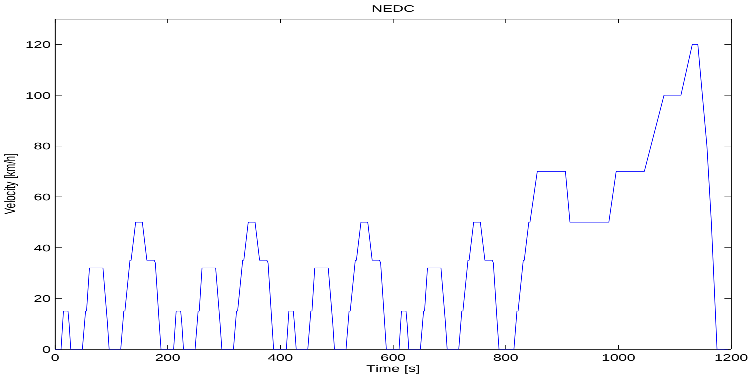

Figure 21.1. Illustration of the New European Drive Cycle (NEDC).

		Criteria	Unit	Note
Acc.		>4	m/s^2	
Acc. 0-50	[km/h]	<4	s	
Acc. 0-100	[km/h]	<13	s	
Acc. 80-120	[km/h]	<13	s	@ 4:th gear
Grad. at 1	[km/h]	>30	%	
Top Speed		>180	km/h	
Range		>600	km	

Table 21.2. Minimum vehicle performance criteria. [10, concawe EUCAR, 2006]

Reference Results	
Energy Consumption MJ/100 km	CO_2-equivalent g/km
223.5	168

Table 21.3. Results for reference vehicle. [10, concawe EUCAR, 2006]

	Results		Comparison	
	Consump. [MJ/100 km]	CO_2-eq. [g/km]	Consump. [%]	CO_2-eq. [%]
PISI				
Gasoline	190.0	140.3	-15	-16
Ethanol	190.0	136.6	-15	-18
CNG	187.2	107.6	-16	-36
Hydrogen	167.5	0.5	-25	-100
DISI				
Gasoline	187.9	138.8	-16	-17
Ethanol	187.9	135.1	-16	-19
DICI				
Diesel	172.1 176.7	127.8 131.1	-23 -21	-24 -22
BioDiesel	172.1 176.7	132.9 136.4	-23 -21	-21 -19
DME	172.1	117.6	-23	-30
FT-Diesel	172.1 176.7	123.6 126.8	-23 -21	-26 -25

Table 21.4. Results for future ICE:s when driving according to NEDC. In case there are two values presented, the first value represents an engine configuration with diesel particulate filter (DPF) and the second value without DPF. [10, concawe EUCAR, 2006]

21.1 Results

The results for the IC-engines are presented in table 21.4. The DICI engines have higher efficiency due to the lack of the throttle and higher compression ratio. The lower emissions depend on that CO_2-equivalent equation (19.1) does not account for particles in the emissions. Biodiesel has higher emission value than ordinary petro-diesel. This shows that just examining the generated emissions of a vehicle is not enough to decide which fuel should be considered as clean fuel. The emissions during production must be included.

	Results		Comparison	
	Consump. [MJ/100 km]	CO_2-eq. [g/km]	Consump. [%]	CO_2-eq. [%]
No Reformer				
Hydrogen	94	0.0	-58	-100
Reformer				
Gasoline	162.4	120.1	-27	-29
Diesel	162.4	121.3	-27	-28
Methanol	148	109.4	-34	-35

Table 21.5. Results for future FC:s when driving according to NEDC. [10, concawe EUCAR, 2006]

The results for the fuel cells are presented in table 21.5. The use of pure hydrogen is superior to the use of reformers regarding efficiency and emissions.

	Results		Comparison	
	Consump. [MJ/100 km]	CO_2-eq. [g/km]	Consump. [%]	CO_2-eq. [%]
PISI				
Gasoline	161.7	119.6	-28	-29
CNG	139.4	80.7	-38	-52
Hydrogen	148.5	0.5	-34	-100
DISI				
Gasoline	163.0	120.5	-27	-28
DICI				
Diesel	141.1	105.1	-37	-37
	145.7	108.4	-35	-35
BioDiesel	141.1	109.3	-37	-35
	145.7	112.7	-35	-33
DME	141.1	96.7	-37	-42
FT-Diesel	141.1	99.9	-37	-40
	145.7	104.8	-35	-38
FC, no Reformer				
Hydrogen	83.7	0.0	-63	-100

Table 21.6. Results for future hybrids when driving according to NEDC. In case there are two values presented, the first value represents an engine configuration with diesel particulate filter (DPF) and the second value without DPF. [10, concawe EUCAR, 2006]

The tank-to-wheel results for hybrids are presented in table 21.6. By comparing the consumption values for hybrids to the values for the powertrains only containing a combustion engine (table 21.4), it can be seen that for gasoline the consumption is lowered by 15% or 28.3 MJ/(100 km) while for diesel the corresponding improvement is 18% or 31 MJ/(100 km). This difference should be the other way around due to the poor efficiency for low loads of the PISI engine. The values can be explained by that [10, concawe EUCAR, 2006] assume that the efficiency improvement till 2010 for the PISI engine, operating on gasoline, is 15%. The corresponding value for DICI engine, fed with diesel, is only 3%. The significant higher improvement of efficiency for PISI engines probably has its source in minimizing the throttle loss which is greatest for low loads. This causes the hybridization profit to be about equal for both DICI and PISI engines.

Chapter 22

Well-to-Wheel Results

In this chapter the WTT-analysis and TTW-analysis are summed up to create the results of the WTW-analysis. One result of the TTW-analysis was the average fuel consumption for different fuels and powertrains. By knowing how much fuel that is consumed, it is possible to use the result of the WTT-analysis to calculate the total energy input. This is done by simply multiplying the energy content of the fuel consumed in the NEDC cycle by the required energy input to produce 1 MJ of the specific fuel. The mathematical expression is shown in equation (22.1). The overall emissions are calculated in a similar way. By adding the generated emissions when producing the amount of fuel consumed in the vehicle to the measured emissions in the exhaust gases the result is the overall generated emissions. The formula is presented in equation (22.3).

$$W_{\text{tot}} = W_{\text{car}} \cdot W_{\text{prod}} \tag{22.1}$$

$$W_{\text{prod}} = 1 + W_{\text{loss}} \tag{22.2}$$

$$E_{\text{tot}} = E_{\text{car}} + \frac{W_{\text{car}}}{100} \cdot E_{\text{prod}} \tag{22.3}$$

where

W_{tot} : Total energy consumption including the production energy. [MJ/100 km]
W_{car} : Energy content in the consumed fuel. [MJ/100 km]
W_{prod} : Total energy input during the production process. [MJ/MJ]
W_{loss} : Energy loss during the production. [MJ/MJ]
E_{tot} : Total CO_2-eq emissions including emissions during production. [g/km]
E_{car} : CO_2-eq emissions during driving. [g/km]
E_{prod} : CO_2-eq emissions during the production process. [g/MJ]

Reference Results	
Energy Consumption MJ/100 km	CO_2-equivalent g/km
259.3	197.3

Table 22.1. Results for the reference vehicle, PISI engine propelled on gasoline.

The result for the reference powertrain in this WTW-analysis is presented in table 22.1 and are based on the same vehicle as in the TTW-analysis using gasoline produced as described in the WTT-analysis and calculated using equations (22.1) to (22.3). By comparing the values in table 22.1 to the values presented in table 21.3 it can be seen that there is an increase of energy consumption and emissions by respectively 16% and 17%. The additional consumption and emissions is accordingly directly connected to the processing of the fuel.

There exist a complete list of all fuels in Appendix A where all abbreviations found in tables 22.2 to 22.6 are presented and Appendix C to Appendix E include basic production descriptions. By applying equations 22.1 to 22.3 to the values presented in the Well-to-Tank Analysis (Chapter 20) and the Tank-to-Wheel Analysis (Chapter 21), the total Well-to-Wheel result is generated for different fuel-powertrain combinations. The results are presented in tables 22.2 to 22.6.

By examining these tables it can be seen that the most influencing factor of the emissions is its origin and not the powertrain. Fuels derived from biomass have significant lower emissions than fossil fuels. On the other hand, biomass based fuels often has a poor energy efficiency. Ethanol from sugar beet pulp (EtOH_2) is the fuel with the least efficient production process. The total energy input is 237% higher than the reference propulsion system. A more likely way of producing ethanol in Europe is using popular wood (EtOH_3) or crop residues (EtOH_1). They have similar energy efficiency but significant differences in greenhouse gas emissions. This difference is because crop residues are waste material while popular wood has to be grown, maintained, and harvested. The biofuel that stands out, both in energy efficiency and emission values, is biomethane (CMG_1), with an energy consumption close to the reference vehicle and almost zero CO_2-equivalent emissions. It is in fact cleaner than most of the hydrogen operated powertrains.

It is important to note the difference between these tables and tables 21.4 to 21.6, where only the emissions during combustion was measured. The most significant difference can be found by comparing the emissions connected to hydrogen. The tank to wheel emission results for hydrogen was in a class by itself because hydrogen combustion mainly creates water. But by including the emissions connected to the production, as done in table 22.2 to 22.6, it can be seen that hydrogen created from natural gas is, second to gasoline, the fuel that generates the most GHG emissions of all fuels presented in table 22.2.

		Results		Comparison	
PISI	Source	Consump. [MJ/100 km]	CO_2-eq. [g/km]	Consump. [%]	CO_2-eq. [%]
Gasoline	Oil	220.4	165.2	-15	-16
EtOH_1	Bio	528.2	30.8	104	-84
EtOH_2	Bio	874.0	3.0	237	-98
EtOH_3	Bio	566.2	80.9	118	-59
EtOH_4	Bio	425.6	75.0	64	-62
CNG_1	NG	209.7	122.4	-19	-38
CNG_3	NG	230.3	137.9	-11	-30
CMG_1	Bio	277.1	1.6	7	-99
CGH2_1	NG	263.0	148.2	1	-25
CGH2_3	Bio	309.9	12.1	20	-94
CGH2_5	Bio	314.9	36.3	21	-82
CGH2_7	Bio	375.2	1.2	45	-99

Table 22.2. Overall energy consumption and emissions for evaluated fuels in PISI powertrain.

		Results		Comparison	
DISI	Source	Consump. [MJ/100 km]	CO_2-eq. [g/km]	Consump. [%]	CO_2-eq. [%]
Gasoline	Oil	218.0	163.4	-16	-17
EtOH_1	Bio	522.4	30.4	101	-85
EtOH_2	Bio	864.3	3.0	233	-98
EtOH_3	Bio	559.9	80.0	116	-59
EtOH_4	Bio	420.9	74.2	62	-62

Table 22.3. Overall energy consumption and emissions for evaluated fuels in DISI powertrain.

DICI	Source	Results Consump. [MJ/100 km]	 CO_2-eq. [g/km]	Comparison Consump. [%]	 CO_2-eq. [%]
Diesel	Oil	192.6	145.4	-26	-26
		197.7	149.1	-24	-24
BioDiesel_1	Bio	364.9	96.1	41	-51
		374.6	98.6	44	-60
BioDiesel_2	Bio	301.2	52.7	16	-73
		309.2	54.1	19	-73
DME_1	NG	278.8	166.0	8	-16
DME_2	Bio	356.2	9.7	37	-95
DME_3	Bio	356.2	13.8	37	-93
FT_1	NG	299.5	174.9	16	-11
		307.5	179.5	19	-9
FT_2	NG	289.1	170.2	11	-14
		296.9	174.7	15	-11
FT_3	Bio	383.8	17.4	48	-91
		394.0	17.8	52	-91

Table 22.4. Overall energy consumption and emissions for evaluated fuels in DICI powertrain. In case there are two values presented, the first value represents an engine configuration with diesel particulate filter (DPF) and the second value without DPF. DME does not require a DPF present due to the lack of soot generation.

Fuel Cell	Source	Results Consump. [MJ/100 km]	 CO_2-eq. [g/km]	Comparison Consump. [%]	 CO_2-eq. [%]
No Reformer					
CGH2_1	NG	147.8	82.9	-43	-58
CGH2_3	Bio	173.9	6.9	-33	-97
CGH2_5	Bio	176.7	20.1	-32	-90
CGH2_7	Bio	210.6	0.4	-19	-100
Reformer					
Gasoline	Oil	188.4	141.4	-27	-27
Diesel	Oil	181.7	137.9	-30	-29
MeOH_1	NG	239.8	146.7	-8	-24
MeOH_2	NG	238.3	149.1	-8	-35
MeOH_3	Bio	276.8	17.9	7	-91
MeOH_4	Bio	401.1	22.1	55	-89

Table 22.5. Overall energy consumption and emissions for evaluated fuels in FC powertrain.

		Results		Comparison	
Hybrid	Source	Consump. [MJ/100 km]	CO_2-eq. [g/km]	Consump. [%]	CO_2-eq. [%]
PISI					
Gasoline	Oil	186.6	140.8	-28	-29
CNG_1	NG	156.1	91.7	-40	-54
CMG_1	Bio	257.9	1.7	0	-99
CGH2_1	NG	233.1	131.5	-10	-33
CGH2_3	Bio	274.7	10.8	6	-95
CGH2_5	Bio	279.2	32.3	8	-84
CGH2_7	Bio	332.6	1.2	28	-99
DISI					
Gasoline	Oil	189.1	141.9	-27	-28
DICI					
Diesel	Oil	157.9	119.5	-39	-39
BioDiesel_1	Bio	299.1	79.1	15	-60
BioDiesel_2	Bio	246.9	43.5	-5	-78
DME_1	NG	228.6	136.3	-12	-31
DME_2	Bio	292.1	8.2	13	-96
DME_3	Bio	292.1	11.6	13	-94
FT_1	NG	245.5	142.0	-44	-28
FT_3	Bio	314.7	12.8	21	-94
FC, no Reformer					
CGH2_1	NG	131.4	73.8	-49	-63
CGH2_3	Bio	154.8	5.8	-40	-97
CGH2_5	Bio	157.4	17.9	-39	-91
CGH2_7	Bio	187.5	0.3	-28	-100

Table 22.6. Overall energy consumption and emissions for evaluated fuels in hybrid powertrain. The values represent an engine configuration without a diesel particulate filter present.

Part V

Analysis of Future Use and Production of Alternative Fuels and Powertrains in Sweden

Chapter 23

Analysis

The Swedish countryside varies greatly from north to south. In the south there is a well expanded agriculture landscape while in the north, forest occupies most of the land. There is also a differ in climate, while the ocean affects the temperature in the south, the north is more as an inland landscape with widely temperature differences between summer and winter. This makes it more profitable to practice agriculture in the southern regions.

Sweden is not evenly populated, though most of the populated area is in the southern regions. The driving of vehicles differs with population. The low population in the north generates big traveling distances while in the south, the transportation distance is often much shorter. Driving in the countryside most often contains relatively high, constant speed, while city driving includes multiple stops and low velocities at intersections, stop lights, queues etc., which leads to frequent idling.

As discussed earlier in this report the total energy efficiencies of the fuels are affected by the distance, the feedstock and the fuel are required to be transported. Placing filling stations close to the production facilities will improve the efficiency and thereby lowering the retail price and also reduce the generating of greenhouse gases. This would motivate to build several smaller fuel production facilities, but on the other hand bigger facilities often allows a greater efficiency than smaller and it has economical benefits to have one big production facility rather than several smaller concerning construction, operating, and maintenance expenses. This affects the retail price.

Highly populated areas, like cities, have trouble with soot (see section 16.2), due to the heavy traffic load. In Los Angeles this has led to strict regulations regarding soot formation and in Stockholm vehicles traveling into the central areas of the city must pay a fee. The goal for this is to ease the traffic load, not only for improvement of air quality but also to increase the passibility.

Because of the varying in population and climate, different fuels and propulsion systems are suitable in different regions. As most feedstock used for alternative fuel production either has compatible users or is limited in quantity, it is important to optimize the usage by minimizing unnecessary transports and use efficient powertrains that are suitable for where it is to be used. This part of the report will use the above factors and facts presented earlier in order to determine the best possible way to produce alternative fuels and propel Swedish vehicles. Fuel cells with reformer will not be considered as an option because the price is to high compared to the winning in efficiency and emissions. Neither will the HCCI engine due to the difficulty of controlling it results in a uncertainty for future commercial production.

23.1 Driving Scenarios

City driving contains low loads for the engine due to slow driving and idling. This implies that the engine should have good efficiency at low loads which exclude the use of PISI and DISI engines. The DICI engine has relatively good efficiency at low loads and should therefore be more suitable for cities. However, DICI engines using petro-diesel or diesel based on biomass have a tendency of forming soot which is a noteworthy drawback. The favorable properties of DME as low soot formation still allow the DICI engines to be a good alternative for city driving. More complex powertrains as hybrids or fuel cell vehicles are the two best alternatives for city operating vehicles as they have good energy efficiency at low loads and when standing still they do not consume any energy at all, except for minor tasks as for example air conditioning, dashboard etc. Hybrids are exceptionally suitable for city driving because of the braking, performed at intersections and traffic lights, which allows the regeneration of energy to charge the battery. The complement to the electric drive could be either a DICI or PISI engine. The greatest advantage of the DICI engine with good energy efficiency at low loads is redundant with use in a hybrid because the electric drive is operating in those regions. The advantage of low soot generation in PISI and DISI engines weighs heavier than the slightly higher energy efficiency of DICI engines. This makes the PISI and DISI engines more suitable for the complement to the electric drive in city driving.

When vehicles most part of the time are driven in the countryside, the speed is quite constant throughout the whole drive. Once again there is a matter of weighing soot generation against energy efficiency. The basic speed limit in Sweden is 70 km/h which represents a quite low engine load and the throttle in a PISI or DISI engine then generates a rather significant efficiency drop compared to the DICI engine. Concerning the emissions, the countryside does not have the same soot problem as cities because of the lighter traffic load. Using a hybrid system would further increase the efficiency and reduce the formation of soot but as the speed stays fairly even during the whole trip the winnings would be substantial smaller than when used in city driving. Fuel cell propelled vehicle would be optimal due to the high efficiency and clean emission.

23.2 Industrial Vehicles

Local vehicle fleets as city buses and company vehicles are most suitable for starting the conversion to an alternative fuel infrastructure due to the limited area they are operating in and that they often are big fuel consumers. City buses have the same routes everyday and always return to the base at the end of their shift. This does not require a high standard for the infrastructure, concerning availability. However, the reliability must be 100% because the loss of income for the companies if the vehicles are forced to stand still due to fuel shortage. It is a good way of starting up, improve, and practice the technologies until a public breakthrough. In order to convert an industrial vehicle fleet to alternative fuels there must be some winnings for the company, not necessarily direct economical winnings. For many companies it is important to appear as a environmental friendly company and uses this in its commercial interest. This might also affect the subcontractors causing a domino effect. The location of the first filling stations is immensely important. In order to convert vehicle fleets to alternative fuels the access to a filling station must be acceptable. The most profitable area to place a filling station is in industrial areas where often several vehicle fleets are located. If the fuel is a gaseous product this is especially important due to maximizing the use of each filling station might make it economical defensible to use pipelines instead of trailers to refill the station. This is good for the overall energy efficiency and the emissions connected to the transportation of the fuel.

The big distances in Sweden result in a big transportation fleet consisting of trucks. They travel for long distances mainly at their speed limit of 80 km/h. The size of the vehicle creates a big drag, with the result of a quite high engine load. One of the biggest expenses for the transportation companies is the fuel cost. The slightly higher efficiency of DICI engines than PISI engines lowers the fuel cost significantly, that is a reason to that almost all bigger vehicles use the DICI powertrain. To complement the DICI engine with an electric engine would improve the engines efficiency when driving in cities or societies, but as most of the journey is at constant speed this affect is redundant.

Agriculture machines, as tractors, often work in low load which is one reason the use of DICI engines. The driving scenario for an agriculture machine rarely consists of breaking with the result of no regeneration of energy is possible and therefore the use of a hybrid system is hard to motivate.

	Results			
	Consump. [MJ/100 km]	CO_2-eq. [g/km]	Source	Powertrain
CMG_1	277.1	1.6	Organic wastes	PISI
CGH2_7	375.2	1.2	Organic wastes	PISI
CGH2_3	309.9	12.1	Wood residues	PISI
DME_2	356.2	9.7	Wood residues	DICI
FT_3	383.8	17.4	Wood residues	DICI
EtOH_1	528.2	30.8	Crop residues	PISI
CGH2_5	314.9	36.3	Popular wood	PISI
BioDiesel_2	301.9	52.7	Rape seed	DICI
DME_3	356.2	13.8	Popular wood	DICI
EtOH_3	566.2	80.9	Dedicated crops	PISI

Table 23.1. Overall energy consumption and emissions for biomass based fuels in DICI or PISI powertrain.

23.3 Summary of Well-to-Wheel Analysis

Table 23.1 contains a summary of the well-to-wheel analysis and table 23.2 presents the energy conversion efficiency for the most interesting biomass based fuels. The fuels are divided into three sections depending on the origin of the fuel and are sorted in a declining efficiency order. The three origins are organic wastes, other residues and dedicated crops. All values presented in these tables are based on values presented in part "Well-to-Wheel Analysis" and the belonging appendixes. Methanol is not evaluated in the tank-to-wheel analysis which hinders presentation of well-to-wheel values. But as can be seen by comparing the tables, none of the presented fuels overtake one other regarding overall efficiency due to different powertrains. This implies that methanol should remain as the second most energy efficient fuel with its origin in wood residues. The following chapter includes a discussion of benefits and disadvantageous factors for each of these fuels.

	Efficiency [%]	Source
CMG_1	67.6	Organic wastes
CGH2_7	44.6	Organic wastes
CGH2_3	54.1	Wood residues
MeOH_3	53.5	Wood residues
DME_2	48.3	Wood residues
FT_3	44.8	Wood residues
EtOH_1	36.0	Crop residues
CGH2_5	53.2	Popular wood
BioDiesel_2	57.1	Rape seed
DME_3	48.3	Popular wood
EtOH_3	33.6	Dedicated crops

Table 23.2. Energy efficiency for production of biomass based fuels.

Chapter 24

End User Cost

It can be seen in table 24.1 that the retail price of alternative fuels is about the same as for petro-diesel and gasoline.

The retail price for future vehicles with alternative powertrains is of interest, because it directly affects the sales which limit the production quantities of the fuels. Alternative fuels are often tax reducted, but also the possession of an alternative fuel vehicle has its economical benefits as free parking, relieved road taxes among others. These things must meet the extra expense of purchasing an alternative fuel vehicle in order to make a commercial breakthrough. The results presented in this chapter only concern the major differences in expense of the vehicle as e.g. electric motor, batteries, fuel cells, fuel tank etc. Table 24.2 presents a forecast of prices for different powertrains in 2010 based on expected improvements. A more detailed description can be found in Appendix F.

As can be seen in table 24.2 the prices for ICE powertrains are not considerably higher when operating on alternative fuels than oil based fuels. This implies that only the price of the fuel hinders a commercial breakthrough for each fuel. All the ICE powertrains can be produced and presented to the public at a reasonable cost. The vehicles using gaseous fuels have their greatest expense in the fuel tank.

	Retail price		
	[SEK/dm^3]	[SEK/GJ]	[%]
Gasoline(95)	11.29	351	ref.
Diesel	11.29	314	-10.6
Biomethane	10.16 (per m^3)	311	-11.4
Biodiesel	10.45	317	-9.7
Ethanol(E85)	8.64	380	8.2

Table 24.1. Retail price for fuels at filling station. [34, Statoil, 2006-09-03]

	Fuel	Power [hp]	Cost [k€]	Diff. [%]	Uncertainty [%]
ICE					
PISI	Gasoline	103	19.560	ref.	-
DISI	Gasoline	94	19.850	1.5	± 5
PISI(dedicated)	CNG	114	21.513	10.0	± 5
PISI(bifuel)	CNG	103	22.098	13.0	± 5
DICI	Diesel	99	20.960	7.2	± 5
DICI+DPF	Diesel	99	21.360	9.2	± 5
DICI	DME	99	22.335	14.2	± 10
PISI	H_2	103	24.310	24.3	0 to 15
Hybrid ICE					
DISI	Gasoline	94+19	25.780	31.8	0 to 50
PISI	CNG	91+19	26.933	37.7	0 to 50
DICI	Diesel	99+19	27.190	39.0	0 to 50
DICI+DPF	Diesel	99+19	27.590	41.1	0 to 50
PISI	H_2	103+19	29.778	52.2	0 to 100
Fuel Cells					
FC	H_2	107(100)	31.193	59.5	0 to 100
FC hyb.	H_2	107(100)	34.505	76.4	0 to 100
Ref.+FC hyb.	Gasoline /Methanol	107(100)	43.895	124.4	0 to 100

Table 24.2. Prices of alternative propulsion system vehicles. [10, concawe EUCAR, 2006]

The cost for storing liquefied or compressed hydrogen is calculated to 575 € per kg fuel with the result in an expense of 5175 € for a 9 kg storage capacity of hydrogen. The price for DME or a CNG tank is considerable lower as they do not require as high pressure as hydrogen. The price for a DME tank is 1500 € and 1838 € for a CNG tank. Hybrids are more expensive as they have one ICE and one electric motor completed with additional powertrain equipment as a battery and a torque coupler. The greatest expense is the battery with a cost of 3600 €. The lifetime of a battery highly depends on the maintenance which relies on the control system. Most important is to always have a high charge in the battery with no deep discharges. The first serial manufactured hybrid is Toyota Prius which uses a NiMH battery. Toyota considers all the hybrid specific parts, as lifetime components and are delivered with a warranty of 8 years or 160000 km [35, Toyota, 2006]. Fuel cell operated vehicles are considerable more expensive than ICE:s mainly due to the cost of the fuel cell which is calculated to 8400 € and with the addition of a reformer the cost increases to 20080 €.

Chapter 25

Discussions of Different Powertrains and Fuels

This chapter will present a discussion of certain fuel- powertrain combinations. The starting point of the discussion is which fuel sources will be accessible in Sweden. The first priority is to use waste material, for example sewage and residual wood, to produce fuel, because they are not compatible resources. Residual wood will be separated from organic waste in this chapter to separate gasification and digestion processes. In order to minimize the Swedish reliability of fossil fuels, waste material must be complemented by farmed feedstock dedicated for fuel production.

25.1 Organic Waste

Biomethane can be generated from organic waste with good well-to-wheel result. The first step from organic waste by anaerobic digestion is biogas. The biogas can then either be purified into biomethane or transformed into synthesis gas which can be further processed into multiple fuels. Table 23.1 shows that hydrogen has slightly better emissions result while biomethane has significantly better efficiency result regarding the well-to-wheel analysis unless hydrogen is combusted in a fuel cell. Hydrogen will be discussed in section 25.2 so it will not be presented in this section.

25.2 Waste Wood

Waste wood can be used to produce DME, FT-diesel, methanol, ethanol, hydrogen, and biomethane. The path from wood to biomethane is not evaluated in this report. Hydrogen and methanol have the greatest well-to-tank results with a small advantage for hydrogen.

25.3 Dedicated Crop

Farmed feedstock as salix and rape are competitive regarding cultivation of land. The farmer is most likely to grow the crop that has the greatest economical benefits. Therefore it is crucial to produce as much fuel as possible from each cultivated acre of feedstock both regarding the price and to maximize the amount of biomass based fuels on the market. Salix is strictly grown to produce energy. Either it is burned to produce heat and electricity or it is further processed into a vehicle fuel. Rape and wheat on the other hand are a part of the human food chain which increases the price. Salix, rape, or wheat cultivation is not profitable in the northern part of Sweden, but there is another sort of energy crop known as "reed phalaris" which can be grown there. The outcome is not as good as for salix but still as high as 140.4 GJ/(ha·year). Reed phalaris can be used as a feedstock both for ethanol and synthesis gas production.

25.4 Biomethane

Biomethane is a gaseous product and has a low energy density regarding volume. This yields in a limited transportation potential both regarding economical and efficiency issues. The biomethane producers use truck transport to areas where there is a possibility of building a biomethane plant in a close future. Long transportation distances will increase the cost for the companies which lead to a higher retail price for biomethane. Biomethane propelled vehicles are more expensive than vehicles propelled by a liquid fuel, mainly due to the need for a pressurized tank. This gap must close during the use of the vehicle in order for customers to choose biomethane propelled vehicles. It can be seen in table 24.1 that biomethane is cheaper, regarding equivalent amount of energy, than gasoline or diesel. This makes it profitable to purchase a biomethane propelled vehicle. If the biomethane companies start to transport biomethane long distances the retail price will rise and the extra expense of purchasing a biomethane propelled vehicle will be harder to recover.

The feedstock is created in big quantities and densities in the cities and therefore the transportation distances can be kept short. The primal target should be vehicle fleets operating inside or close to the city boundaries. If most of the cities contain a biomethane production facility and the quantity of fuel allows greater expansion outside local fleets, a commercial breakthrough is possible in the southern region of Sweden. This because distances between cities are relatively short with the effect that biomethane propelled vehicles can travel freely in those regions. Also by limiting the number of fuel stations the usage of each is maximized and if there is a big enough usage of the biomethane fuel stations this would motivate pipeline transportation. It would increase efficiency as well as lower the greenhouse gas emissions. If biomethane can be produced in a quantity that exceeds the demand of biomethane in the cities it is of interest to transport biomethane to lower populated areas.

Biomethane is used in PISI powertrains which has lower efficiency than DICI powertrains, but complementing with an electric motor reduces this difference. The hybrid system is utterly suitable for city driving due to the frequent use of the brake where energy can be regenerated and the electric motor is sufficient in the low engine load city driving often contains. The soot problems in the bigger cities would be eased when use of this powertrain and the use of biomethane will also almost entirely remove the overall greenhouse gas emissions. In the south of Sweden and along the west coast natural gas has an infrastructure that could be used for biomethane which in general is the same as refined natural gas. Vehicle propelled on biomethane can also use refined natural gas and vice versa. Biomethane production facilities have limited production quantities which only can supply a certain number of vehicles and if that number is exceeded a new plant must be built. This would lead to a surplus of biomethane, but as natural gas can be used to fill in the shorting in quantities the build of the extra biomethane production facility can wait until it is economical profitable, making the transfer period a lot smother.

25.5 Hydrogen

The transportation of hydrogen is a problem, both regarding the low volumetric energy density, which is the lowest of all evaluated fuels, and the explosiveness of the fuel. The amount of energy needed for igniting hydrogen is only 8% of that of gasoline which has the second lowest requirement of energy for ignition. In case of an accident in transportation, for example a tank that fails, with the result of a severe leak, a liquid fuel would spill to the ground only forming a combustible mixture on the surface where the fuel diffuses, while a gaseous product would form a big combustible volume in the air. With the low energy demand for ignition of hydrogen it is likely there would be an explosion, while a liquid fuel rather would form a fire. Methane also has this safety issue but the energy requirement for ignition is 15 times higher than that of hydrogen and the interval where the mixture of air and methane is combustible are about one seventh of that of hydrogen and air. This sets high safety standards to both the hydrogen transportation tankers and the tanks located in the vehicles, which affect the retail price of hydrogen as well as the hydrogen propelled vehicles. As can be seen in chapter 24, the price estimation for a vehicle tank containing 9 kg of hydrogen is over 5000€. This can be compared to the retail price for an average vehicle today which is bit above 20000€. The additional price of a hydrogen tank is considerable which together with the assumption that hydrogen will remain expensive makes it hard to economically motivate the purchase of a hydrogen propelled vehicle. Also the expense of a fuel cell operating on any fuel is not economical and will probably not be so in a nearby future, unless great breakthroughs in the fuel cell technology.

25.6 Methanol and Ethanol

Methanol is a really good alternative fuel based on the well-to-tank results and the properties presented so far in this report. The same infrastructure as for gasoline can be used for methanol and the high octane rating suggests a high efficiency when used in ICE engines. The technology for using methanol in engines exists as it is most often used in remote controlled toys but more importantly in different racing events, for example Indy Racing League. There are disadvantages for methanol as corrosiveness both to the metal parts and gaskets of the engine and its intoxicating to humans. These unmeritorious factors have instead led to usage and development of ethanol which is gentler to the engine and is not that toxic to humans. Both fuels are used in the PISI engine which is the most common powertrain in modern vehicles. The reason why ethanol can not easily be considered the better fuel of the two is the significant differ in well-to-tank results. In order to produce the same amount of fuel, regarding energy content, ethanol (EtOH_1) requires twice as much energy input than in production of methanol (MeOH_3). Ethanol also has a cold start problem when used in vehicles. The low evaporation rate of ethanol causes troubles in the winter. Sweden does not use pure ethanol but instead uses E85 which is a mixture of 85% ethanol and 15% gasoline. This increases the evaporation rate. The common solution to the cold start troubles is to inject loads of fuel at time of start in order to increase the amount of evaporated fuel. There are also discussions about using E75 in the winter but the most energy efficient and environmental friendly solution is to use direct injection that increases the evaporation rates due to the formation of droplets in the injection nozzles and allows use of pure ethanol. Methanol for use in PISI or DISI engines is not included in the tank-to-wheel analysis, but the similarity to gasoline and ethanol, especially regarding octane rating, should put an engine fed with methanol in the same energy efficiency as those. The higher density of oxygen in methanol might even improve the emissions.

25.7 DME

Biomethane, hydrogen, methanol and ethanol all work in a PISI engine with the advantage of low soot formation. The poor efficiency of the engine is however a significant drawback compared to the DICI engine which on the other hand has problem with soot and NO_x in the emissions.

DME combines the advantageous efficiency of a DICI engine with low soot and NO_x formation. A control strategy known as Exhaust Gas Recirculation (EGR) is used in order to lower the NO_x emissions of a DICI engine. Recirculating the exhaust gases yields in a lower temperature inside the cylinder, the more exhaust gases present the lower the temperature. NO_x generation occurs in high temperature, so by lowering the temperature, the NO_x formation is reduced. The drawback of this strategy is that soot formation increases with falling temperature which limits the amount of recirculated exhaust gases for diesel fuels. The lack of carbon-carbon bindings and the high density of oxygen in DME result in no soot formation. This allows a big amount of recirculated exhaust gases in order to further reduce the NO_x formation compared to other diesel fuels. The well-to-wheel result for DME is second to biodiesel in energy efficiency and best in GHG emissions when concerning biomass based fuels suitable for DICI engines. As discussed earlier DME is a gas but is liquefied under a pressure of 5 bar. This can be compared to biomethane that is transported under a pressure of about 200 bar or hydrogen under a pressure of between 400 and 700 bar. The result is a cheaper pressurized tank than for the other gaseous fuels and is estimated to 1500€. The overall cost of the vehicle is estimated to be about 14% higher than the reference vehicle and 7% higher than the diesel operated vehicle (See Appendix F for a detailed description of estimated costs.). There are some safety issues regarding DME, in addition to those discussed earlier for gaseous products. DME is heavier than air, in contrast to biomethane and hydrogen which is lighter than air. In case of a severe leak in for example the transportation container, hydrogen and biomethane would rise up into the atmosphere while DME would fall to the ground creating puddles of fuel. This causes an increased explosion risk due to DME will remain on the ground until something ignites it or until the area is sanitized, while biomethane and hydrogen will vanish if they are not ignited directly.

25.8 Biodiesel and FT-diesel

Other biomass based fuels suitable for DICI engines are biodiesel and FT-diesel. Both are worthy replacements to petro-diesel regarding infrastructure and compatibility to the existing diesel vehicles. Biodiesel has higher energy efficiency while FT-diesel is cleaner regarding greenhouse gas emissions. Mainly this is caused by the FT-diesel considered in this study come from residual wood and not farmed feedstock as biodiesel has its origin in. This is recurringly for all fuels; the energy efficiencies are similar but the emissions are higher when using farmed feedstock than when use of residual products. This is because the emissions generated during the cultivation of the land. The infrastructure already exists for these fuels as there are great similarities to petro-diesel and the ordinary diesel engine only needs small modifications as gasket changes to be converted for use of biomass based diesel. The main difference between biodiesel and FT-diesel is its origin. Biodiesel is produced from rapeseed while FT-diesel is produced from popular wood (Salix) or waste wood. Biodiesel can also be produced from sunflowers and soybeans, but rapeseed has the greatest energy efficiency, the highest energy density and is also the most suitable for cultivation in the Swedish climate. The higher energy efficiency of biodiesel from rapeseed compared to FT-diesel, with its origin in Salix, is not necessarily that interesting. The well-to-tank result does not include the first energy conversion, plants uses energy from the sun to grow and encapsulate some of the energy in itself. The higher efficiency the plants have of binding solar energy the faster they grow. Salix grows significantly faster than the rapeseed plant which implies that the energy conversion for salix is greater than for rapeseed. Instead of only examining the energy conversions for the production facilities it is of greater interest to also include the amount of each feedstock that can be harvested per hectare and year. According to [28, Agriwise, 2006] salix produces 180 GJ/(ha·year) while rape only produce 75.6 GJ/(ha·year). By assuming that all the energy input in respective process is the feedstock, the resulting fuel production per hectare and year is 2.23 m^3 or 80.72 GJ of FT-diesel and 1.31 m^3 or 43.2 GJ of biodiesel.

Chapter 26

Summary

This report has presented properties and basic production process information in *Part II* for most of the fuels which may propel our vehicles in the future. *Part III* includes an introduction to the technologies found in modern powertrains along with their advantages and drawbacks. The result from two well-to-wheel analyses has been presented in *Part IV* and used in order to compare different fuels and powertrains to each other. The analysis in *Part V* used the information presented in previous parts to different driving scenarios in order minimize emissions and cost for a future infrastructure in Sweden.

26.1 Conclusions

The facts presented in this report have shown that gaseous fuels have benefits regarding well-to-wheel efficiency and emissions. Biomethane should be produced by organic waste while wood should be transformed to into hydrogen. Taking into account the infrastructural difficulties concerning gaseous fuel this scenario is not likely in a close future. Liquid fuels have great advantages regarding low cost equipment connected to transportation, filling procedure and storage, compared to the equipment needed for handling gaseous fuels. Although hydrogen can be used in ICE engines it will not enter the market until the fuel cells meets the durability and economical demands of the vehicle market. The significantly better well-to-wheel result for biomethane compared to the liquid biomass based fuels will most likely result in an increase usage of biomethane in the next couple of years. However, there is one factor that may hinder the expansion of biomethane usage, and that is the expansion of ethanol usage. Ethanol has the worst well-to-wheel result of all biomass based fuels, but the similarity to gasoline and the access to imported ethanol have caused that filling station companies and the vehicle industry to choose to target ethanol as the primary biomass based fuel. The result of this is that ethanol may hinder expansion of other biomass based fuels. FT-diesel and biodiesel are both worthy supplements for fossil diesel and they may widely enter the market in few years.

26.2 Acknowledgments and Reservations

This report has presented values in the well-to-wheel analysis which has been used as a base for the analysis of future fuel usage. However, the analysis of future fuel usage has not categorized the fuels based on the exact values but rather only if the well-to-wheel outcome has shown significant differences between the fuels. Because of this the analysis of future fuel usage should be rather insensitive for efficiency changes in the production processes and powertrains. There are two areas that the outcome of this report is sensitive to and that is if fuel cells can be manufactured at a low cost and with an acceptable durability along with that the infrastructure issues for hydrogen is solved. The second area the outcome of this report is sensitive to is politics. If new emission regulations are initiated this may require a rapid alteration of fuel usage. This will benefit fuels which already have well defined production processes as i.e. ethanol while FT-diesel and DME production which still is under development may be pushed aside.

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Appendix A

Fuels

Fuels			
	Table	Source	Remark
BioDiesel_1	E.7	Biomass	Glycerin
BioDiesel_2	E.7	Biomass	Glycerin Replacement
CGH2_1	D.8	NG	EU-mix, 45 MPa
CGH2_2	D.8	NG	EU-mix, 88 MPa
CGH2_3	E.1	Biomass	Woody Residues, 45 MPa
CGH2_4	E.1	Biomass	Woody Residues, 88 MPa
CGH2_5	E.2	Biomass	Popular Wood, 45 MPa
CGH2_6	E.2	Biomass	Popular Wood, 88 MPa
CGH2_7	E.3	Biomass	Organic Waste, 45 MPa
CGH2_8	E.3	Biomass	Organic Waste, 88 MPa
CMG_1	E.8	Biomass	-
CNG_1	D.1	NG	EU-mix, 4 MPa
CNG_2	D.1	NG	EU-mix, 0.1 MPa
CNG_3	D.2	NG	LNG
DME_1	D.9	NG	-
DME_2	E.9	Biomass	Crop Residues
DME_3	E.10	Biomass	Popular Wood
EtOH_1	E.5	Biomass	Crop Residues
EtOH_2	E.5	Biomass	Sugar Beet Pulp
EtOH_3	E.5	Biomass	Popular Wood
EtOH_4	E.5	Biomass	Sugar Beet
FT_1	D.5	NG	EU-mix
FT_2	D.6	NG	Maritime
FT_3	E.6	Biomass	-
MeOH_1	D.3	NG	EU-mix
MeOH_2	D.4	NG	Maritime
MeOH_3	E.4	Biomass	Allothermal
MeOH_4	E.4	Biomass	Autothermal

Table A.1. Abbreviations used throughout this report for different fuels produced in various ways.

Appendix B

Reference Vehicle

	Value	Unit
Curb weight	1181	[kg]
Weight class	1250	[kg]
Drag coefficient	0.321	-
Front area	2.1	[m^2]
Tire radius	0.309	[m]
Tire inertia	0.7	[$kg\cdot m^2$]
Engine displacement	1.6	[l]
Engine inertia	0.125	[$kg\cdot m^2$]
Efficiency differential + gear	90	[%]
Transmission ratio of differential gear	4.25	-
Transmission ratio:		
Gear 1	3.455	-
Gear 2	1.944	-
Gear 3	1.370	-
Gear 4	1.032	-
Gear 5	0.850	-

Table B.1. Definition of reference vehicle. [10, concawe EUCAR, 2006]

Appendix C

WTT Oil

Scenario:

Crude oil is delivered to Europe via maritime vessels where it's refined to gasoline diesel and naphtha in a nearby refinery. The fuels are then transported to a depot via pipeline, inland shipping or railroad tank trailer. The transport to the refueling station is done with tank trailer trucks averaging 150 km.

Crude Oil Extraction			
	Input	Output	Unit
Crude Oil	1,025	1,000	[MJ/MJ]
CO_2-equivalent	-	3.3	[g/MJ]

Table C.1. Energy requirement and GHG-emissions connected to the extraction of crude oil. [21, General Motors, 2002]

Maritime Transportation			
	Input	Output	Unit
Heavy Fuel	0,010	-	[MJ/MJ]
Crude Oil	1,000	1,000	[MJ/MJ]
CO_2-equivalent	-	0.8	[g/MJ]

Table C.2. Energy requirement and GHG-emissions connected to the transporting of crude oil from the oil field to the refinery. [21, General Motors, 2002]

	Gasoline		Diesel		
	Input	Output	Input	Output	Unit
Crude Oil	1,1	-	1.06	-	[MJ/MJ]
Fuel	-	1,000	-	1.000	[MJ/MJ]
CO_2-equivalent	-	7.4	-	4.7	[g/MJ]

Table C.3. Energy requirement and GHG-emissions connected to the refining process of crude oil to gasoline and diesel. [21, General Motors, 2002]

Fuel Storage and Transport			
	Input	Output	Unit
Energy consumption	0.02	-	[MJ/MJ]
Fuel	1.00	1.00	[MJ/MJ]
CO_2-equivalent	-	1.1	[g/MJ]

Table C.4. Energy requirement and GHG-emissions connected to the storaging and distribution of gasoline, diesel and naphtha. [21, General Motors, 2002]

EURO 4		
Fuel Consumption (Diesel)	12.6	[MJ/km]
CO_2	938	[g/km]
CH_4	0.065	[g/km]
Payload	26	[t]

Table C.5. EURO 4 limits and truck assumptions. [21, General Motors, 2002]

Appendix D

WTT Natural Gas

D.1 Compressed Natural Gas

Scenario:

EU-mix from natural gas is delivered to the refueling station with a suction pressure of either 4 MPa or 0.1 MPa and fueling the vehicle via a 25 MPa discharge.

	4 MPa [CNG_1]		0.1 MPa [CNG_2]	
	Energy Loss [MJ/MJ$_{\mathrm{CNG}}$]	CO_2-eq [g/MJ$_{\mathrm{CNG}}$]	Energy Loss [MJ/MJ$_{\mathrm{CNG}}$]	CO_2-eq [g/MJ$_{\mathrm{CNG}}$]
NG EU-mix	0.09	6.5	0.09	6.6
Low Pressure Distribution	-	-	0.01	2.9
Filling station	0.03	1.4	0.11	4.9
Total	0.12	7.9	0.20	14.3

Table D.1. Energy loss and GHG-emissions connected to the extraction, transportation/distribution, storage and refueling of compressed natural gas. [21, General Motors, 2002]

Scenario:

Natural gas is liquefied close to the natural gas field and transported over 10.200 km via maritime vessels to European ports where the LNG is further transported by trailer trucks averaging 500 km to a filling station. There the LNG is evaporated into CNG and the vehicle refueling is carried out using a 25 MPa discharge pressure.

	[CNG_3]	
	Energy Loss [MJ/MJ$_{\mathrm{CNG}}$]	CO_2-eq g/MJ$_{\mathrm{CNG}}$]
NG-extraction and processing	0.02	3.2
Liquefaction	0.08	5.3
LNG terminal	0.01	0.7
Maritime LNG transport	0.07	4.7
LNG terminal	0.01	0.7
Trailer truck transport	0.02	1.2
Refueling station	0.01	0.4
Total	0.23	16.2

Table D.2. Energy loss and GHG-emissions connected to the overall process from extraction to refueling of natural gas with the intermediate process of liquefaction. [21, General Motors, 2002]

D.2 Methanol

In this section two possible routes will be investigated, methanol production of natural gas from the European natural gas mix or methanol production in a foreign location close to a natural gas field and transported to Europe via maritime vessels.

Scenario:

European natural gas mix(EU-mix) is processed to methanol in a methanol synthesis plant and transported by pipelines, inland ships or railroad tankers to a depot from where it's distributed to filling station using trailer trucks averaging 150 km.

	[MeOH_1]	
	Energy Loss [MJ/MJ_{MeOH}]	CO_2-eq [g/MJ_{MeOH}]
EU-mix	0.13	9.5
MeOH plant	0.46	13.9
Distribution	0.03	1.7
Total	0.62	25.2

Table D.3. Energy loss and GHG-emissions connected to the overall process from extraction to methanol at refueling station with the intermediate step of EU-mix. [21, General Motors, 2002]

Scenario:

Methanol is produced close to a natural gas field in a self sufficient synthesis plant and transported over 10200 km via maritime vessels to a European port where it's stored in a depot until the last distribution to refueling stations averaging 500 km, which is carried out by trailer trucks.

	[MeOH_2]	
	Energy Loss [MJ/MJ_{MeOH}]	CO_2-eq [g/MJ_{MeOH}]
NG-extraction and processing	0.03	4.1
MeOH plant	0.46	13.9
Maritime MeOH transport	0.08	5.9
Distribution	0.04	2.9
Total	0.61	26.8

Table D.4. Energy loss and GHG-emissions connected to the overall process from extraction to methanol at refueling station with the intermediate step of maritime transport. [21, General Motors, 2002]

D.3 FT Diesel

FT-diesel from natural gas follows the same two scenarios and routes as methanol, therefor no extensive explanations will be presented. The results are displayed in table D.5 for the scenario including EU-mix natural gas and in table D.6 for the scenario of conversion close to a natural gas field.

	FT-diesel [FT_1]	
	Energy Loss [MJ/MJ$_{\text{FT-diesel}}$]	CO_2-eq [g/MJ$_{\text{FT-diesel}}$]
NG EU-mix	0.14	10.4
FT-diesel plant	0.59	18.4
Distribution	0.02	1.1
Total	0.74	29.8

Table D.5. Energy loss and GHG-emissions connected to the overall process from extraction natural gas to FT-diesel at refueling station. [21, General Motors, 2002]

	FT-diesel [FT_2]	
	Energy Loss [MJ/MJ$_{\text{FT-diesel}}$]	CO_2-eq [g/MJ$_{\text{FT-diesel}}$]
NG Extraction and Processing	0.03	4.4
FT-Diesel Plant	0.59	18.4
Maritime MeOH transport	0.04	2.8
Distribution	0.03	1.6
Total	0.68	27.1

Table D.6. Energy loss and GHG-emissions connected to the overall process from extraction to FT-diesel at refueling station with the intermediate step of maritime transport. [21, General Motors, 2002]

D.4 Hydrogen

Conversion of NG to Hydrogen			
	Input	Output	Unit
Natural Gas	1.417	-	[MJ/MJ]
Hydrogen	-	1,000	[MJ/MJ]
Heat	-	0.150	[MJ/MJ]
CO_2	-	288	[g/MJ]
CH_4	-	0.057	[g/MJ]

Table D.7. Energy requirement and GHG-emissions connected to the conversion of natural gas into hydrogen. [21, General Motors, 2002]

There are two different pressure levels at the filling stations hence vehicle tanks either has a pressure of 35 MPa or 70 MPa at 15°C. The quite big margin between vehicle tank pressure and the pressure at the filling station is necessary because the increase of temperature due to the filling procedure. In order to compress the hydrogen, electricity demanding compressors is used which require, respectively, 0.018 $\mathrm{kWh_{El}}$ and 0.021 $\mathrm{kWh_{El}}$ per $\mathrm{MJ_{CGH2}}$. Table D.8 shows energy loss and GHG-emissions for the entire route.

Scenario:

European natural gas mix (EU-mix) is processed to compressed hydrogen (CH_2) in a central facility including steam export and distributed via pipelines averaging 50 km to a filling station with a suction pressure of 1.5 MPa and pressurized to either 45 MPa or 88 MPa and dispensed into vehicle tanks.

	45 MPa [CGH2_1]	
	Energy Loss [MJ/MJ_{CGH2}]	CO_2-eq [g/MJ_{CGH2}]
NG EU-mix	0.11	8.3
Hydrogen Plant	0.26	71.7
Distribution	0.00	0.0
Filling Station	0.20	8.2
Total	0.57	88.2

	88 MPa [CGH2_2]	
	Energy Loss [MJ/MJ_{CGH2}]	CO_2-eq [g/MJ_{CGH2}]
NG EU-mix	0.11	8.3
Hydrogen Plant	0.26	71.7
Distribution	0.00	0.0
Filling station	0.24	9.9
Total	0.61	89.9

Table D.8. Energy loss and GHG-emissions connected to the overall process from extraction of natural gas to compressed hydrogen at refueling station. [21, General Motors, 2002]

D.5 DME

Scenario:

Natural gas is piped 4000 km to a DME plant from where it's distributed to a filling station and dispensed.

	DME [DME_1]	
	Energy Loss [MJ/MJ$_{\mathrm{DME}}$]	CO$_2$-eq [g/MJ$_{\mathrm{DME}}$]
Supply and Production	0.59	26.4
Distribution and Dispensing	0.03	1.7
Total	0.62	28.1

Table D.9. Energy loss and GHG-emissions connected to producing, distributing and dispensing DME from natural gas. [11, concawe EUCAR, 2006]

Appendix E

WTT Biomass

E.1 Compressed Hydrogen

Scenario:

Residual woody biomass is transported 50 km to an allothermal gasification plant where it's converted to compressed hydrogen and distributed by pipelines to a filling station located 10 km away. The hydrogen is dispensed to a vehicle with a pressure of either 45 MPa or 88 MPa.

	45 MPa [CGH2_3]		88 MPa [CGH2_4]	
	Energy Loss [MJ/MJ$_{CGH2}$]	CO_2-eq [g/MJ$_{CGH2}$]	Energy Loss [MJ/MJ$_{CGH2}$]	CO_2-eq [g/MJ$_{CGH2}$]
Supply	0.10	6.2	0.10	6.3
Gasification	0.51	-0.1	0.51	-0.2
Distribution	0.23	0	0.26	0
Filling station	0	0.9	0	1.0
Total	0.85	6.9	0.88	7.1

Table E.1. Energy loss and GHG-emissions connected to producing and distribute compressed hydrogen from residual woody biomass. [21, General Motors, 2002]

Scenario:

Biomass from popular wood is transported 50 km to a allothermal gasification plant where it's converted to compressed hydrogen and distributed by pipelines to a filling station located 10 km away. The hydrogen is dispensed to a vehicle with a pressure of either 45 MPa or 88 MPa.

	45 MPa [CGH2_5]		88 MPa [CGH2_6]	
	Energy Loss [MJ/MJ_{CGH2}]	CO_2-eq [g/MJ_{CGH2}]	Energy Loss [MJ/MJ_{CGH2}]	CO_2-eq [g/MJ_{CGH2}]
Supply	0.14	22.1	0.15	22.6
Gasification	0.50	-3.2	0.50	-3.7
Distribution	0.24	0	0.27	0
Filling station	0	2.5	0	2.9
Total	0.88	21.4	0.92	21.8

Table E.2. Energy loss and GHG-emissions connected to producing and distributing compressed hydrogen from popular wood. [21, General Motors, 2002]

Scenario:

Organic waste is converted to biogas using fermentation and distributed via pipelines to a filling station where it's reformed into hydrogen and compressed to either 45 MPa or 88 MPa and dispensed to a vehicle.

	45 MPa [CGH2_7]	
	Energy Loss [MJ/MJ$_{CGH2}$]	CO$_2$-eq [g/MJ$_{CGH2}$]
Biogas plant	0.63	-83.4
Distribution	0.00	0
Reforming	0.50	83.7
Compression and Dispensing	0.10	0.1
Total	1.24	0.4

	88 MPa [CGH2_8]	
	Energy Loss [MJ/MJ$_{CGH2}$]	CO$_2$-eq [g/MJ$_{CGH2}$]
Biogas plant	0.63	-83.4
Distribution	0.00	0
Reforming	0.50	83.7
Compression and Dispensing	0.12	0.1
Total	1.25	0.4

Table E.3. Energy loss and GHG-emissions connected to producing, distributing and dispensing compressed hydrogen organic waste. [21, General Motors, 2002]

E.2 Methanol

Scenario:

Biomass from residual wood is transported 50 km to a gasification plant where it's converted to synthesis gas followed by the methanol synthesis and distributed to a filling station via truck trailers averaging 150 km.

	Allothermal [MeOH_3]		Autothermal [MeOH_4]	
	Energy Loss [MJ/MJ$_{\mathrm{MeOH}}$]	CO_2-eq [g/MJ$_{\mathrm{MeOH}}$]	Energy Loss [MJ/MJ$_{\mathrm{MeOH}}$]	CO_2-eq [g/MJ$_{\mathrm{MeOH}}$]
Supply	0.09	5.4	0.13	22.6
Gasification	0.76	-68.4	1.56	-68.1
Distribution	0.02	1.2	0.02	1.2
Total	0.87	-61.8	1.71	-59.0

Table E.4. Energy loss and GHG-emissions connected to producing and distributing methanol from residual woody biomass. [21, General Motors, 2002]

E.3 Ethanol

Scenario:

Biomass from crop residues/sugar beet pulp/popular wood is transported 50 km to a plant where it's converted to ethanol and distributed to a filling station via truck trailers averaging 150 km.

	Crop Residues [EtOH_1]	
	Energy Loss $[\mathrm{MJ/MJ_{EtOH}}]$	CO_2-eq $[\mathrm{g/MJ_{EtOH}}]$
Supply	0.09	6.2
Gasification	1.67	-62.8
Distribution	0.02	0.9
Total	1.78	-55.7

	Sugar Beet Pulp [EtOH_2]	
	Energy Loss $[\mathrm{MJ/MJ_{EtOH}}]$	CO_2-eq $[\mathrm{g/MJ_{EtOH}}]$
Supply	-	-
Gasification	3.58	-71.3
Distribution	0.02	0.9
Total	3.60	-70.3

	Dedicated Crop Plantation [EtOH_3]	
	Energy Loss $[\mathrm{MJ/MJ_{EtOH}}]$	CO_2-eq $[\mathrm{g/MJ_{EtOH}}]$
Supply	0.19	29.9
Gasification	1.77	-60.1
Distribution	0.01	0.9
Total	1.98	-29.3

	Sugar Beet [EtOH_4]	
	Energy Loss $[\mathrm{MJ/MJ_{EtOH}}]$	CO_2-eq $[\mathrm{g/MJ_{EtOH}}]$
Supply	0.21	37.4
Fermentation	1.01	-70.7
Distribution	0.02	0.9
Total	1.24	-32.4

Table E.5. Energy loss and GHG-emissions connected to producing and distributing ethanol from different sources. [21, General Motors, 2002]

E.4 FT-Diesel

Scenario:

Residual wood is transported 50 km to a biomass plant where it's converted to diesel via FT-synthesis and distributed to a filling station via truck trailers averaging 150 km.

	[FT_3]	
	Energy Loss [MJ/MJ_{Diesel}]	CO_2-eq [g/MJ_{Diesel}]
Supply	0.08	5.1
Processing	1.14	-67.5
Distribution	0.01	0.7
Total	1.23	-61.7

Table E.6. Energy loss and GHG-emissions connected to producing and distributing diesel from residual woody biomass. [21, General Motors, 2002]

E.5 Biodiesel

Scenario:

Rapeseed or sunflower seed is collected and transported 50 km to a processing plant where it's converted to diesel and distributed to a filling station via truck trailers averaging 150 km.

	[BioDiesel_1] Glycerin Heat Credit		[BioDiesel_2] Glycerin replacement Material Credit	
	Energy Loss [MJ/MJ_{Diesel}]	CO_2-eq [g/MJ_{Diesel}]	Energy Loss [MJ/MJ_{HC}]	CO_2-eq [g/MJ_{Diesel}]
Supply	0.29	61.7	0.29	61.7
Processing	0.82	-83.5	0.44	-108.6
Distribution	0.01	0.4	0.01	0.4
Total	1.12	-21.4	0.75	-46.6

Table E.7. Energy loss and GHG-emissions connected to producing and distributing diesel from vegetable oil. [21, General Motors, 2002]

E.6 Biomethane

Scenario:

Organic waste is converted to biomethane via fermentation and purification and distributed through pipelines to a filling station where it's compressed to 25 MPa and dispensed to a vehicle.

	Biomethane [CMG_1]	
	Energy Loss [MJ/MJ$_{CMG}$]	CO_2-eq [g/MJ$_{CMG}$]
Biogas Plant	0.43	-56.8
Distribution	0	0
Filling Station	0.05	0.1
Total	0.48	-56.7

Table E.8. Energy loss and GHG-emissions connected to producing, distributing and dispensing biomethane. [21, General Motors, 2002]

E.7 DME

Scenario:

DME is produced from wood residuals and transported to a refueling station where it is dispensed.

	[DME_2] Energy Loss [MJ/MJ$_{DME}$]	 CO_2-eq [g/MJ$_{DME}$]
Supply and Production	1.05	-63.8
Distribution and Refueling	0.02	1.0
Total	1.07	-62.7

Table E.9. Energy loss and GHG-emissions connected to producing, distributing and dispensing DME from wood waste. [11, concawe EUCAR, 2006]

Scenario:

DME is produced from popular wood and transported to a refueling station where it is dispensed.

	[DME_3] Energy Loss [MJ/MJ$_{DME}$]	 CO_2-eq [g/MJ$_{DME}$]
Supply and Production	1.05	-61.3
Distribution and Refueling	0.02	1.0
Total	1.07	-60.3

Table E.10. Energy loss and GHG-emissions connected to producing, distributing and dispensing DME from popular wood. [11, concawe EUCAR, 2006]

Appendix F

Prices for Different Vehicles

	Gasoline		Diesel	
	PISI ref.	DISI	DICI +DPF	DICI
Engine Power [hp]	103	94	99	99
Baseline Vehicle	18.600	18.600	20.300	20.300
Baseline Engine + transmission	-2.310	-2.310	-3.720	-3.720
Alternative Engine + transmission	2.770	3.060	3.780	3.780
Stop and Go System	200	200	300	300
Euro IV Exhaust Treatment	300	300	700	300
Total Price [k€]	19.560	19.850	21.360	20.960
Diff. from ref. [%]	ref.	1.5	9.2	7.2

Table F.1. Prices of Internal Combustion Engines Vehicles.[10, concawe EUCAR, 2006]

		CNG		H_2	DME
		PISI dedicated	PISI bi-fuel	PISI	DICI
Engine Power	[hp]	114	103	103	99
Baseline Vehicle		18.600	18.600	18.600	20.300
Baseline Engine + transmission		-2.310	-2.310	-2.310	-3.720
Alternative Engine + transmission		3.010	2.770	2.770	3.780
Gasoline Tank		-125	-	-	-
Alternate Tank		1.838	1.838	5.175	1.500
Stop and Go System		200	200	300	300
Euro IV Exhaust Treatment		300	300	700	300
Double Injection System		-	700	-	-
Total Price	[k€]	21.513	22.098	24.310	22.335
Diff. from ref.	[%]	10.0	13.0	24.3	14.2

Table F.2. Prices of Internal Combustion Engine Vehicles.[10, concawe EUCAR, 2006]

	Gasoline	CNG	Diesel		H_2
	DISI	PISI	DICI	DICI	PISI
		ded.	+DPF		
Engine Power [hp]	94	91	99	99	103
Electric Motor Power [hp]	19	19	19	19	19
Battery Size [kWh]	6	6	6	6	6
Baseline Vehicle	18.600	18.600	20.300	20.300	18.600
Gasoline Tank	-	-125	-	-	-125
Alternative Tank	-	1.838	-	-	5.175
Baseline Engine + transmission	-2.310	-2.310	-3.720	-3.720	-2.310
Alternative Engine + transmission	2.660	2.100	3.780	3.780	2.770
Euro IV Exhaust Treatment	300	300	700	300	-
Electric Motor + Controller	600	600	600	600	600
Li-Ion Battery	3.600	3.600	3.600	3.600	3.600
Powertrain and Vehicle Components	2.630	2.630	2.630	2.630	2.630
Alternator + Starter	-300	-300	-300	-300	-300
Total Price [k€]	25.780	26.933	27.590	27.190	29.778
Diff. from ref. [%]	31.8	37.7	41.1	39.0	52.2

Table F.3. Prices of Hybrid Vehicles.[10, concawe EUCAR, 2006]

	Fuel Cells		
	FC	Hybrid FC	Reformer + Hybrid FC
Fuel Cell Power [hp]	107	107	107
Electric Motor Power [hp]	100	100	100
Battery Size [kWh]	-	6	6
Hydrogen Storage Cap. [kg]	4.7	4.2	-
Baseline Vehicle	18.600	18.600	18.600
Gasoline Tank	-125	-125	-
Hydrogen Tank	2.703	2.415	-
Baseline Engine + transmission	-2.310	-2.310	-2.310
Fuel Cell System	8.400	8.400	20.080
Electric Motor + Controller	2.025	2.025	2.025
Li-Ion Battery	-	3.600	3.600
Powertrain and Vehicle Components	2.630	2.630	2.630
Alternator + Starter	-300	-300	-300
Catalyst	-430	-430	-430
Total Price [k€]	31.193	34.505	43.895
Diff. from ref. [%]	59.5	76.4	124.4

Table F.4. Prices of Fuel Cell Vehicles.[10, concawe EUCAR, 2006]

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