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Economical Feasibility of an Innovative Vehicle Fleet

Diploma Thesis

Graz University of Technology
Faculty of Mechanical Engineering and Economic Sciences
Field of Study: Mechanical Engineering and Business Economics

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Graz,20 August 2010 ………………………………………………..

Fabian Köhler

Acknowledgement:

First of all I would like to thank my supervisor of this project Dipl.-Ing. Erich Ramschak for his great guidance and advice. I am grateful for involving me in the NextHyLights project and his trust to achieve the set goals.
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Last but not least I want to take the chance to thank the whole NextHyLights project partners, industry partners and colleagues for their collaboration.

Abstract:

The AVL List GmbH, with about 4500 employees and a turnover of 700 Million Euros, is one of the leading companies for powertrain, powertrain simulation and testing equipment in the automotive industry.
To strengthen this position in future, AVL researches and investigates future power concepts like fuel cells.
Thus the NextHyLights project, with its main goal to plan a high volume demonstration of hydrogen fuel cell vehicles, is supported and partly funded by AVL. The diploma thesis should help the company with this task.
Approach was, firstly to list all possible prototypes and demonstrators, then assess them and present the work to the project consortium who decided that forklifts should be investigated in more detail. Result was, that under certain circumstances and with current funding hydrogen demonstrations are possible. In order to reach this result a close collaboration with project and industry partners was necessary.
In the past, conventional electrical battery vehicles were modified to fuel cell vehicles. Calculations showed that currently battery vehicles are cheaper in acquisition and operation than hydrogen fuel cell alternatives.
A different picture can be seen with diesel forklifts, where higher operating costs occur at high capacities. The ideal demonstration enterprise for hydrogen forklifts uses the vehicles with high capacities indoor. To reduce the financial gap and to avoid emissions diesel powered forklifts should be substituted.
Customer confirmed that with electrical forklifts bigger than 5 tons, problems occur with range and durability of the batteries. Thus in this segment almost just diesel forklifts are used.
Recommendation to the industry is to build a 5 to 8 ton forklift and to demonstrate it under high capacity with the state-of-the-art fuel cell technology.

Kurzfassung:

Die AVL List GmbH mit 4500 Mitarbeitern, davon 2000 in Graz und einem Jahresumsatz von 700 Millionen Euro, ist eine der weltweit führenden Know-how Träger für Antriebsstränge, dessen Simulation und Testeinrichtungen in der Kraftfahrzeugbranche. Um diese Position in Zukunft weiter auszubauen beschäftigt sich die Unternehmung mit zukunftsweisenden alternativen Antriebskonzepten, wie auch Wasserstoff- Brennstoffzellen.

Das NextHyLights Projekt, mit dem Ziel, eine Grossdemonstration von Wasserstofffahrzeugen zu planen, wird daher von AVL aktiv unterstützt und auch mitfinanziert. Die Diplomarbeit soll die Firma bei der Durchführung des Projekts unterstützen.

Dazu wurden mögliche Demonstrationsfahrzeuge und Prototypen untersucht, verglichen, und dem Projektkonsortium präsentiert. Dieses entschied dann, Gabelstapler im Projekt weiter zu verfolgen und detailliert zu untersuchen.

Ergebnis der Untersuchung war, dass eine Großdemonstration unter gewissen Randbedingungen möglich und auch finanzierbar ist. Um dieses Ergebnis zu erhalten, wurde eng mit NextHyLights Projekt- aber auch Industriepartnern europaweit zusammengearbeitet.

In der Vergangenheit wurden bei Einzeldemonstrationen Batteriefahrzeuge auf Brennstoffzelle umgebaut. Berechnungen zeigten jedoch, dass Batteriefahrzeuge zurzeit in der Anschaffung und im Betrieb günstiger sind als Brennstoffzellenfahrzeuge.

Anders ist die Situation beim Diesel betrieben Stapler, der bei höheren Kapazitäten höhere Betriebskosten aufweist als Brennstoffzellenfahrzeuge.

Das ideale Demonstrationsunternehmen für Wasserstoffstapler betreibt diese in der Halle, im drei oder vier Schichtbetrieb und über das ganze Fahrzeugleben lang. Um die Kostenlücke möglichst klein zu halten und Emissionen zu vermeiden, sollten Dieselfahrzeuge und nicht Batteriefahrzeuge ersetzt werden.

Stapler mit über fünf Tonnen Nutzlast haben Probleme bei Reichweite und Batteriehaltbarkeit, weshalb in dieser Gewichtsklasse kaum Elektrostapler anzufinden sind.

Die Empfehlung daher an die Industrie ist, in dem Segment von fünf bis acht Tonnen Nutzlast einen Brennstoffzellenstapler zu bauen und unter hoher Auslastung zu demonstrieren.

Index:

1 Introduction

1.1 The Company AVL List GmbH[1]

With 4500 employees, 2000 in Graz and 2500 worldwide, AVL generates a turnover of about 700 Million Euro. The three mayor business units are:

Powertrain Engineering (PTE)

AVL develops and improves all kinds of powertrain systems and is a competent partner to the engine and automotive industry. In addition AVL develops and markets the simulation methods which are necessary for the development work.

Instrumentation and Test Systems (ITS)

The products of this business area comprise all the instruments and systems required for engine and vehicle testing. Following picture gives an overview over all AVL ITS Solutions.

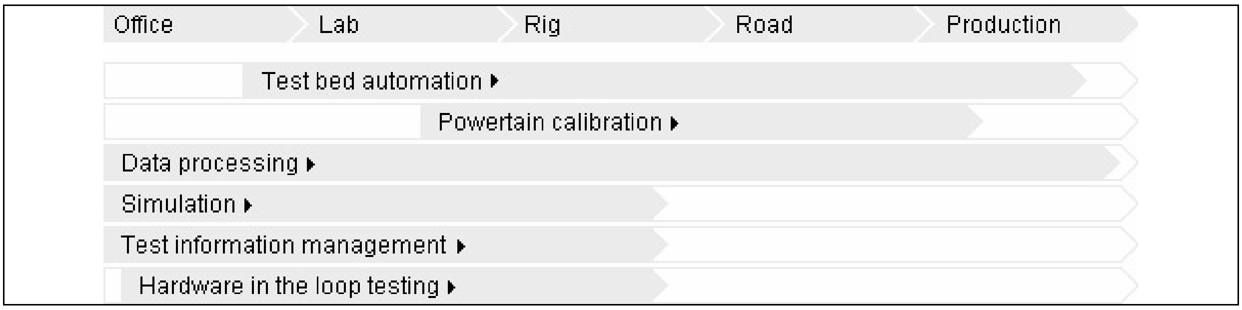

Figure 1: AVL ITS Solutions

Advanced Simulation Technologies (AST)

The developed simulation software for design and optimization of powertrain systems cover all phases of the development process.

Products are:

AVL BOOST – Thermodynamic cycle simulation, Aftertreatment and Acoustic

AVL CRUISE – Vehicle System and Driveline Analysis

AVL EXCITE – Flexible multi-body dynamic system simulation

AVL FIRE – Computational fluid dynamics (CFD) for conventional and alternative powertrain development

AVL ADVISOR – Advanced Vehicle Simulator

1 Cf. https://www.avl.com/, 30.07.2010

1.2 The NextHyLights Project

Abstract:
The Supporting Action NextHyLights will work in close cooperation with and under supervision of Fuel Cells and Hydrogen Joint Undertaking (FCH JU). NextHyLights will directly contribute to the FCH JU activities regarding the preparation of the next calls and will be prepared to react flexibly on FCH JU requirements. It will use the Multi Annual Implementation Plan (MAIP) as the basis and will help to detail it towards the Annual implementation plans (AIPs) taking the ambitions and opportunities of all stakeholders into account. The concept of the project is to develop a strategy (Master Plan) on how to bridge the gap between today's demo projects and the start of large scale demonstrations by building upon existing knowledge from various activities including former projects like: HFP & HyWays, R2H, HyLights (methods, instruments and databases), HyFleet:CUTE, ZERO REGIO, HYCHAIN and other demo projects (hardware experience). The Master Plan development requires the separate preparation of detailed work and roll-out plans for the vehicle segments 'passenger cars', 'buses' and 'other vehicles' which will be checked against each other for coherence and then be integrated in the overall plan.

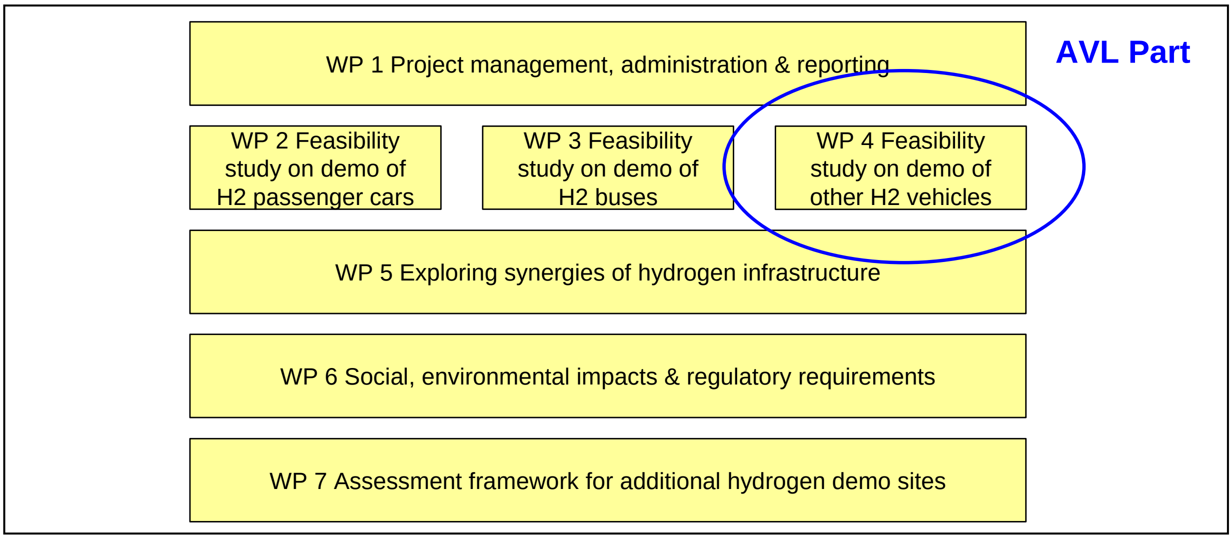

Figure 2: Work packages in NextHyLights

Project details:

Start date: 01 January 2010 End date: pending
Duration: 12 months Project status: ongoing

Project Partners:

Participant organisation name	**Country**
AVL List GmbH	A
Bucher-Guyer AG	CH
Centro Ricerche Fiat SCPA	I
Daimler AG	D
Element Energy	UK
Energy Research Centre of the Netherlands	NL
Ludwig-Bölkow-Systemtechnik GmbH	D
Proton Motor Fuel Cell GmbH	D
Škoda Electric a.s.	CZ
Statoil ASA	N
Total Raffinage Marketing	F
Vattenfall Europe Business Services GmbH	D

Figure 3: Project members of NextHyLights

For a successful project execution a close collaboration between all project partners and the European Union (EU) is mandatory. The close collaboration will be supported in regular meetings.

1.3 Task of the Diploma Thesis

For the NextHyLights project the status quo for all vehicles and the feasibility study for forklifts should be worked out.

1.3.1 Status Quo Report

An overview of existing demonstrations, their applications and associated data will be elaborated. This task will also incorporate a review of past and existing demonstration projects. Found demonstrators will be assessed and presented to the project group.

The material for the presentation has to be made and presented. The results of this sub-task will be collected in a written status quo report.

1.3.2 Feasibility Study

Interpretation of data and sketching of scenarios (AVL, Bucher, PM, S-ELC, SH)
Feasible scenarios for H_2 vehicles in the commercial area including the infrastructure will be elaborated and reported.

Topics of the feasibility study:

- Vehicles
- Technologies
- Locations and volumes
- Strategic and operational interfaces to passenger cars and buses
- Cost, financing instruments
- Critical success factors, key process indicators

Out of the synthesis, recommendations will be derived which will not only be considered in the further planning activities of this project but will be directly communicated to and discussed with FCH JU in order to allow an efficient and swift process concerning the preparation of next FCH JU calls.
Conclusions and recommendations will undergo a thorough review by the industry partners to ensure that they are of the highest value as input for the next project stage as well as for the preparation of the next FCH JU calls.

1.3.3 Time Schedule for the Diploma Thesis

The following time schedule gives an overview of the thesis and is suited to the EU project time schedule.

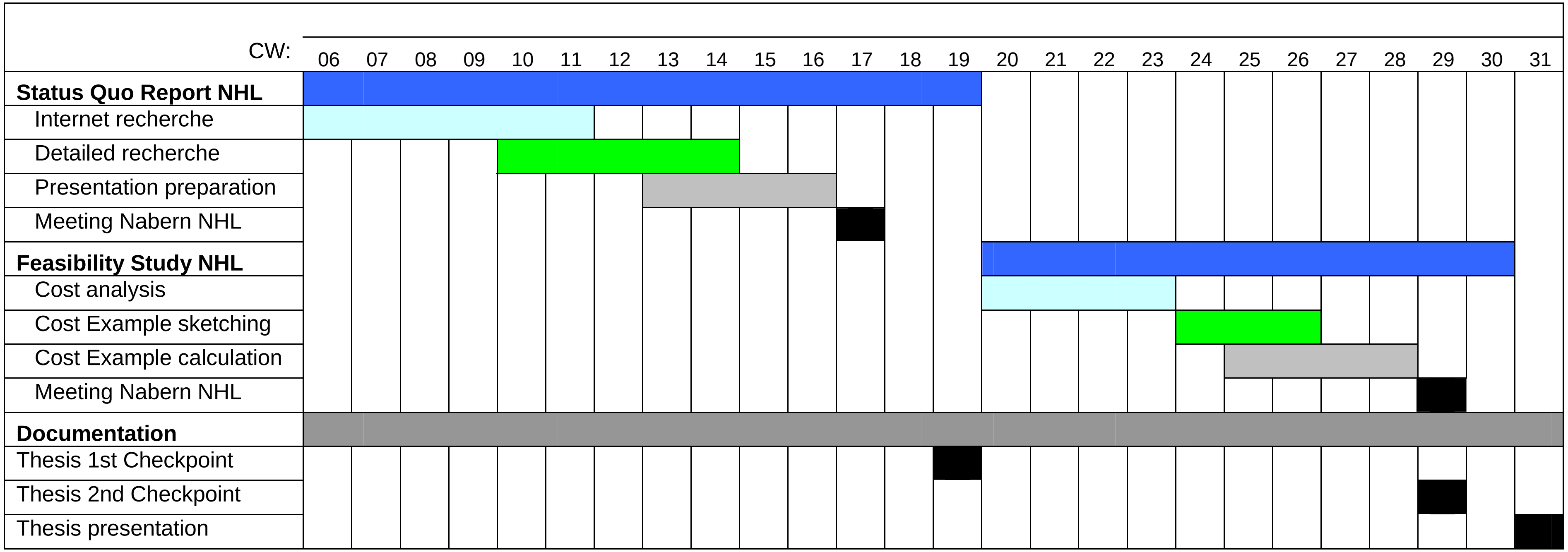

Figure 4: Timeframe for the thesis

1.4 Approach

First start was an internet search and the attempt to find all demonstrators worldwide. More difficult than expected was to distinguish between concept cars, prototypes and demonstrators. The result was a list of all demonstrators worldwide.
For reasons of differentiation and clear identification in this study certain boundary conditions for the listed vehicles have to be defined:

- Fuel cells as main energy converter: i.e. no H_2-ICE vehicles, but including every constellation of fuel cell - battery - super cap hybrids
- Hydrogen as sole fuel – i.e. no methanol-FC solutions
- Transportation of persons or goods – i.e. no mobile auxiliary power units (laptop)
- Contact to the ground but including ships – i.e. no aircrafts, rockets
- Vehicles already demonstrated – i.e. no concept cars
- Introduced after year 2000

These boundary conditions were made by AVL in close collaboration with the project partners. The result of this approach was an overview over “other vehicles”. The following task was to narrow down applications to some, for high volume possible demonstration vehicles. Therefore detailed information from all relevant manufacturers in the different application areas of “other vehicles” was requested and the received data sheets were collected and coarsely assessed.
These results and assessments were presented at the NextHyLights project meeting and it was decided concordantly that the three vehicle groups mentioned below (Figure 5: Process for diploma thesis) should be investigated in detail.

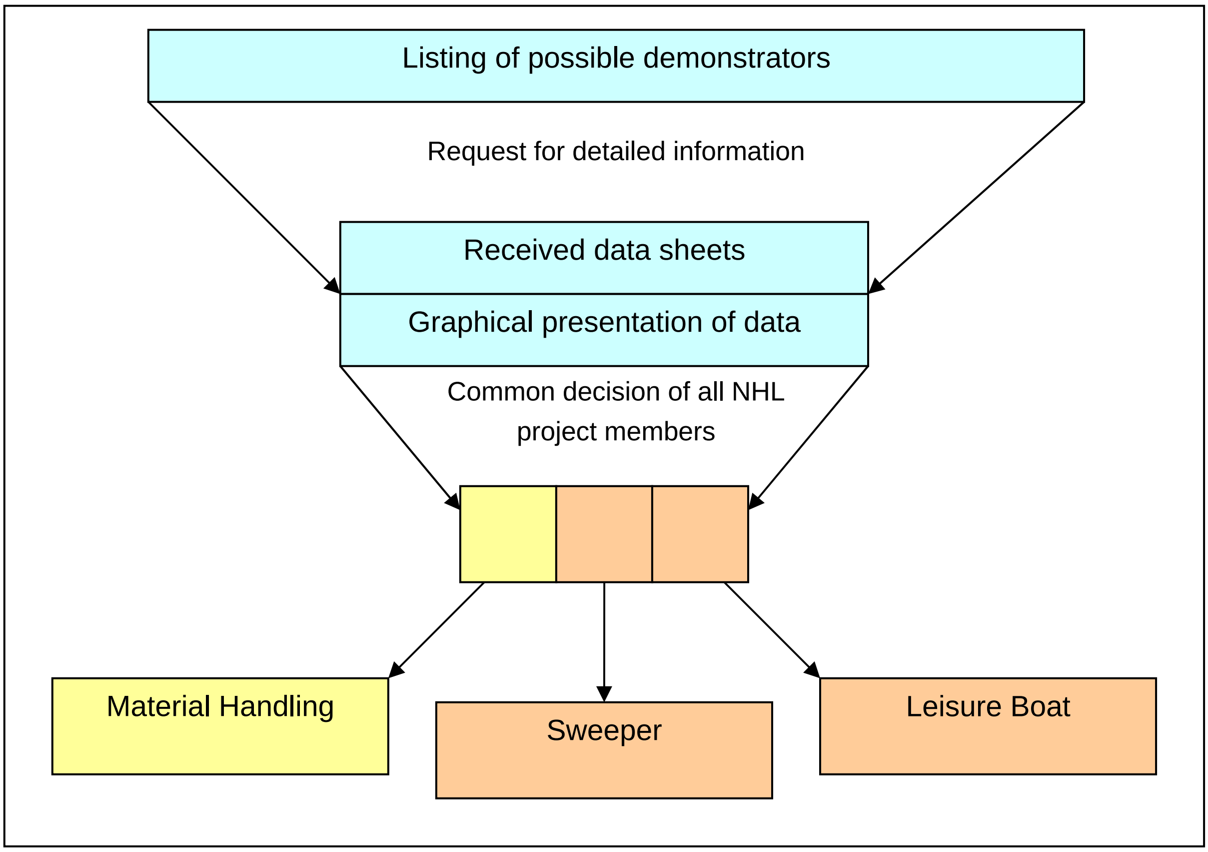

Figure 5: Process for diploma thesis

The diploma thesis ends after the feasibility study for material handling vehicles. Thus the sweeper and the leisure boat are not content of the thesis.

2 Basics

This topic should give an overview, starting from the global energy situation and narrow down to hydrogen as a possible way in the future.

2.1 Energy Tomorrow

2.1.1 Governmental Energy Targets

Energy is an essential source for life and wealth for all of us in the industrialized countries. The energy politics influences the economy, the environment and the climate.

Therefore the European governments agree on almost the same energy targets. Representative for this thesis the three energy targets in the Austrian governmental program[2]:

- Secure and economical energy
- Conscious and efficient use of energy
- Efficient use of renewable energy

Or the European Union Targets:

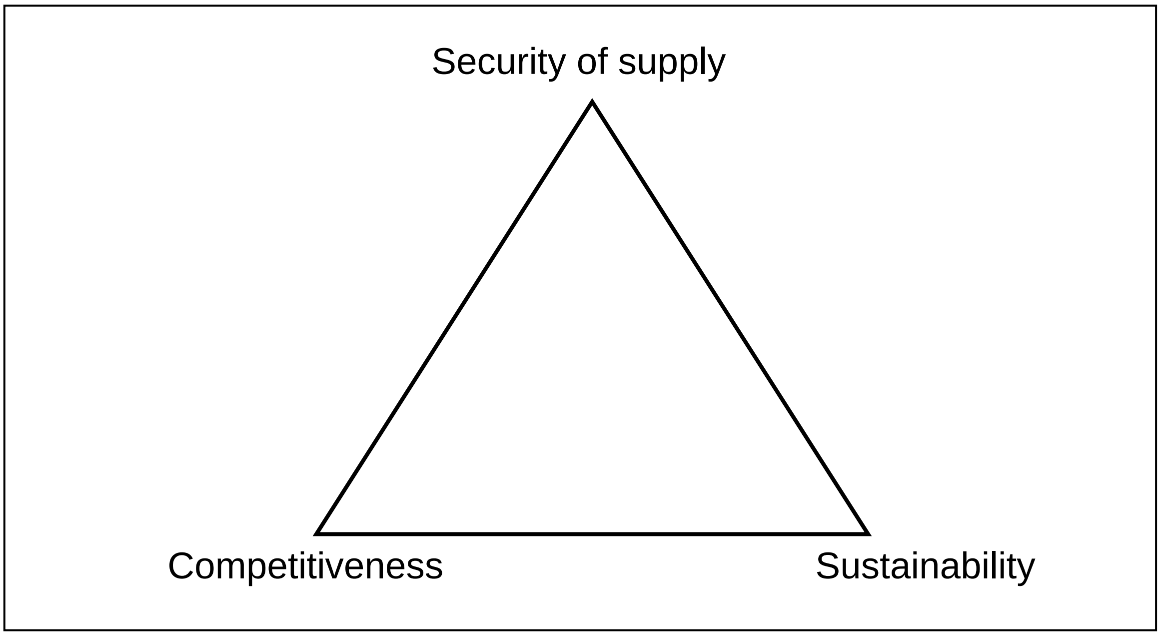

Figure 6: European Union energy targets[3]

2.1.2 Global Long Term Energy Demand

The world energy demand is increasing steadily. Long term energy scenarios show that the 2010 world demand will almost double up till 2090.
Despite the oil peak in the next years the energy demand increases and the further demand will be covered by regenerative energy like wind, sun or biomass.

[2] Cf.REGIERUNGSPROGRAMM 2008-2013 (2008), p.31

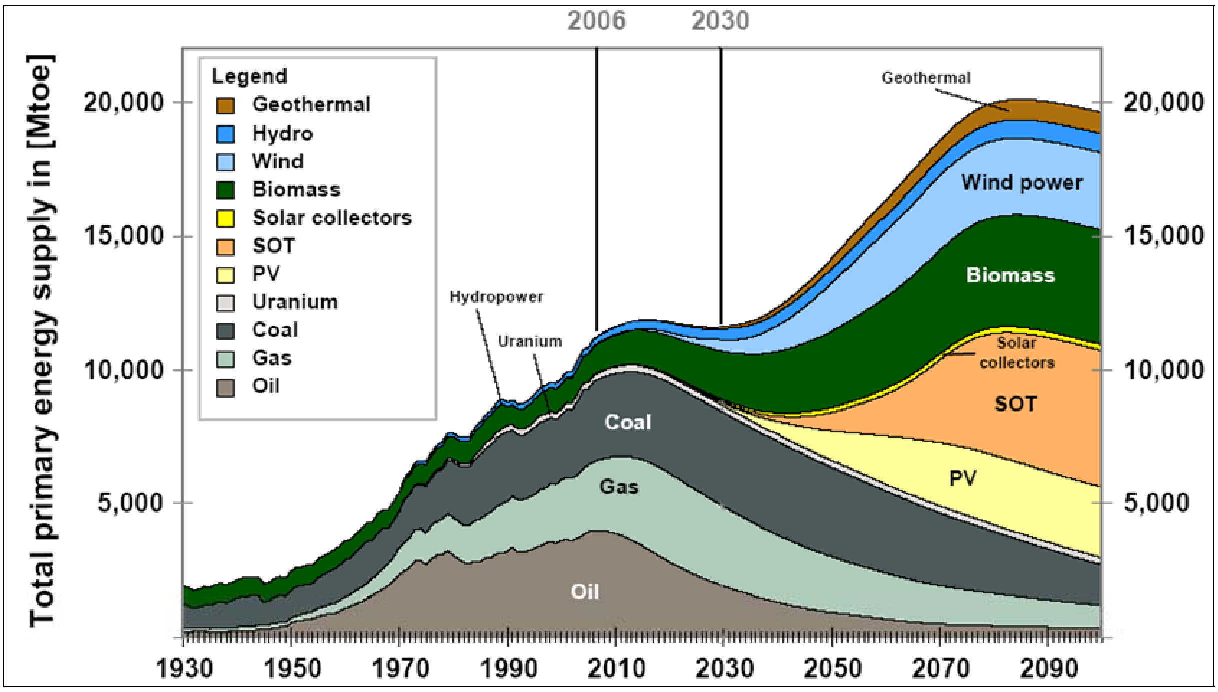

Figure 7: World energy demand till 2100[4]

SOT…Solar Thermal Power Plants
PV… Photo Voltaic

This scenario, investigated in 2008, shows the all over world energy demand and possible energy sources to satisfy it. Today the main energy source is not sustainable. Oil, Gas and Coal are the main energy sources. Despite the increasing demand between 2010 and 2015 the conventional energy sources will start to decline. This gap has to be closed wit regenerative energies, like geothermal, wind, biomass or sun energies.

The total energy composition from 1930 has not changed significantly till 2010. In the next years the first changes in the energy composition will occur, which means that the time today is crucial and extensive for the whole energy sector.

2.1.3 Global Energy Mix

The following chart shows the energy mix now and in 2020. Oil will remain the number one energy source for the next decade. But also other limited sources like gas or oil will not see a decrease. Renewable energy sources and biomass have a proportion of 22% (2006). Generally the energy composition will not change significantly over the next years.

[3] Cf. EU Commission, Green Paper (2006), p.1ff
[4] EWV/DWBV (2009) p. 9

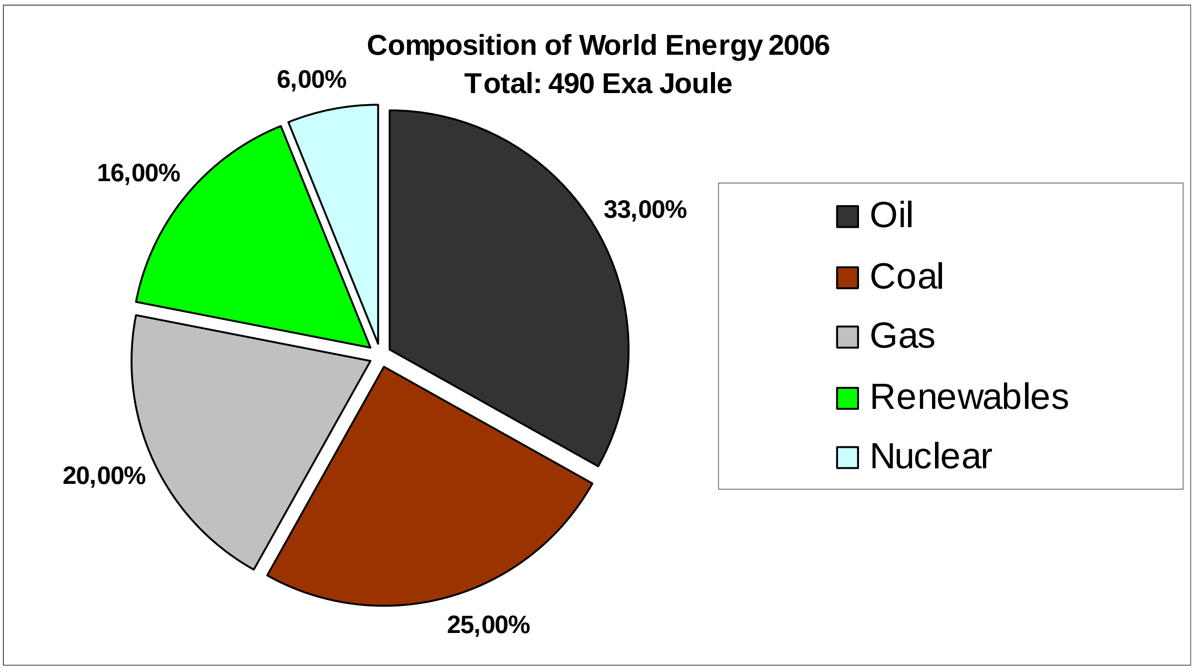

Figure 8: Global energy composition 2006[5]

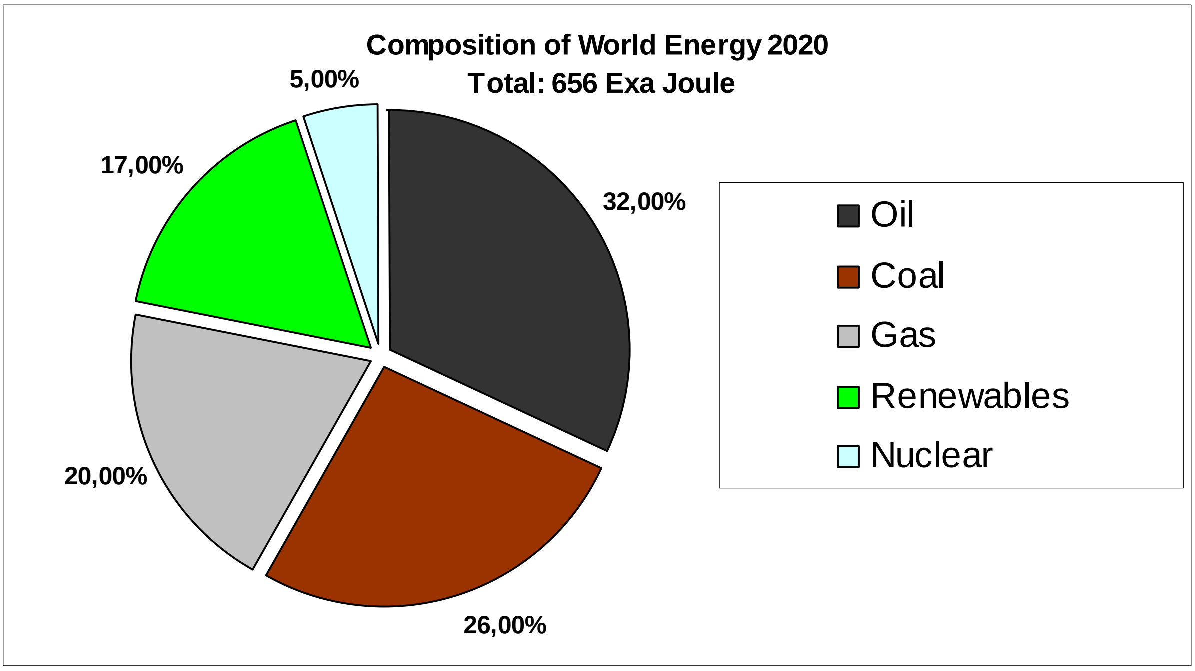

Figure 9: Global energy composition 2020[6]

McKinsey announces that the global energy demand will not change in the next decade. Renewables and coal will slightly increase and nuclear and oil will be reduced by 1 per cent. The total energy demand will increase from 490 Exa Joule to 656 Exa Joule, which means a plus of 33%. The long term energy demand (figure 7) does not see this increase.

[5] Cf. MGI, (2009), p.38 and IEA (2009), p.6
[6] Cf. MGI, (2009), p.38

2.1.4 Energy and Transport

The transportation sector needs energy. On road vehicles are usually powered by gasoline or diesel, which are a product from crude oil. This is valid for kerosene in aircrafts as well. In the following charts it can be seen that transport consumes 16% of the world's energy. This figure stays the same in the forecast for 2020.

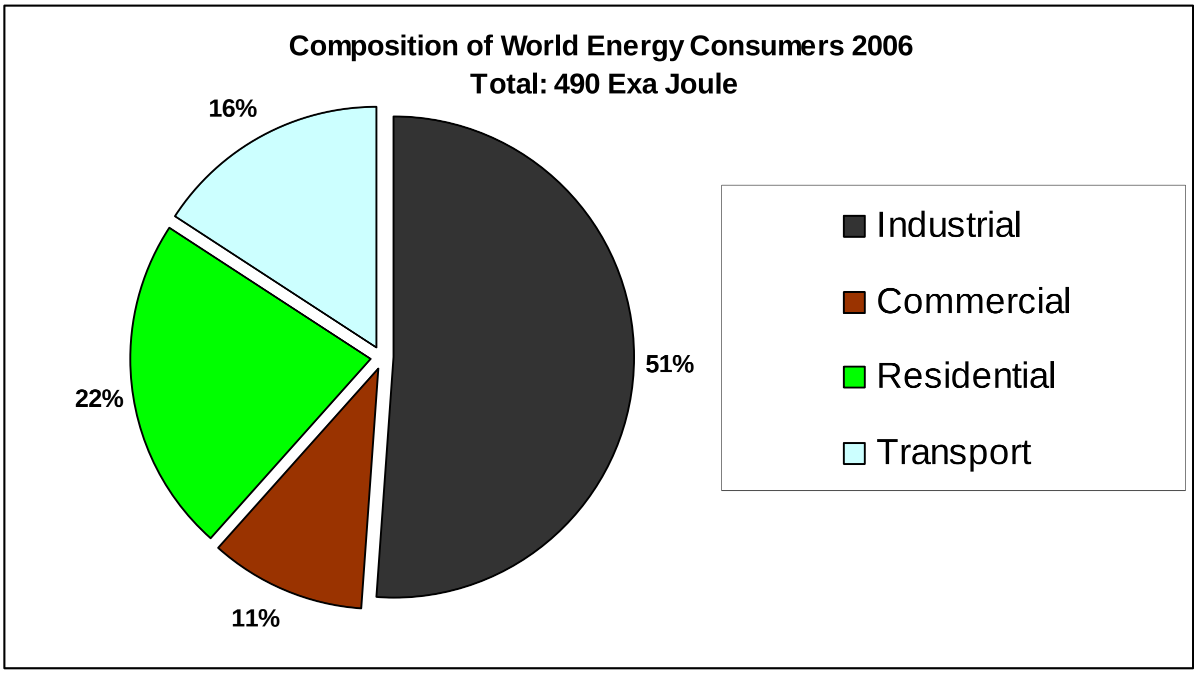

Figure 10: World energy consumers 2006[7]

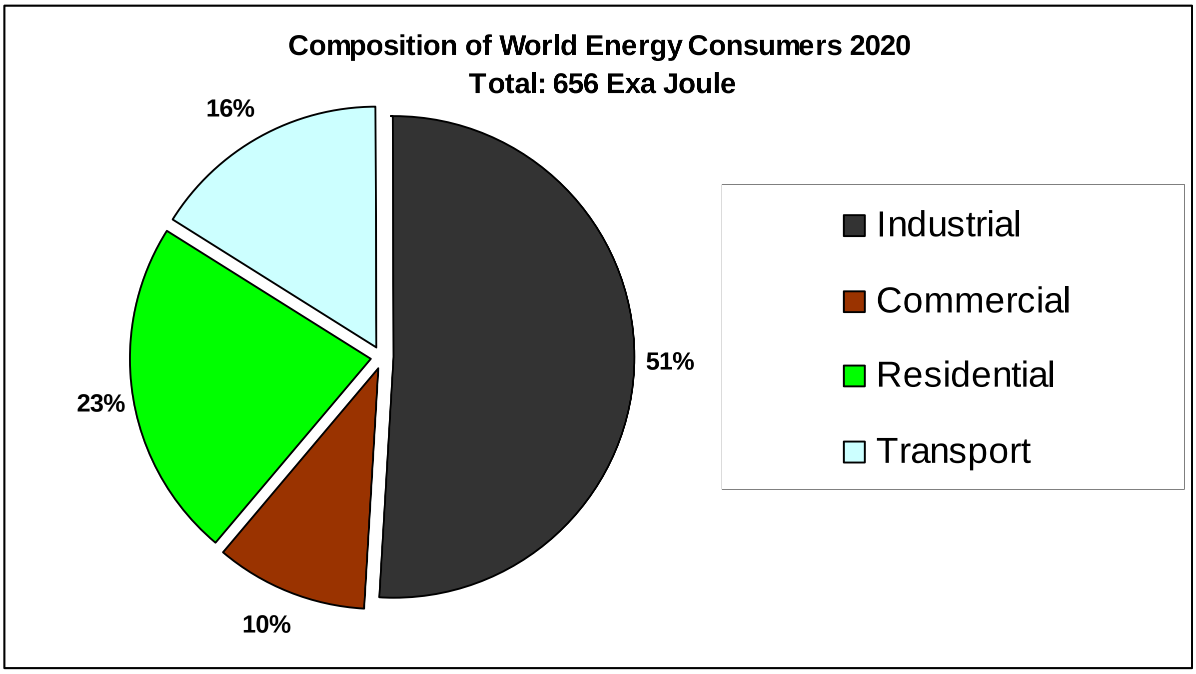

Figure 11: World energy consumers 2020[7]

[7] Cf. MGI(2009), p.37

Apparently the total energy consumption and the total energy production is the same. Due to converting processes and so efficiencies from primary to secondary energies, which are consumed, usually a difference can be seen. In this report the consumed energy is based and calculated back to a primary energy level.

2.1.5 Oil Peak

The following picture shows the production of oil worldwide. In this report from Ludwig Bölköw Stiftung for the Energy Watch Group (EWG) it is presumed that the world energy peak was in 2006.

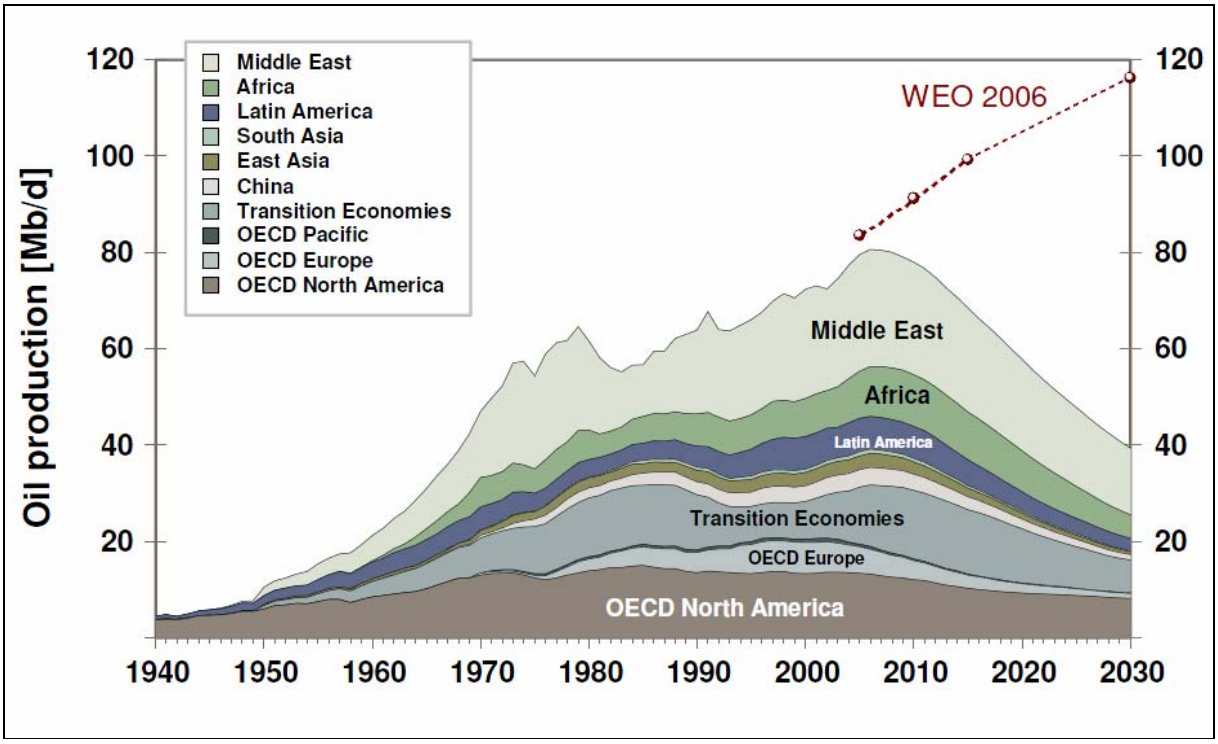

Figure 12: World oil production scenario[8]
OECD… Organization for Economic Co-operation and Development
WEO… World Energy Outlook

Oil will not be used up instantly. Much more likely is the oil peak theory. Peak oil is the point in time when the highest rate of global oil extraction is reached, after which the rate of production continuously declines. This concept is based on the observed production rates of single oil wells and the combined production rate of a field of related oil wells. The total production rate of an oil field over time usually grows exponentially until the rate peaks and then declines until the field is depleted.

[8] EWG/ LBS (2008), p.12f

2.1.6 Preliminary Conclusions

On the one hand renowned institutions like McKinsey expect an increasing energy demand and no significant changes in the energy mixture till 2020 and at the same time as well renowned institutions like the German Ludwig-Bölkow Stiftung see the peak oil production reached in 2006.
In every case, to reach the targets of almost all European Countries and so the European Union (chapter 2.1.1) actions have to be taken now.
Anyhow, the future will bring changes in the energy and the related traffic sectors. A shortage of oil in the world will increase the oil price and this impacts the whole economy. When this time comes it is crucial that the whole energy sector, but the traffic sector as well, will be prepared and future technologies should be available at this time. The following chapter gives an overview of possible future technologies.

2.2 Technologies and Fuels of the Future[9]

Several technologies and fuels are investigated for future scenarios. These concepts cover the most promising future technologies for automotive applications.
So alternatives could be for:

- **Internal combustion engine**
  - **Gasoline engines**
    - Natural gas
    - Liquefied petroleum gas (LPG)
    - Alcohol fuels(Ethanol, Methanol)
    - **Hydrogen**
  - Diesel engines
    - Fatty acid methyl ester (Biodiesel)
    - Synfuels or Sunfuels
    - Dimethylether
    - Emulsions
- **Electric motor**
  - **Fuel Cells**
    - **Hydrogen**
    - Methanol(Alcohol)
  - Direct electrical energy
    - Battery

[9] Robert BOSCH GmbH (2007) p.327ff

This is a small overview of possible future technologies. One discussed approach is to substitute gasoline or diesel with renewable fuels. Many fuels are possible and regenerativly producible. First alternative fuel for the cheap and well researched internal combustion engine (ICE) is natural gas, which is already is use and can be bought, e.g. in the Opel Zafira. Disadvantage is that natural gas not sustainable. Liquefied petroleum gas is a mixture of propane and butane and a by-product of the crude oil refining process. Alcohol fuels like ethanol or methanol can directly replace, or be mixed with conventional gasoline.

For diesel motors alternatives can be the fatty-acid methyl ester (FAME) or better known as biodiesel. This fuel is produced from rape seed oil or soya. Synfuel (not renewable produced) or Sunfuel (renewable produced) is the same product but different created.

There are many more technologies which enable other combinations of fuels and technologies. The advantage would be that in the intersection phase bi-fuel cars could operate, that means that cars can be powered by two fuels. E.g. Gasoline and Ethanol (Bentley Supersports)

In this case current infrastructure does not have to be changed massively.

Another approach is changing the powertrains of the car from internal combustion engines to electric motors. In this case total zero emission vehicles can be realized. The energy supply system could be a fuel cell or a battery. Infrastructure for these vehicles would have to be established totally new and big challenges have to be coped. Find some of these challenges in chapter 2.5.1.

2.3 Hydrogen

As mentioned in the previous chapters hydrogen is a possible energy carrier of the future. This chapter will introduce the medium and technologies to produce, distribute, store and convert hydrogen.

2.3.1 Medium H_2

Hydrogen is the lightest element in our period system. Its chemical short form is H. H is the basis of our period system too with a weight of 1 g/mol. Thus it is the element to define the unit Mol. Hydrogen is by far the most abundant element in our universe by weight. As a molecule hydrogen exists in its pure form together with a second hydrogen atom as H_2. Hydrogen connected with Oxygen is water (H_2O), and water is absolutely essential for life. Hydrogen, as the lightest gas, found its first famous application in air balloons for transport. H_2 oxidizes with O_2 from air to form only water (H_2O) as product. This process sets energy free.

Lower heat value: 120 [MJ/kg] = 33,33 [kWh/kg] ≙ 3,33 liters of diesel
Upper heat value: 142 [MJ/kg]= 39,44 [kWh/kg]
Density gaseous: 0,09 [kg/Nm^3]

Table 1: Hydrogen as an energy carrier[10]

2.3.2 Production of H_2[11]

In the year 2000, 45 billion kg of H_2 was produced worldwide. In the European Union (EU-15) 5,5 billion kg H_2 was made, 49 % by reforming natural gas and 29 % by coal gasification. This means about 70% of all produced hydrogen caused emissions. [12]

Researchers are developing various methods to produce hydrogen in a cost effective way. Some of these methods are environmental friendly.

Steam Reforming

Three different types of natural gas reforming exist. Due to the highest efficiency, the common way to produce hydrogen is to use methane in natural gas and high temperature steam. This process is called steam methane reforming, and accounts about 95 percent of the US hydrogen production today. The partial oxidation reforms longer carbon hydrogen molecules. The autothermic reforming process is a combination of both.

All of these methods produce Carbon dioxide, thus they promote the global warming and are not environmental friendly.

Electrolysis

Electrolysers use electrical energy to split water into hydrogen(H_2) and oxygen(O).

The required electricity could be produced by renewable energy, like solar, wind or water. This process is the reverse process like in the fuel cell. The environmental footprint depends on electrical energy production.

Nuclear High-Temperature Electrolysis

Additional to the normal electrolysis nuclear reactor heat could be used to heat up the water. The chemical split of water requires less energy if the water is hot.

High-Temperature Thermochemical Water-Splitting

[10] Eichlseder/ Klell (2010), p.39f
[11] Eichlseder/Klell(2010), p.59ff
[12] http://hyfleetcute.com/data/HyFLEETCUTE_Brochure_Web.pdf, p.8, 01.07.2010

Instead of Nuclear heat you can produce high temperatures by solar concentrators (special lenses that focus and intensify sunlight).

Gasification

In the gasification process, coal or biomass is converted into gaseous components. The chemical reaction is performed by applying heat under pressure and in the presence of steam. Many chemical reactions produce in the end a synthesis gas, which could be enriched with steam to produce more hydrogen.

The way to produce hydrogen directly from coal by gasification and reforming processes is much more efficient than burning coal to make electricity which is used to make hydrogen afterwards.

Like coal, biomass can be gasified by using high temperatures and steam to produce hydrogen. Biomass has the big advantage that resources consume CO_2 in the atmosphere as part of their natural growth process.

Photobiological and Photoelectrochemical

Special microbes, such as green algae and cyanobacteria, consume water in the presence of sunlight, and so they produce hydrogen as a byproduct of their natural metabolic processes. Similarly, photoelectrochemical systems produce hydrogen from water using special semiconductors and energy from sunlight. Efficiency does not matter for this process.

Kvaerner Process

The Kvaerner Process is a Norwegian Development with its special attitude to create carbon instead of carbon dioxide. Thus as a result two burnable products are produced. $CH_4 \rightarrow C + 2\ H_2$

A plasma arc splits hydrogen and carbon at 1600°C. This high temperature leads to thermal challenges and makes the process quite elaborate.

The efficiency of this process is close to 100%.

Efficiencies of the Production Processes:

The following picture shows the different energies to produce one kWh pure hydrogen. The first three are the different natural gas reforming methods. The yellow columns are electrolysis processes at different pressures. Black and red are gasification of coal and biomass.

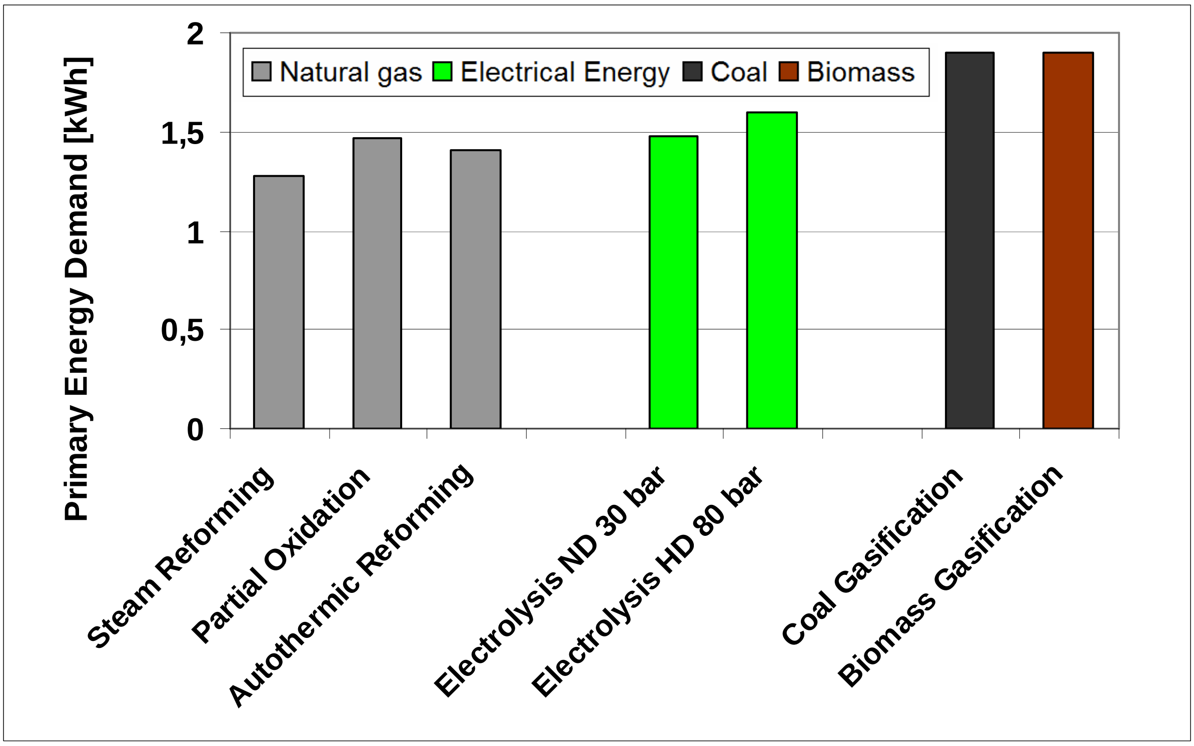

Figure 13: Energy used to produce 1 kWh H_2[13]

And so following efficiencies are realized:

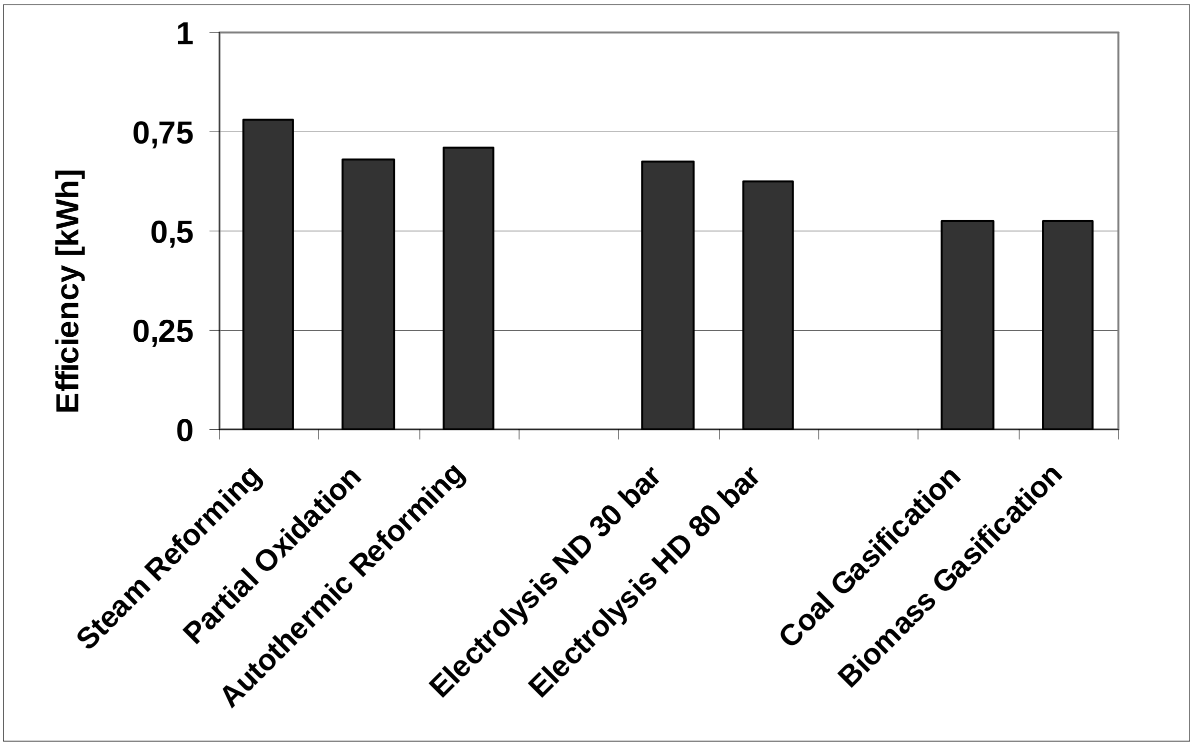

Figure 14: Efficiencies for different Hydrogen producing processes[14]

[13] Eichlseder/ Klell (2008), p.50

2.3.3 Surplus Hydrogen[15]

In a former EU project “Roads2HyCom” investigations were performed about the current hydrogen situation in Europe. Total production of H_2 in Western Europe is about 90 billion m^3. Consumption, mainly by refining, ammonia, methanol and metal industries, is about 61 billion m^3.
23bn m^3 of this gap is by-product hydrogen, which means hydrogen produced inadvertently, in a chemical industry. Based on different scenarios 2-10 billion m^3 of hydrogen would be available, enough to fuel 1 to 6 million vehicles.

2.3.4 Distribution of H_2[16]

Hydrogen Pipelines

There is a long history of transporting oil and natural gas through pipelines. But hydrogen is transported through steel pipelines for several industrial proposes too. If hydrogen is pumped only with a 10-20 [bar] pressure, regular steel is enough to accomplish the sealing requirements. This means that some of the existing oil and natural gas pipeline infrastructure could be used to distribute hydrogen. The only caveat is the carbon levels in the pipe metal, with lower levels of carbon being more suited for hydrogen transportation. Natural gas pipes that are made from plastic (PVC) would be too porous for hydrogen and thus cannot be used.

Transportation of Liquid Hydrogen

Liquid hydrogen (LH_2) is formed at at 21.2 K (-251.95° C) and requires a very energy intensive cooling process along with cryogenic tanks for storage. Certain specialized application that require liquid hydrogen, it can be transported in special tankers.
Liquid hydrogen has an energy density of 33,3 [kWh/kg] or 2,36 [kWh/cdm].
For a comparison, common fuels have about 10 [kWh/kg] and, due the density of around 1, about [10kWh/dm^3].

Road Transportation of Hydrogen

Hydrogen is currently being transported in both, liquid and as a compressed gas using special tanker trucks. This method though will continue as a method of delivering fuel to end users or distribution depots from a central processing or storage facility.

[14] Eichlseder/ Klell (2008), p.51
[15] Cf. Roads2HyCom (2007) Deliverable 2.1 and 2.1a, p.3
[16] Cf. http://www.hydrogentrade.com/distribution/, 15.03.2010

2.3.5 H_2 Storage[17]

Compressed Hydrogen Gas

Compressed Hydrogen gas, short CHG, can be stored in storage tanks that can hold it at the required pressure. Usually the tanks can be made either with steel, aluminum or copper alloys. Special carbon fibers could be used to reduce the weight of the tanks. Common pressures are 200, 350, and 700 bar. The higher the pressure, the higher the energy density and thus, the bigger the cylinder sheets. Weight is the biggest problem of this storage form. The steel tanks are most often used for static applications, where weight is not a hindrance as the steel tanks tend to be heavy. High pressure tanks also appear in some test automobiles. But, of course, safety and space keep significant concerns. Another problem is leakage. Due to the fact that hydrogen is the smallest molecule diffusion through the material is difficult to avoid.

Liquid Hydrogen

Hydrogen can be stored as a liquid (LH2) at 21.2 K (-251.95° C) at ambient pressure in cryogenic tanks. Liquid hydrogen has been the fuel of choice for rocket applications for a long time. Once liquefied, it can be maintained as a liquid in cooled and pressurized containers which have to be quite large since (LH_2) has a very low density. The cooling and compressing process requires energy, resulting in a net loss of about 30% of the energy stored in the liquid hydrogen. Most famous promoter of this technology was automotive manufacturer BMW, researching the use of liquid hydrogen as a fuel for automobiles.

Metal Hydrides

At high temperatures and under the right pressure, hydrogen reacts with many transition metals and their alloys to form hydrides. A Hydride is a compound that contains hydrogen. It is stable compared to native hydrogen and can be stored, transported or used in several applications. A second reaction to release the hydrogen is required when the fuel is used in fuel cells for example. In catastrophic events, the metal hydride storage system for hydrogen is considered safe. But here, weight is a bigger problem. This problem together with high costs reduces the applications to some prototypes and military activities, like the German submarine U-212A.

[17] Cf. http://www.hydrogentrade.com/storage/, 15.03.2010

Hydrogen Stored in the Form of Ammonia

Ammonia (NH3) is the second most commonly produced chemical in the world. It is used for the production of several products. It can be used to store hydrogen chemically with the ability to release it in a catalytic reformer as well. Ammonia provides quite high hydrogen storage densities and can be stored very comfortably either as a liquid or in solid form. Important is to mention that ammonia is poisonous for human beings.

Hydrogen Storage in Carbon Nanotubes

Carbon nanotubes are (microscopic) cylindrical carbon molecules that can be used in a wide range of applications like diodes or transistors. One possible application is the ability to store hydrogen within its microscopic structure. The US Department of Energy has established a standard whereby carbon materials need to have a storage capacity of 6.5% of their own body weight if they are to be used for transportation use. Research continues on the use of carbon nanotubes for hydrogen storage. One of the drawbacks with nanotubes though is their extremely high cost. About one kilogram of the material costs approximately USD 50.000.

Comparison of Storage Technologies

In the following picture energy densities of different storage systems are compared. Common storage like gasoline is in the chart as well. In the first view it is obvious that densities of new technologies are much lower than gasoline. The tank is a crucial factor to reach requirements on range, but efficiency is a mayor factor as well.

And efficiencies for hydrogen and electrical battery solutions are much higher than common ICE engines.

When comparing all zero emission storage systems the liquid hydrogen has the best values. Current Li Ion Batteries have an energy density of 150Wh/kg, what is less than a 10th of current 700 bar tanks used in the Mercedes B-Class. At this point it has to be mentioned that batteries can not be emptied totally, which reduces the available power again.

Not included in these figures is the weight of the fuel cell system. The battery can be used directly as an energy provider, whereas the hydrogen has to be converted to electrical energy by a fuel cell.

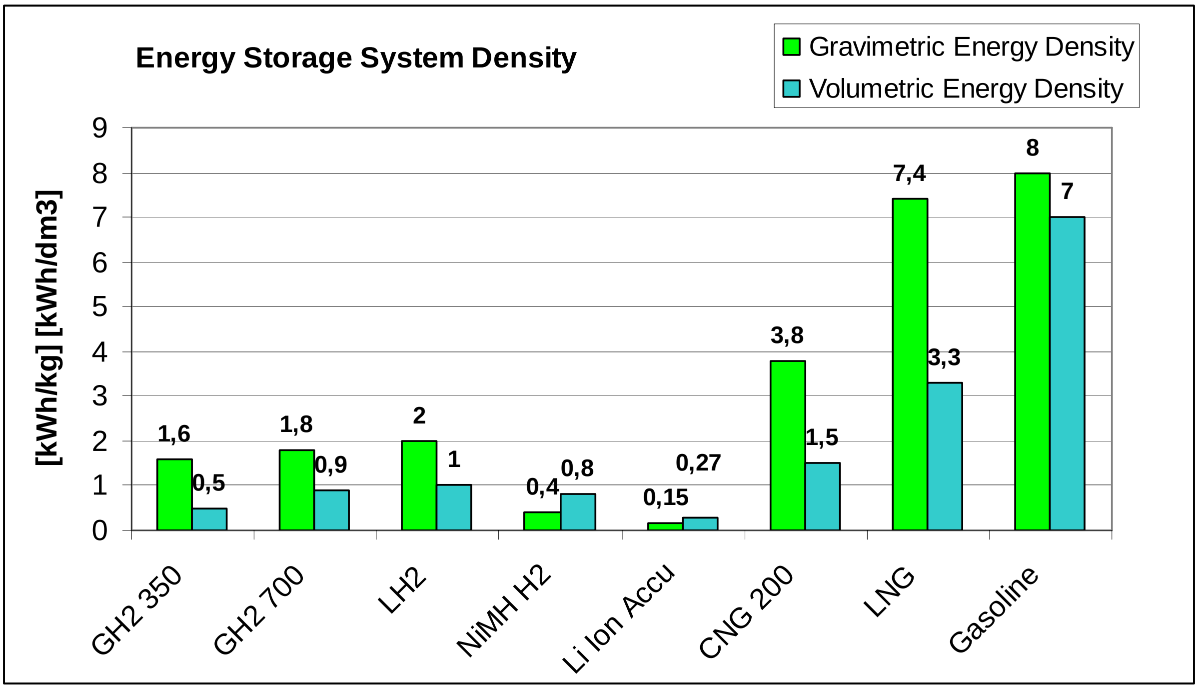

Figure 15: Energy density of storage systems[18]

GH2… Gaseous Hydrogen
LH2… Liquid Hydrogen
NiMH… Nickel Metal Hydrid
Li Ion… Lithium Ion Accumulator
CNG… Compressed Natural Gas
LNG… Liquid Natural Gas

2.4 H_2 Technologies

Several technologies are already researched and known. Hydrogen is a chemical storage of energy. What we really want in a vehicle is a mechanical rotation at the tire. So the direct way is to convert it with an ICE or a turbine. But all these machines work with burning processes, and are so limited in efficiency. The maximum efficiency for a ICE is limited due the Carnot-Process.
Another way, maybe more complicated but more effective as well, is to produce electricity with a fuel cell (up to 70% efficiency) and to use the electrical energy with an electric motor to generate the rotation at the tire (efficiency >90%).

[18] Cf. Eichlseder/Klell(2010), p.121

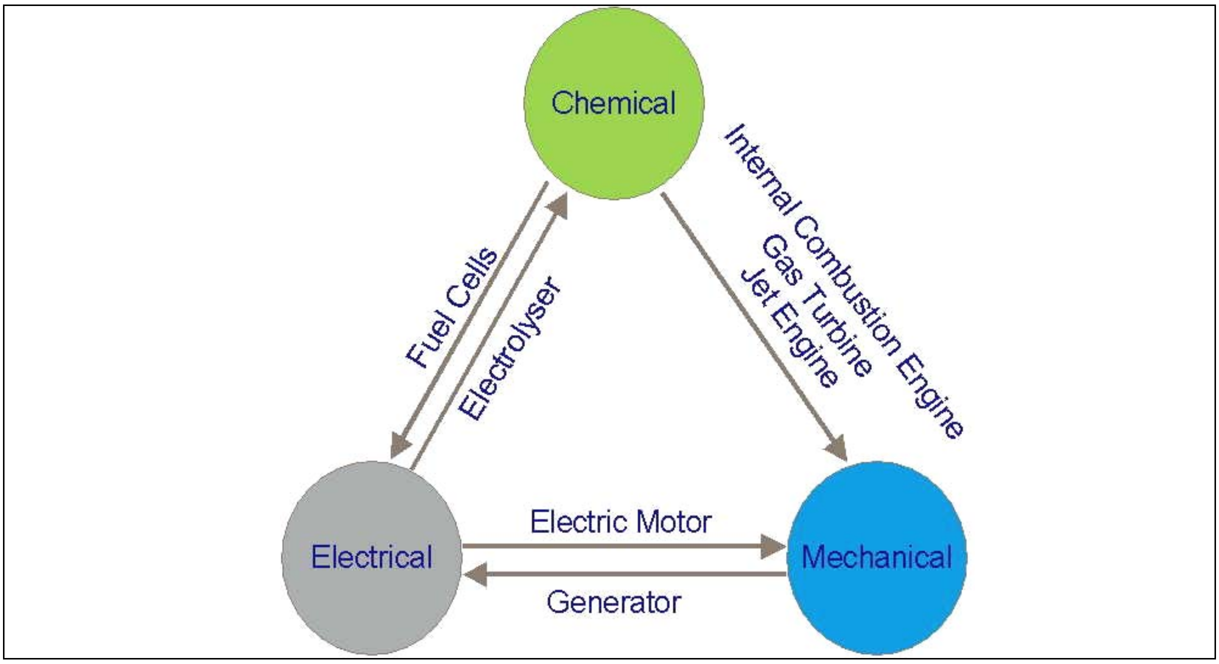

Figure 16: Technologies to convert hydrogen[19]

2.4.1 Fuel Cell[20]

Basics

A Fuel cell converts the chemical energy of hydrogen into electrical energy in an efficient and, in terms of hydrogen, emission free way.

For the sake of completeness, it is possible to convert methanol and other liquids to electrical energy as well. But in this case the chemical reaction produces carbon dioxide. Nevertheless, fuel cells are very flexible in terms of the variety of their potential applications. They can provide energy for all electrical systems, as large as a utility power station and as small as a laptop computer. Actually, the fuel cell and its tank do the same as a battery, they provide electrical energy.

Compared to batteries fuel cell has some advantages. The energy density is higher (see chapter 2.3.5) and the refueling process does not take so long.

However, fuel cells have several benefits over conventional combustion-based technologies currently used in many power plants and passenger vehicles as well. Driven with pure hydrogen they produce no CO_2 and none of the air pollutants that create smog or cause health problems. The only byproduct is water.

[19]Cf. http://www.ika.rwth-aachen.de/r2h/index.php/Hydrogen_and_Fuel_Cell_Technology, 20.03.2010

[20]Cf. http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/basics.html, 23.03.2010

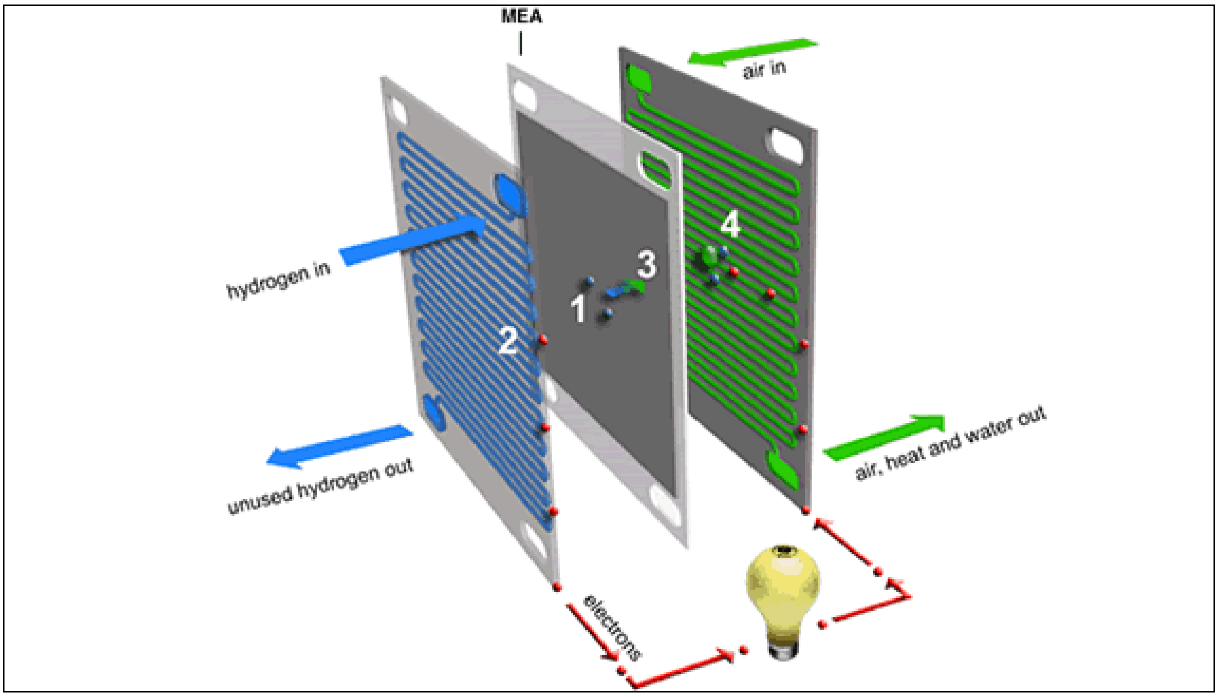

Figure 17: Fuel cell scheme[21]

The most popular fuel cells use hydrogen, or hydrogen-rich fuel (2) and oxygen, mostly in air (4) or pure, to create electricity by an electrochemical process. A single fuel cell consists of an electrolyte and two catalyst-coated electrodes, a porous anode and cathode. While there are different H_2-fuel cell types, all fuel cells work very similarly:

Hydrogen, or a hydrogen-rich fuel, is fed to the anode (2) where a catalyst, mostly platinum, separates hydrogen's negatively charged electrons from positively charged ions (protons).

At the cathode (4), oxygen combines with electrons and the protons, resulting in water.

For polymer electrolyte membrane(PEM) fuel cells, protons move through the electrolyte to the cathode to combine with oxygen and electrons, producing water and heat.

For alkaline, molten carbonate, and solid oxide fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons.

[21]http://www.alternative-energy-news.info/technology/fuel-cells/, 23.3.2010

The electrons from the anode cannot pass through the electrolyte to the positively charged cathode; they must travel around it via an electrical circuit to reach the other side of the cell. This movement of electrons is an electrical current.
To increase the current, several of these plates are connected together to a fuel cell stack shown in the next picture:

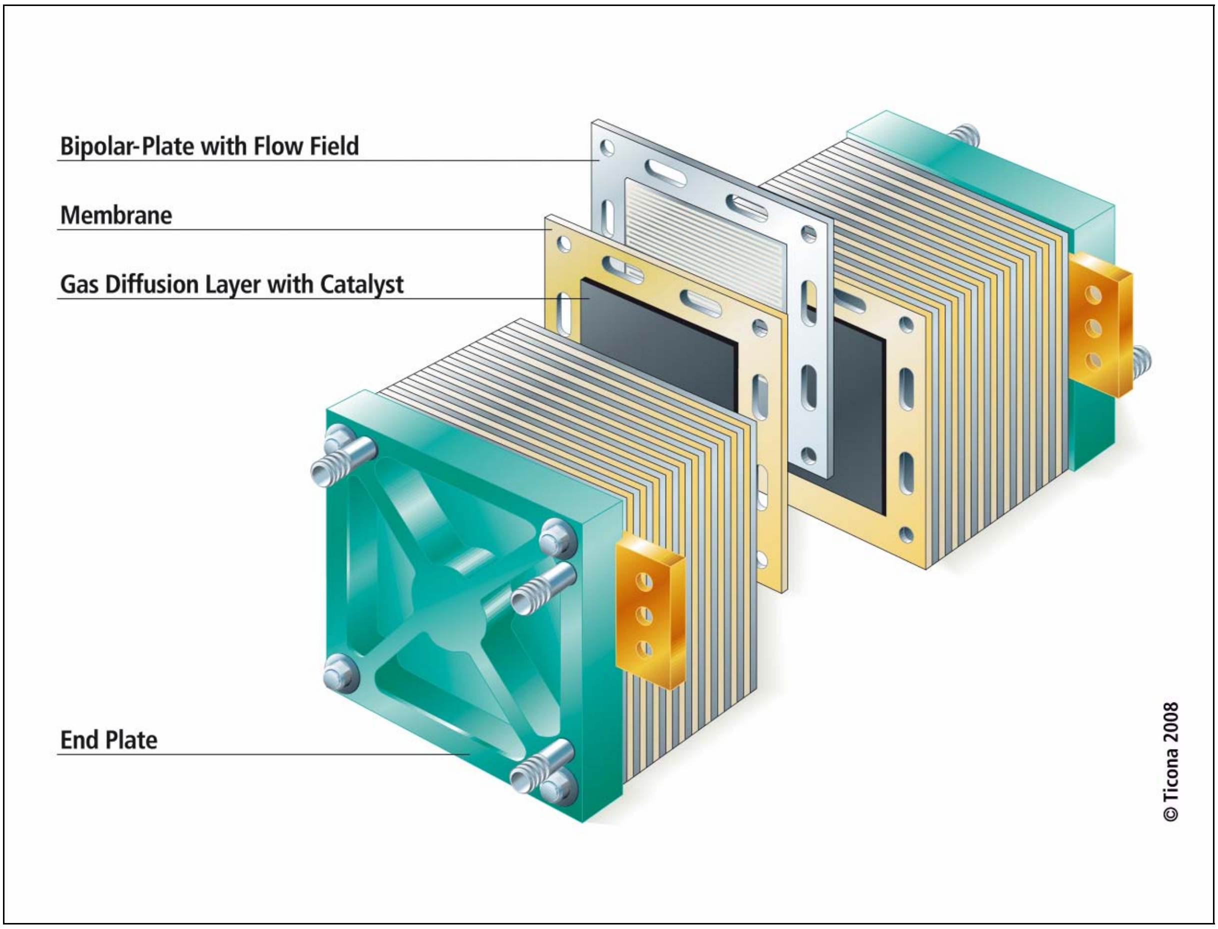

Figure 18: Fuel cell stack[22]

2.4.2 Hydrogen in Internal Combustion Engines[23]

Hydrogen ICE works quite similarly to conventional IC Engines. Usually they are adopted from gasoline, diesel or natural gas engines. As mentioned before, the big advantage is the direct conversion of hydrogen in mechanical rotation. Thus lighter and cheaper power trains can be realized, as you can see in the following picture.

[22] https://www.ticona-photos.com/sites/PhotoDB/PL/Forms/DispForm.aspx?ID=1420, 23.3.2010
[23] Cf. http://www.ika.rwth-aachen.de/r2h/index.php/Hydrogen_Internal_Combustion_Engine, 23.03.2010

Of course, like all high temperature processes, the H_2-engines have a natural maximum due to the Carnot process but it's still higher than a common gasoline engine due to leaner air-fuel ratio and higher compression ratios.

The following chart shows a comparison of H_2-ICEs and H_2-FC-Vehicles:

	Advantages	Disadvantages
Hydrogen ICE Vehicle	+ Well-researched and understood technology + Existing engine and technology hardware + Existing production facilities + Thermal management + Power density + Cheap production methods available	- NOx control and aftertreatment required - Lower efficiency
Hydrogen Fuel Cell Vehicle	+ Substantial fuel economy benefit over H_2-ICE (and a smaller but still essential benefit over hybrid H_2-ICE) + Zero tailpipe emissions + Quiet, good Noise, Vibration, Harshness (NVH) + Possible government incentives for development	- Vehicle/powertrain weight(low power density) - Vehicle/powertrain cost - Thermal management - Water management in cell - Precious metal supply/cost - System life - Servicing cost, complexity & infrastructure - Requirement for hybrid application (to achieve good transient response)

Table 2: H_2-ICE/FC comparison[24]

[24] Cf. http://www.ika.rwth-aachen.de/r2h/index.php/Hydrogen_Internal_Combustion_Engine, 23.3.2010

2.4.3 H_2 Safety[25]

Like many other fuels with high energy density, hydrogen has to be handled with care. But, like other fuels as well, if certain standards and specifications are considered, hydrogen is not more dangerous than other fuels.
E.g. hydrogen is non-toxic and will not contribute to groundwater pollution. If hydrogen leaks out, it does not create fumes.
As the lightest element hydrogen does not form puddles like liquids. In case of a leakage it volatilizes very quick.
Hydrogen is not just the lightest; it is the smallest element as well, which means that an unintentional crowed is quite unlikely. But if a crowed occurs, very little energies are enough to fire a possible hydrogen/air mixture.
Nevertheless, in the past 50 years hydrogen has been produced, distributed and used in several industries in a very safe way.

2.5 H_2 Introduction Challenge

2.5.1 The Hen-Egg-Problem[26]

Every new power concept for vehicles brings the problem of new infrastructures. Even battery vehicles and the emerging electrical energy demand to charge them will bring challenges in the electrical energy grid. Among all technologies, hydrogen is the one that is mostly affected by this issue.

The problems:
Three big Hen-Egg Problems occur in the whole situation:

1. Firstly, no vehicle manufacturer will provide vehicles, if no infrastructure is available.
2. Secondly, the vehicles are too expensive for users, but without users advantages of economies of scale can not be realized.
3. And thirdly, if hydrogen (H_2-infrastructure) is too expensive for users, economies of scale for hydrogen refuelling stations and hydrogen production can not be performed.

[25] Cf. http://www.hydrogenassociation.org/safety, 23.3.2010
[26] Cf. TETZLAFF (2008), p.278

The four big stakeholders in this situation are the infrastructure industry, the automotive industry and the end user. Each of these parties is dependent on the others and can not establish a successful business on its own. This means that all of these three parties have to exist. Infrastructure and vehicles are technological ready and in demonstration. Another question is the end user acceptance, which would complete the triangle for a demonstration and commercialization.

Narrow 4 and 7 shows an influence of costs on the price. As a first assumption price is a sum of costs and margin. The market volume for both, infrastructure and vehicles is a factor of orders and price. So, narrow number 5 and 6 show the influence of orders on the market.

Non of these stakeholders can grow on its own, thus it is very important that a close collaboration between all institutions, including the customer, is secured.

In the following picture a coarse overview of the situation is shown. The red arrows show the three previous mentioned Hen-Egg constellations and the black arrows the influence factors in one direction.

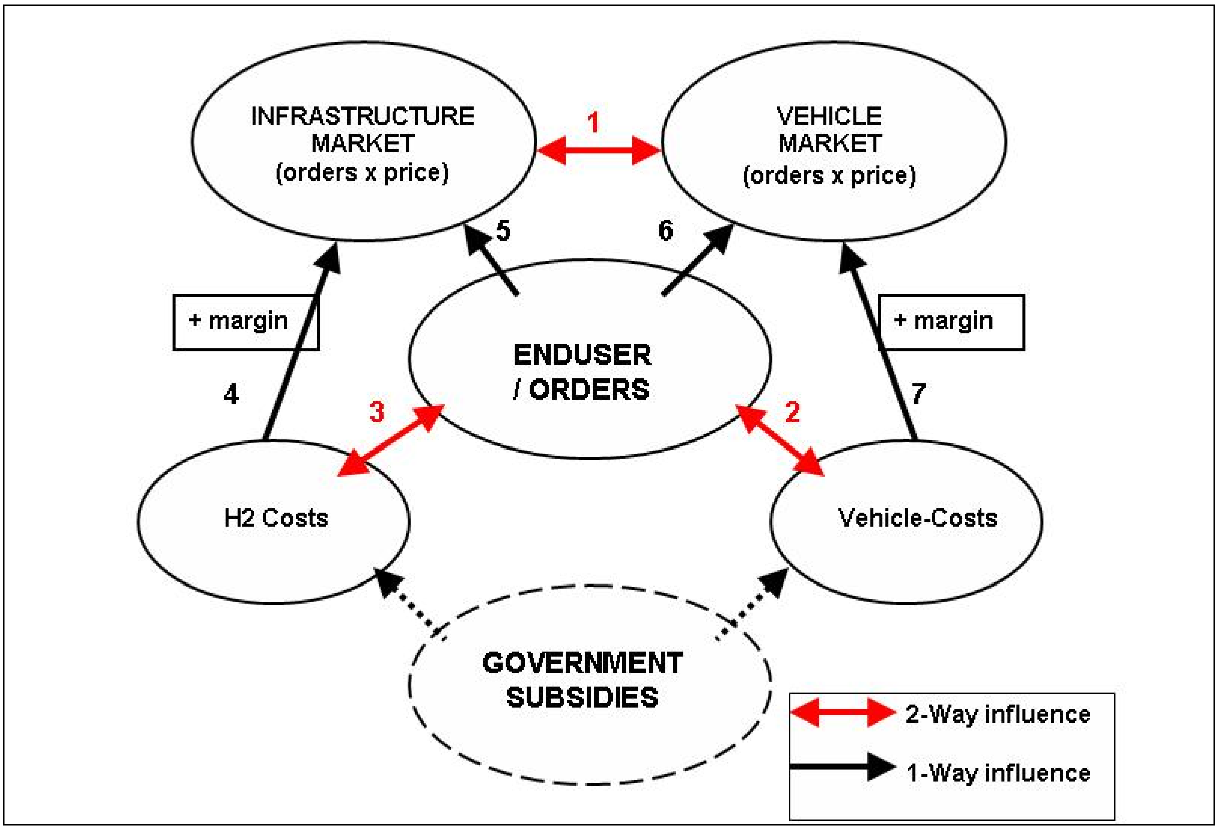

Figure 19: Graphical presentation of Hen-Egg problems

A possible way out of this situation is to fund directly the vehicles and the hydrogen infrastructure. This would create a market and would make hydrogen as a technology more competitive to alternatives.

2.5.2 Early Markets

The rollout strategy of the European Union is to promote applications where vehicles could be supplied with fuel from one point. In this case, at least the Hen-Egg problem between infrastructure market and vehicle market falls away.
These projects are also important to collect real life data of the usage of new technologies and secondly to demonstrate that the technology is ready and works.
With many of these projects also economical improvements (Hen-Egg problems 2 and 3) can be achieved.

Examples for early markets:

- Material handling vehicles
- Municipal vehicles
- Boats and ships on continental waters
- Onsite vehicles
- Busses
- Delivery fleets

2.6 Summarized Argumentation for Hydrogen

Hydrogen has the potential to substitute current technologies in a wide range. Based on the previous chapters arguments of hydrogen are summarized.

The production of hydrogen is environmental friendly.
As seen in chapter 2.3.2 technologies like electrolysis or biomass gasification are ready to produce hydrogen in an environmental friendly way. Better than to produce new hydrogen is to use by-product hydrogen from industry, which exists and is cheaper.
Distribution of hydrogen is ready.
Technologies to distribute hydrogen (chapter 2.3.4) are researched and industrially used. For industry purposes these methods are applied and well researched. Another alternative is to produce hydrogen local in smaller quantities.
Storage systems have appropriate power density.
As seen in figure 15 hydrogen storage methodologies are very good compared to other sustainable energy concepts. Based on the vehicle concept every required range can be realized by increasing the tank size.

Efficiency is sufficient.

Hydrogen in a fuel cell has much better efficiencies than a conventional ICE. This further increases the range of the vehicle. Current demonstrators fulfil the customer requirements on range. The well-to-wheel efficiency, which means the efficiency including production, distribution and conversion, does not matter if the energy source is environmental friendly and sustainable.

Refuelling is quick.

Refuelling time is comparable to common gasoline or diesel technologies. Therefore with hydrogen cars also long trips with short refuelling stops are possible.

Hydrogen is safe.

Like described in chapter 2.4.3, hydrogen is industrial handled for many years in a very safe way. Also current demonstrations had no problems with this technology in terms of safety.

In a nutshell hydrogen vehicles can offer the same comfort and characteristics than conventional vehicles. Already current demonstrators fulfil the same requirements like common vehicles. The main argument of critics is the low well-to-wheel efficiency does not matter if the energy source is environmental friendly and sustainable.

3 Basics to Invest Calculations

3.1 Investment

First of all it is necessary to say that in this diploma thesis investment calculation methods are used to identify the costs of a demonstration and the financial gap to conventional technologies. The main thought is to provide a potential customer with figures about how much a demonstration is more expensive than his fleet before.

3.1.1 Terms

Investment[27]

(Investire.lat= to vest. Eng./einkleiden Ger.)

Investment is the transfer from financial capital to assets. Based on this definition different forms of investments can be distinguished in:

[27] Cf. Däumler/Grabe(2003), p.16

Objects:	Real investment (Production, Plant) Finance investment Immaterial investments (Research/ Advertisments)
Purpose:	Establishment investment Replace investment Rationalization investment Extension investment Social- Secure-investment
Duration of use:	Short term Mid term Long term
Chronological:	Start investment Continuity investment
Investor:	Private Public

Table 3: Forms of investment

This categorization is not alternative; it is more a combination of all.

Depreciation[28]

Definition: Depreciation is a calculated worth decrease of an asset in a defined period of time.

Thus depreciation is a main component to “steer” earnings of an enterprise. Because earnings influence the taxes strict regulations for depreciation are fixed in laws.

The calculated worth decrease is not necessarily the real worth decrease of an item.

So, different depreciation calculation methods can be used in the cost accounting and the accountancy.

Reasons for depreciations can be abrasion, decrease of replacement costs and technological or economical overhaul.

[28] Cf. Blohm/Lüder (1991), p.37f

Linear depreciation

Depreciation can be calculated linearly, meaning that the value of the item decreases every year by the same worth.

Depreciation = (Invest. – Returns)/ Duration of usage

Declining depreciation

Another method is to decrease the value by a fixed percentage every year.

Linear(10 a)		Declining (30%)	
100000	10000	100000	30000
90000	10000	70000	21000
80000	10000	49000	14700
70000	10000	34300	10290
60000	10000	24010	7203
50000	10000	16807	5042
40000	10000	11765	3529
30000	10000	*8235*	*2745*
20000	10000	*5490*	*2745*
10000	10000	*2745*	*2745*
0		*0*	

Table 4: Examples: €100.000 depreciation for 10 years

The last three values at the declining method are linear.

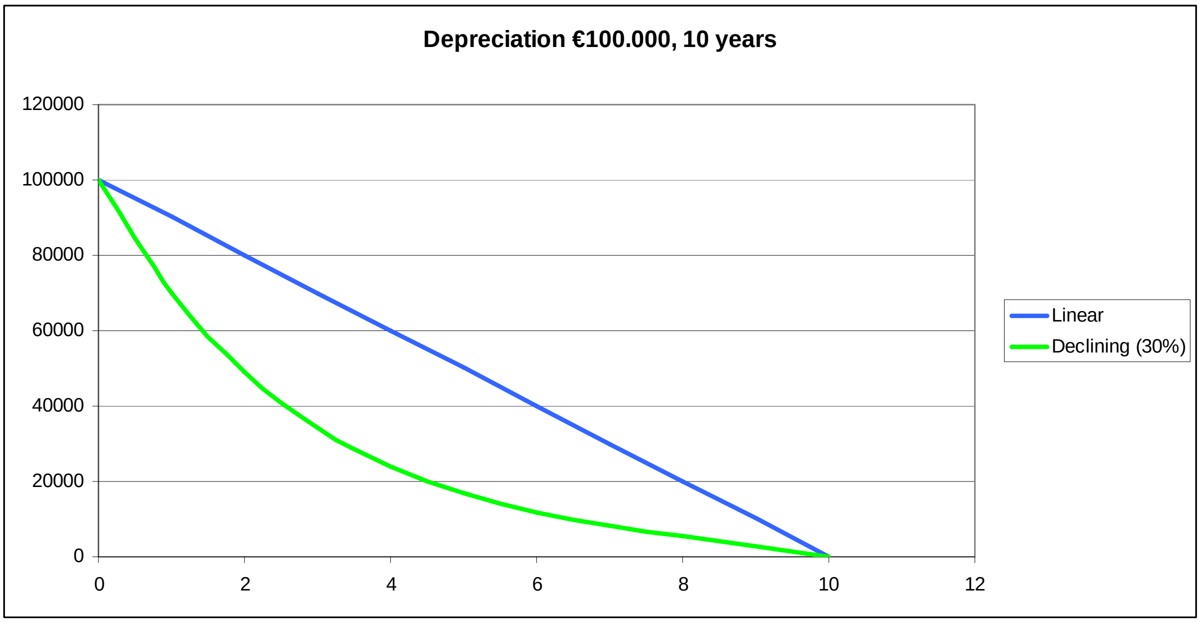

Figure 20: Depreciation methods

Interests[29]

Interests for calculations have to be fixed. The definition of interests for investments is:

"The interests are the subjective minimum expectations of an investor to the investment."[29]

In addition the financing conditions and the risks have to be included. With this interest rate the whole investment is checked then.

As mentioned before the interests are based on the financing methods, therefore:

With own capital financing: The lower boundary for the investment is the interest which can be achieved on the capital market.

If the investment is totally externally financed, the external interests are basis of the calculations.

Each mixture of these two methods is possible.

In order to come to suitable interest in view of risks in praxis often utility analyses are used.

Factors for this analysis could be technologies, experiences with these technologies, future costs or selling targets. All these factors have to be evaluated and assessed. The results of the analysis are points which mirror the risk and have to be transferred to interests.

The last here mentioned method is to define the interests after opportunity costs. This means that the interests of the second best investigation are used to calculate the best investment.

[29] Cf. Däumler/Grabe(2003), p.30

3.1.2 Investment Calculation Methods

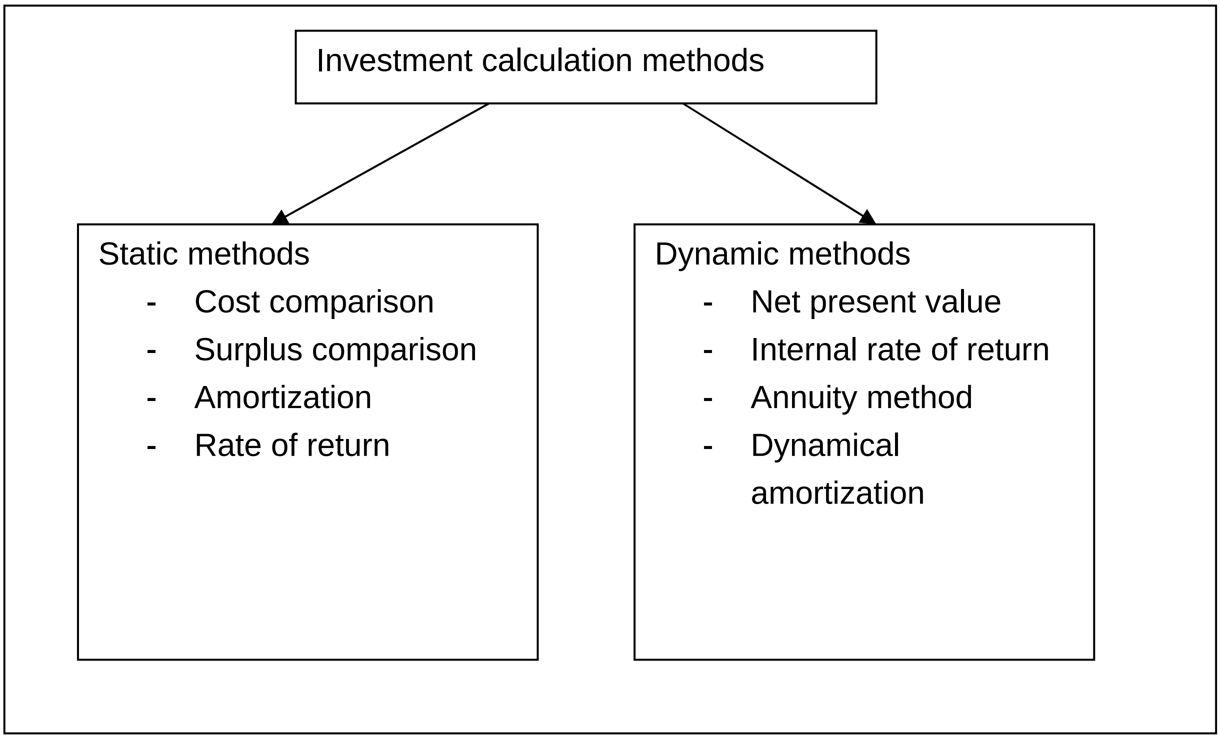

Figure 21: Investment calculation methods[30]

Several investment calculation methods are described in literature. The main differentiation is in static and dynamic calculation methods. The difference is the consideration of the time point when the money is transferred.

Static Calculation Methods

<u>Cost comparison</u>

Basis for this calculating method is the assumption, that the earnings or the output of the different alternatives are the same. Practically almost all alternatives have different attitudes and thus outputs.
So the cost comparison can be used to comprise alternatives or to replace an installed alternative.

On the next page a list of possible costs is listed. Not all of these costs occur at a hydrogen demonstration and are thus neglected in the upcoming chapters.

[30] Cf. Däumler/Grabe(2003) p.27 and Cf. Seicht(1995) p.124

The following costs are mainly involved:[31]

- Depreciation
- Capital costs
- Labor costs
- Material costs
- Maintenance
- Energy
- Space costs
- Tool costs

Surplus comparison

Premises of a surplus calculation are different outputs of investment projects.
If the investments have the same output or just fulfill a set of criteria the cost comparison is the choice.

Amortization time

The static amortization time shows a time from a first negative cash flow to the time when the positive cash flow exceeds the acquisition costs. The static amortization time neglects interests and assumes the interests to zero.
This can be the amortization of a single investment, or the comparison of 2 different investments if one has higher purchase but lower operational costs.
Enterprise policies often dictate maximum amortization times. These are different from branch to branch and range from three to seven years.

Profitability

Profitability is a ratio between surplus and invested capital:

Profitability = surplus / invested capital or less costs / invested capital

Usually profitability is calculated on an annual basis. The result is a figure in percentage on how profitable an investment is.

[31] Verband der chemischen Industrie (1974), p.5

Dynamic calculation methods

Due to interests an amount of money has more value in future. The static calculation schemes do not consider this fact.

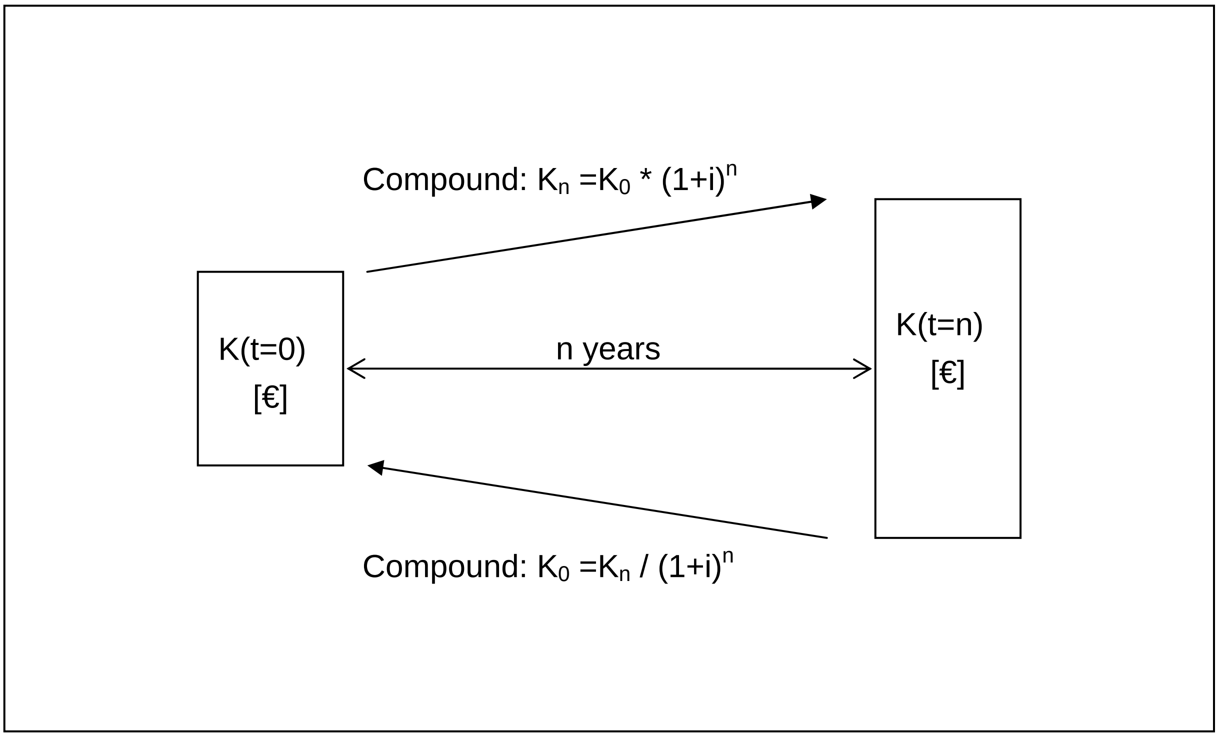

Figure 22: Compound/discount of money

t… Time in years
i … Interests
n … Number of years
K(t=0) … Amount of money now
K(t=n) … Amount of money in n years

In the following chapters only statical investment methods are used, thus here the dynamical investments will not be assed in detail.

Investment versus Financing[32]

Investment is a row of transactions, beginning with a payment.
Financing is a row of transactions, beginning with a deposit.

[32] Cf. Däumler/Grabe(2003), p.18

Every investment has its financing method, a source where the money comes from to establish the investment.

Sensitivity Analysis[33]

A sensitivity analysis complements the investment calculations. With this tool the coherence between input factors and output can be shown.

Two basic questions can be answered by a sensitivity analysis:

a.) How does an output factor react on a fixed deviation of an input factor?
b.) Which value of an input factor is necessary to get a set output factor?

The general process therefore is:

1. Firstly choose the insecure input factors
2. Determine the value for the deviation

3.a. Result is a change of the output value through a deviation of one input factor

3.b. In order to get an answer to the first question in the past the whole equation had to be modified. (Nowadays, this question can be answered with the in MS Excel integrated solver).

4 Status Quo

4.1 Listing of „Other Vehicles“ Demonstrators

The following chart shows a list with main information to “other hydrogen vehicles”.

[33] Cf. Blöhm/Luder(1991), p.234ff

Material Handling					
Name:	**Project location**	**Involved organizations**	**Number of vehicles**		**Detail**
DOD-DLA (Department of Defense- Defense Logistic Department)	Department of Defense in Susquehanna, Pennsylvania	Initiator: U.S. Department of Energy (DOE) and the Defense Logistics Agency (DLA)	40	forklifts (119 planned)	
DOD-DLA	Virginia		20	forklifts	
DOD-DLA	Washington		19	forklifts	
DOD-DLA	Georgia		20	forklifts	
Coca-Cola Forklift	Charlotte, North Carolina	Coca-Cola, Plug Power	40	forklifts	
GM	General Motors at Oshawa Car Assembly Plant	Hyster and Hydrogenics			
Anheuser-Busch	Colorado		23	lift trucks	
FedEx Forklifts	FedEx Freight's Springfield		35	forklifts	
Wal-Mart Wegmans		Crown(New Bremen, Ohio) Barrett Industrial Trucks(Marengo, Illinois, Cellex Power Products(Richmond, B.C.,Canada)	50	pallet trucks	
Whole foods	Maryland, D.C.		61	forklifts	in Oct. 2009
Central Grocers	Chicago Area		220	forklifts 140 + 80(?)	
Sysco	Texas		90	pallet trucks	
United Natural Foods	Florida		65	lift trucks	
13	Projects	Sum US:	683		
Airport Hamburg	Airport Hamburg	Still, Hydrogenics	3	2 tow tractors 1 forklift	Still R07-25, RX 60
BASF Coatings	Münster	Still, Hoppecke	1	forklift	Still FM-X20
Hamburg Harbor	Hamburg	Still, Hydrogenics	1	forklift	Still R60
Hoppecke			1	pallet truck	Still EK12
Linde Gas	Munich	LindeMH, Hydrogenics	2	forklifts	LindeMH E30
HyLOG	Fronius Sattledt	Fronius, LindeMH	2	tow tractors	Linde P30
6	Projects	Sum EuropeMH	10		

Table 5: List of material handling demonstrators worldwide

Name:		Project location	Involved organizations		Number of vehicles	Detail
Sweeper						
hy.muve		Basle	Bucher Guyer Sweeper, Proton Motor	1	Sweeper	
	1	Project				
US Truck						
Tyrano Truck		Port of L.A.	Tyrano	1	Truck	
	1	Project				
Ice Cleaner						
eP-Icebear		Canada	E-Power Synergies	1	Truck	
	1	Project				
Scooters						
Suzuki Burgman		London	Intelligent Energy, Suzuki	2	Scooters	
Vectrix VX-Fce		U.S.		1		
Yamaha FC Aqel		Japan		1		
	3	Project	Sum Scooter:	4		
Bikes						
EVN Bike			Intelligent Energy			
Suzuki Crosscage			Intelligent Energy, Suzuki			
	2	Project				
Passenger Boats						
ZEM Ship Alsterwasser Hamburg		Alsterwasser Hamburg	Proton Motor,	1	Ship	
Duffy Water Taxi San Francisco		San Francisco		1	Ship	
	2	Project	Sum Passenger Boat:	2		
Leisure Boats						
Zebotec Cobalt 233ZET				1	Boat	
Frauscher 600 Riviera HP		Traunsee (Austria)	Frauscher, Fronius, Proton Motor	1	Boat	
Hydroxy 3000				1	Boat	
X/V-1 Sailboat				1	Boat	
“No. 1”				1	Boat	
	5	Projects	Sum Leisure Boat:	5		
Submarine						
Siemens 212		Germany				
Siemens 214 (commercial product)		Germany				
	2	Projects				

Table 6: List of demonstrators worldwide

In total, 36 different kind of applications worldwide:

The tables bases on a internet research about past and ongoing demonstrators which fulfill the project boundary conditions(chapter 1.4).

4.1.1 Interpretation of Different Application Areas

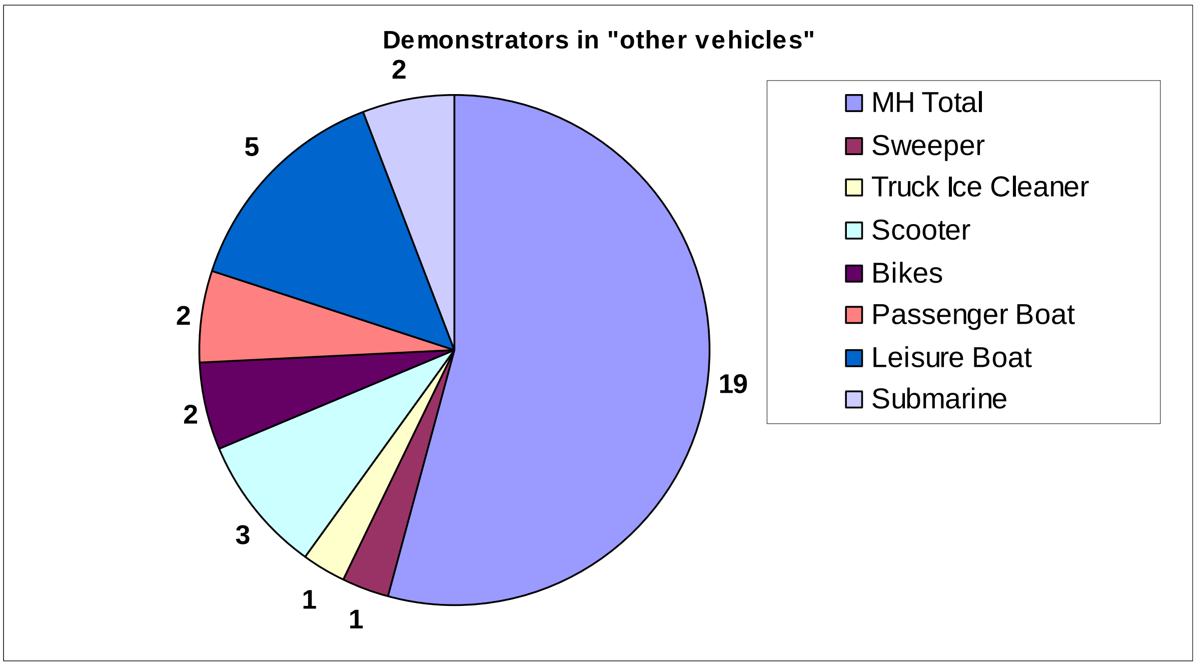

Figure 23 : Demonstration projects in "other vehicles" worldwide

The material handling sector is obviously the biggest group in the “other vehicle” segment. More than 50% of all demonstration projects worldwide are taking place in US and Europe only. From the number of applications the industry ambitions and expectation can be gathered.

In total, about half of all demonstrator applications are located in Europe.

In the US material handling sector are more than twice as many of different projects running than in Europe. In a total number of vehicles about 700 vehicles are around but just the material handling vehicles in the US are on the best way to raise up to 1000 vehicles. A first commercialization of fuel cells in the US material handling sector is expected in short term.

An important difference between EU and US is the funding system of demonstrator projects. The US Government offers direct incentives for the purchase of fuel cell systems in form of a tax credit equal 30% of the purchase price but not more than $3000/kW. [34]

Compared to the US System the European Union Funding system is quite complex. Therefore the right project partners have to find together and need an arrangement.

[34] Cf. Ballard(2009), p.2

An application has to be written and approved. If approved, a funding rate of about 50% is possible.

4.1.2 Hydrogen Storage

The most common hydrogen storage system in all investigated vehicles is the compressed gaseous 350 bar tank.
Additional storage systems are 200 bar, 700 bar CGH_2 and metal hydride tanks. No liquid hydrogen tanks can be found. The tank size is in the most applications designed in a way that important marks, e.g. one shift use, are possible.

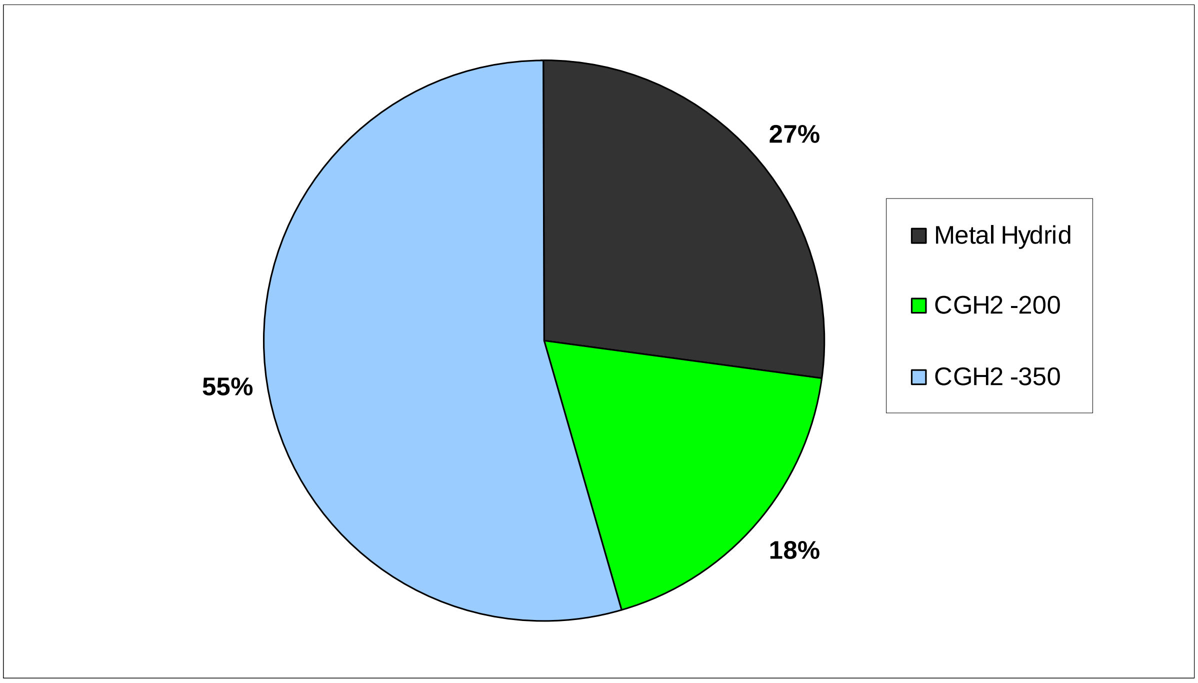

Figure 24: Hydrogen storage systems in "other vehicles"

4.1.3 Classification of „Other Vehicles” Demonstrators

“Other Hydrogen Vehicles” can be classified into the groups:

- Utility vehicles
- Bikes
- Boats

Every vehicle group itself can be sub-classified as follows:

Utility vehicles	**Bikes**	**Boats**
Material handling	Scooters	Passenger Boat
Tractor	Motorbike	Submarine
Sweeper		Leisure/Yachts
Truck		
Ice Cleaner		

Table 7: Classification of "other vehicles"

This classification was chosen on one hand to distinguish the vehicles coarsely in

- three or four wheeled vehicles
- two wheeled vehicles and
- Vehicles on water.

On the other hand, this classification improves the comparability with the two other vehicle groups fuel cell passenger cars and buses.

Finally the entire NextHyLights project covers hydrogen powered fuel cell vehicles in the segments

- Passenger cars
- Buses
- Utility vehicles
- Bikes
- Boats

4.2 Detailed Demonstration Projects

From the former listed European demonstration projects vehicle details were requested. Out of this approach following vehicle manufacturer showed interest to collaborate and handed over deeper project details. However, the "other vehicle" sectors are covered well representative.

Material Handling:	Linde E30 Forklift
	HyLog Linde-MH P30
Scooter:	Suzuki Burgman H_2
Municipal vehicles:	Bucher City Cat 2020 H_2
Boats:	Frauscher Leisure Boat Riviera 600
Ships:	ZEM-Ship Alsterwasser

4.2.1 Detailed Data Acquisition

Based on the internet research we requested some more detailed data from chosen vehicles. Not all manufacturers supported our activities.

One empty data sheet is attached. The filled in data sheets are confidential.

4.2.2 Graphical Comparison of Demonstrators

In figure 25 a comparison of all received vehicle data is shown. Due to this kind of presentation on the first view a lot of information can be gathered. Firstly, a big colored surface argues for the vehicle. Secondly, the big black line shows the characteristics of the conventional vehicle. Thus, if the surface meets the black line, hydrogen meets the conventional vehicle. Were the surface exceeds the black line, hydrogen is better than conventional vehicles.

The three technology factors (Lifetime, Range and Performance) are the ratio between H_2 to common technology. E.g. the range of a H_2 vehicle is 10h and of a battery vehicle is 6 hrs, a factor of 10/6 = 1,7.

The cost factors (Investment Cost Factor, Operational Cost Factor, Total Cost Factor) are the other way round. E.g. common vehicle price is €50.000 compared to the H_2 vehicle of 70.000 a factor of 50.000/70000=0,7
Thus the positive H_2 factors lead to a high figure and the negative factors lead to a high factor as well.
In all cases the H_2 technology is compared to the dominating conventional one on the market.
Typical usage times are the basis for cost investigations. The following gives a coarse cost overview. Some of the projects are much more economic with a higher operating grade. Costs base on a periodic costs calculation. Important to mention is that obviously not all data providers use the same calculating method for e.g. operating cost.

The following diagram should also serve as decision basis for the selection process of most potential and representative vehicles selected to go into more details in the next two deliverables of the project. One calculated data sheet is attached.

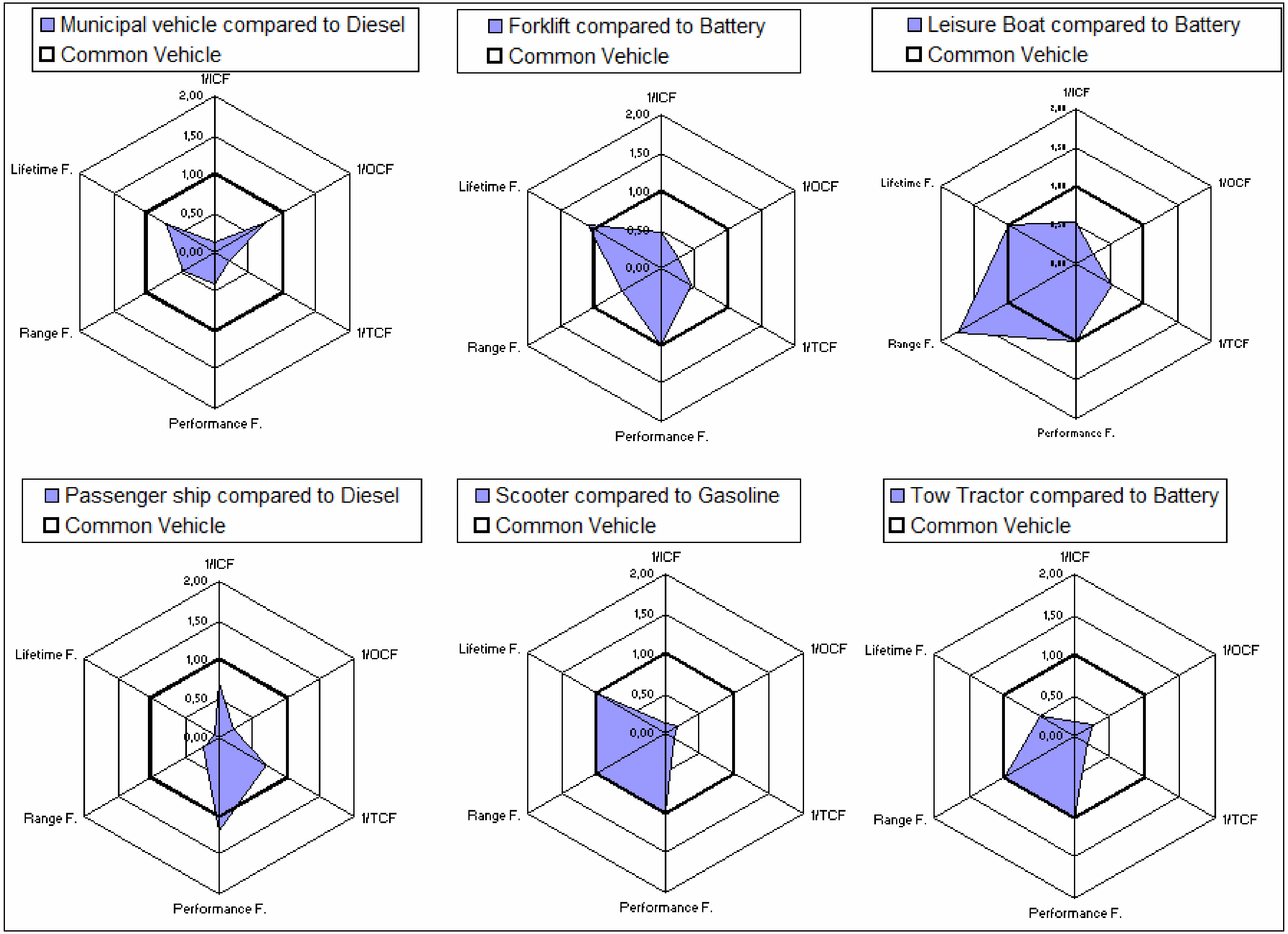

Figure 25: Spider diagram presentation

ICF… Investment Cost Factor, OCF… Operational Cost Factor, TCF… Total Cost Factor (with typical usage [h/a])

Technology factors for the fuel cell demonstrators (compared to pure battery applications) already reach quite good the requirements in

- range (operating time)
- vehicle lifetime
- performance

Bigger gaps are given in cost factors. Since some of the applications are related to very limited number of demonstrators or even one single demonstrator, careful interpretation of these cost factors is necessary.

Qualitative comparison:

	Municipal compared to Diesel	**Forklift compared to Battery**	**Leisure Boat compared to Battery**	**Passenger Ship compared to Diesel**	**Scooter compared to Gasoline**	**Tow Tractor compared to Battery**
Lifetime	+	++	+	--	+	+
Performance	0	+	+	++	+	+
Range	0	0	++	-	+	0
Investment costs	--	0	0	+	--	-
Operational costs	0	-	-	-	-	-
Total costs	-	0	0	0	--	-

Table 8: Qualitative comparison

++ …exceeds conventional technology

+ …meets conventional technology

0 … low behind conventional technology

- … demand for improvements

-- … currently far behind conventional systems

4.3 Other Important Decision Information

Following information should be considered for the selection of the vehicle group.

4.3.1 Potential Customers

Industry	Public Institution	Private Sector
Material handling	Passenger boat	Leisure/Yacht
Tractor	Sweeper	Scooter
Truck	Ice cleaner	Motorbike
Onsite transport		

Table 9: Potential customers for other vehicles

The earliest adopters of H_2-vehicles in relevant numbers will probably be industries where hydrogen is already needed for production. Thus, at least parts of the infrastructure are available.

These industries are:[35]

- Chemical and Pharmaceutical
- Electronic/Semi conductor
- Iron/ Non-iron Metal
- Welding and Cutting
- Glass
- Fats and Oils
- Ammonia
- Power Plants (Cooling Proposes)

Municipal Applications:[36]
Innovative communes or local region examples where hydrogen stations are already installed:

- NRW(D): +/-20 M€ budget in 2008
- Hamburg (D): +/-2 M€ budget in 2008
- Aragon (E): +/-3 M€ budget in 2008
- British-Midlands (UK): +/-4 M€ budget in 2008
- Piemonte(IT): +/-3 M€ budget in 2008
- Rhône-Alpes (FR): +/- 500 K€ budget in 2008 (new strategy in development for the future)

[35] http://www.airproducts.com/HydrogenPortal/hydrogen/production.htm, 25.04.2010
[36] Source confidential

Private Sector (boats for leisure time):

Lakes with emissions restrictions prohibiting ICE boats and ships (which are nearly the most in Europe)

4.3.2 Infrastructure Synergies to Cars and Buses

Station grid	**Single stations**	**Onsite stations**
Car	Bus	Passenger boat
Scooter	Sweeper	Submarine
Truck	Tractor	Leisure/Yacht
		Forklift
		Onsite transport
		Ice cleaner

Table 10: Infrastructure synergies

Station grid: Vehicles are dependent on a close grid of public refueling stations.

Single station: Vehicles operate around a base station and can return to it for refueling.

Onsite station: Vehicles are not allowed or it is not possible to drive on public roads, thus they need an inner-company station.

4.3.3 H_2-FC Vehicle Advantages

Hydrogen vehicles have some advantages against conventional solutions.

Material Handling Vehicles:

- Emission free indoor operation
  Special emission regulations about indoor operating vehicles in several European Countries.
- Low hydrogen refueling time instead of long stand still times for batteries recharging; no exchange of heavy battery backs
- Full performance even at low tank content vs. performance loss of batteries during low state of charge

Municipal Vehicles:

- Zero emission operation
- No particulate matter, no local greenhouse gas emissions
- More silent operation than Diesel based ICE

Boats, Ships:
Zero emission and silent power generation with fuel cells enable operation on lakes and rivers where strong emission restrictions prohibit operation of internal combustion engines.

4.4 Technology Benchmark

In the following tables the costs per unit can be found. These costs are the current costs of the demonstrators. Bigger volume discounts, economy of scale and other price reducing factors were neglected. Conventional technologies are already series high volume products and so well priced. Hydrogen is in all applications a prototype or small volume product and so comparably expansive. At this point it is very important to mention that fuel cells have a high cost reduction potential in future and could become a real alternative.

Data Source for all the following tables in chapter 4.4 are the received data sheets, catalogues and telephone research

4.4.1 Forklift

These power concepts are available:

	Costs per Unit [€]	Fuel economy	in kWh/h	in kgCO2/h	Range [h]	Refueling/ Changing time [min]	Note:
Diesel	40.000	3,4 l/h	33,32	8,976	8	3	Could be prohibited indoor
LPG	40.000	3 kg/h	38,7	9,66	4	4	
CNG	40.000	3 kg/h*	36*	8,25*	4*	4	*CNG-Heatvalue is depending on natural gas quality
Battery	45000**	6,25 kWh/h	6,25		8	3-20	**2 Batteries included
Fuel Cell(H2)	90.000	0,4 kg/h	13,332		4	3	

Table 11: Technology benchmark forklifts (3to)

In the calculations different vehicle performance and so productivity is neglected. Another competitor technology is the hydrogen ICE. But these vehicles will have efficiencies lower than diesel engine and a high price. These vehicles are currently in an early developing stage as well. An additional disadvantage of H_2-ICE vehicles is a NOx output compared to a zero-emission fuel cell truck.

All engine powered trucks produce emissions. The battery and the hydrogen powered trucks do not produce any emissions during their operation. But emissions can occur for the production of the electrical energy. Currently with an average EU electrical energy mix 450g CO_2/kWh appear. [37]

Beside CO_2 the ICE engines (Diesel, LPG, CNG) produce NOx, SOx, HC and CO. Particles could be exhausted, especially in the diesel engine, as well. New systems have particle filters. ICE Diesel vehicles equipped with these filters are under certain circumstances allowed to operate indoor.

4.4.2 Tow Tractors

	Costs per Unit [€]	Fuel economy	in kWh/h	Range [h]	Refueling/ Changing time [min]	Note:
Battery	12.000		0,26	30	20	
Fuel Cell	65.000	0,015kg/h	0,5	40	4	

Figure 26: Technology benchmark tow tractor[38]

With an efficiency of about 50% more compared to the battery version it is slightly above the other FC vehicles. The range of the FC-vehicle is a third higher than of its competitor.

4.4.3 Sweeper- Municipal Vehicle

	Costs per Unit [€]	Fuel economy	in kWh/h	in kgCO2/h	Tank	Range	Refueling/ Changing time [min]	Note:
Diesel	120.000	5,2 liter/h	51	13,7	78 liter	15h	3	
Fuel Cell(H2)	900.000	1,1kg/h	35,7		7,5 kg	7 h	4	

Figure 27: Technology benchmark municipal vehicle[38]

[37] Eichlseder/Klell (2010), p.11
[38] Data Source: Data Sheets, Catalogues and telephone research

It can be seen that the range of the H_2 vehicle is the half of the competing technology. With the fuel cell the energy consumption can be improved by 30 percent. With an emission free hydrogen production concept the emissions of these vehicles can be cut to zero as well.

4.4.4 Passenger Ship

	Costs per Unit [€]	Fuel economy	in kWh/h	in kgCO2/h	Tank	Range [h]	Refueling/ Changing time [min]	Note:
Diesel	1.000.000	9,6l/h	94,1	25,344	1500l	156	10	
Fuel Cell	1.400.000	1,39 kg/h	46,3		50 kg	36	10	

Figure 28: Technology benchmark passenger ship

The energy consumption can be cut down to 50 per cent with the fuel cell alternative. A significantly smaller tank reduces the range from 156 to 36 hrs.

4.4.5 Leisure Boat

Several different boat concepts can be seen:

	Costs per Unit [€]	Fuel economy	in kWh/km	Tank	Range	Refueling/ Changing time [min]	Note:
E-Boat	80.000		0,155	6,2 kWh	40 km		
Fuel Cell(H2)	150.000	1 kg/100km	0,33	23,3 kWh	70 km	3	
Diesel/ Gasoline	50.000	100 l/100km	9	175 liter	175 km	5	much more power

Figure 29: Technology benchmark leisure boat

The fuel cell vehicle in this application has a much higher range than the battery boat.

4.4.6 Scooter

	Costs per Unit [€]	Fuel economy	in kWh/100 km	in gCO2/km	Tank	Range	Refueling/ Changing time [min]	Note:
Gasoline	3.700	3,8 l/100km	34,2	88,54	11 l	290 km	1	
Electric 7kW (Batt)	9.000		3,4		3,7 kWh	110 km		
Fuel Cell (H2)	32.000	0,114kg/100km	3,8		0,4 kg	350 km	1	

Figure 30: Technology benchmark scooter

FC- Efficiency seems to be very high. This could happen due to different drive cycles.

4.5 Infrastructure Aspects

4.5.1 H_2-Onsite Electrolysis: Hydrogenics Solution

Figure 31: Hydrogenics electrolysis refueling station[39]

Hydrogenics electrolysis refueling station
The main modules are electrolyser, compressor, storage and dispenser.

Full station prices vary a lot. The following prices should give a coarse idea.

120 kg/day 350bar fueling station:	1.000.000€
240 kg/day 350bar fueling station:	1.700.000€
60kg/day fueling station 700bar:	1.175.000€
120kg/day fueling station 700bar:	1.660.000€

Calculated with an efficiency of about 50%, and an energy price of €0,10/kWh the energy costs are €0,20/kWh or €6,66/kgH_2. But then the hydrogen still requires energy for compression and dispensing.
Delivery time for these systems is about 12 months.

[39] Hydrogenics Email, 15.05.10

4.5.2 Delivered Hydrogen: TU-Graz Campus

Figure 32: Hydrogen refueling station TU-Graz[40]

Delivery price depends on the delivery distance. Price for hydrogen is about €500-600 per 1000 Nm^3.
Investment for the station is €1.200.000.

4.5.3 Refueling Station for Companies with Hydrogen on Site[41]

This system is an easy solution for companies where hydrogen is already on site.

[40] Eichlseder/Klell(2010), p. 293
[41] Air Products catalogue: http://www.airproducts.com/NR/rdonlyres/F2BF2379-C48E-4DEB-9D00-2044A42E2AC8/0/Fuel_Stations_Fleets.pdf, 22.5.2010

Figure 33: Air Products Series 100 station[42]

For fuel capacities of less than 20 kg/day(about 50 vehicle operating hours per day) and pressures to 350 bar.
These systems cost between €150.000 and €300.000.

4.5.4 Hydrogen Infrastructure Maintenance Costs

Almost all infrastructure solutions lead to the same amount of maintenance. Approximately 10 percent of the investment costs are maintenance costs annually.

4.5.5 Battery Changing Systems

Battery changing systems are a very crucial factor for a substitution to hydrogen solutions. Therefore it is mentioned and explored. A complex, time costly and for workers dangerous changing process reduces the productivity of MH-vehicles. But there are already suggestions around how to accelerate the battery changing process. The general methods are:

Method 1: Forklift battery lifter
This can be done with another forklift or a crane. This process is time costly and dangerous for the workers. An average Battery change takes 20-30min.

[42] http://www.intellergy.com/photo_gallery.htm, 28.07.2010

Method 2: Side battery change

Modern forklifts are designed to change batteries with a hand lift. Here the battery is pulled in and out of the truck from the side. At some other modern systems the batteries have fixed tires, so not even the hand lift is needed. For this process in average 6 min are needed. Here a storage place for the battery is required as well.

Method 3: Battery change with a battery changing station

If more battery vehicles are on site, mostly a battery changing station is built in. the forklift comes to the station and the driver is able to unplug, change and plug the battery within 3 min.

Figure 34: Enersys battery changing station[43]

This changing station is designed for 28 Batteries. With an investment of €16.000 excl. Chargers this is a very cheap solution to accelerate the changing process. If 28 Batteries are in the changing station the same amount is in the vehicles. This means that in total 56 Batteries are on site (excl. spare batteries).

The picture on the next page is a more expensive but totally automatic battery changing station.

[43] Email Enersys Austria, 27.06.2010

Figure 35: Full automatic battery changing station.[44]

Cost example for another battery changing station with full automatic battery changing installed in Austria. 110 Batteries: Investment €270.000 incl. chargers

Batteries can cause infrastructure costs. Not only for the changing station also for the space which is needed to change and store the spare batteries.
An average price for warehouses in Europe is €5/sqm.[44]

5 Feasibility Study for Material Handling-Vehicles

The project consortium decided to investigate the material handling sector in more detail. So the following feasibility study is about material handling vehicles.
Task is as mentioned in the previous chapters to provide information and to investigate how a high volume demonstration has to look like to be successful.

5.1 Advanced Status Quo

In the current research all vehicle groups should be treated in the same way. From this point the whole thesis will focus on material handling vehicles, and here

[44] AVL Controlling

especially with the high volume Class 1 forklifts. In this area the most vehicles are demonstrated and detailed information for the Linde E30 Demonstrator is available.

5.1.1 Classification of Material Handling Vehicles[45]

There are seven classes of forklift that describe the fuel option of the forklift and the use.

Class 1 - Electric Motor Rider Trucks
These vehicles are motorized by industrial batteries and use transistor motor controllers to control travel and hoist functions. These are very versatile and are found from the loading dock to the storage facility. They are usually used in areas where air quality factors need to be considered. These forklifts can be equipped with either cushion or pneumatic tires.

Class 2 - Electric Motor Narrow Aisle Trucks
This forklift is for companies that opt for very narrow aisle operation. This allows them to maximize the use of storage space. These vehicles have developed unique features that are designed to minimize the space occupied by the truck and to improve speed and efficiency.

Class 3 - Electric Motor Hand or Hand-Rider Trucks
These are hand controlled where the operator is in front of the truck and controls the lift truck through a steering tiller. All controls are mounted on the top of the tiller and the tiller is moved side to side to steer the truck. These vehicles are battery powered with the smaller capacity units using industrial batteries.

Class 4 - Internal Combustion Engine Trucks - Cushion Tires
These forklifts are used inside on smooth dry floors for transporting palletized loads to and from the loading dock and the storage area. The cushion tired forklifts are lower to the ground than pneumatic tired forklift truck. This makes cushion tired forklift trucks more useful in low clearance applications.

Class 5 - Internal Combustion Engine Trucks - Pneumatic Tires
These trucks are most commonly seen in industrial outdoor applications. They can be used either inside or outside and used in virtually any type of application. Because

[45] http://logistics.about.com/od/legalandgovernment/a/forklifts.htm, 27.05.2010

of the large capacity range of this series of lift truck, they can be found handling small single pallet loads to loaded 40 foot(12 meter) containers. These lift trucks are powered by internal combustion engines and are available for use with LPG, Gasoline, Diesel, and Compressed Natural Gas fuel systems.

Class 6 - Electric and Internal Combustion Engine Tractors

These vehicles are versatile and can be used in a variety of applications. They can be equipped with either internal combustion engines for outdoor use or battery powered electric motors for indoor use.

Class 7 - Rough Terrain Forklift Trucks

Rough terrain forklifts are fitted with large flotation type tires for outdoor use on difficult surfaces. They are often used at construction sites to transport and lift building materials to various job site locations. They are also common with lumber yards and auto recyclers.

5.1.2 Market Data

Market sizes:

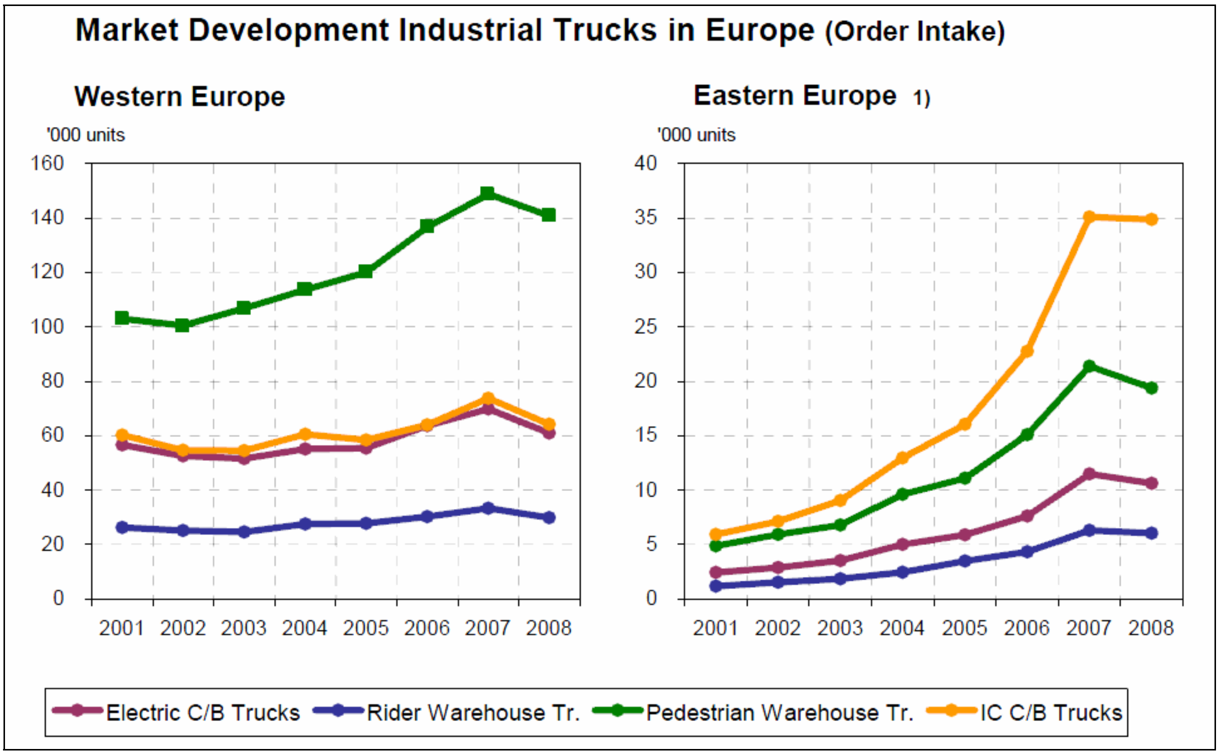

Figure 36: Market sizes for material handling vehicles[46]

[46] FEM-IT-NC/N158 Facts Industrial Truck Market

In West Europe about	140.000 #	Pedestrian Warehouse Trucks (47%)
	65.000 #	ICE-Counterbalanced (C/B) Trucks (22%)
	62.000 #	E-C/B Trucks (21%)
	30.000 #	Rider Warehouse Trucks (10%)
	297.000 #	TOTAL

In east Europe about	35.000 #	ICE-C/B Trucks (50%)
	20.000 #	Pedestrian Warehouse Trucks (28%)
	10.000 #	E-C/B Trucks (14%)
	5.000 #	Rider Warehouse Trucks (8%)
	70.000 #	TOTAL

In East Europe much more ICE trucks are used than in West Europe, also in relation to the whole branch.

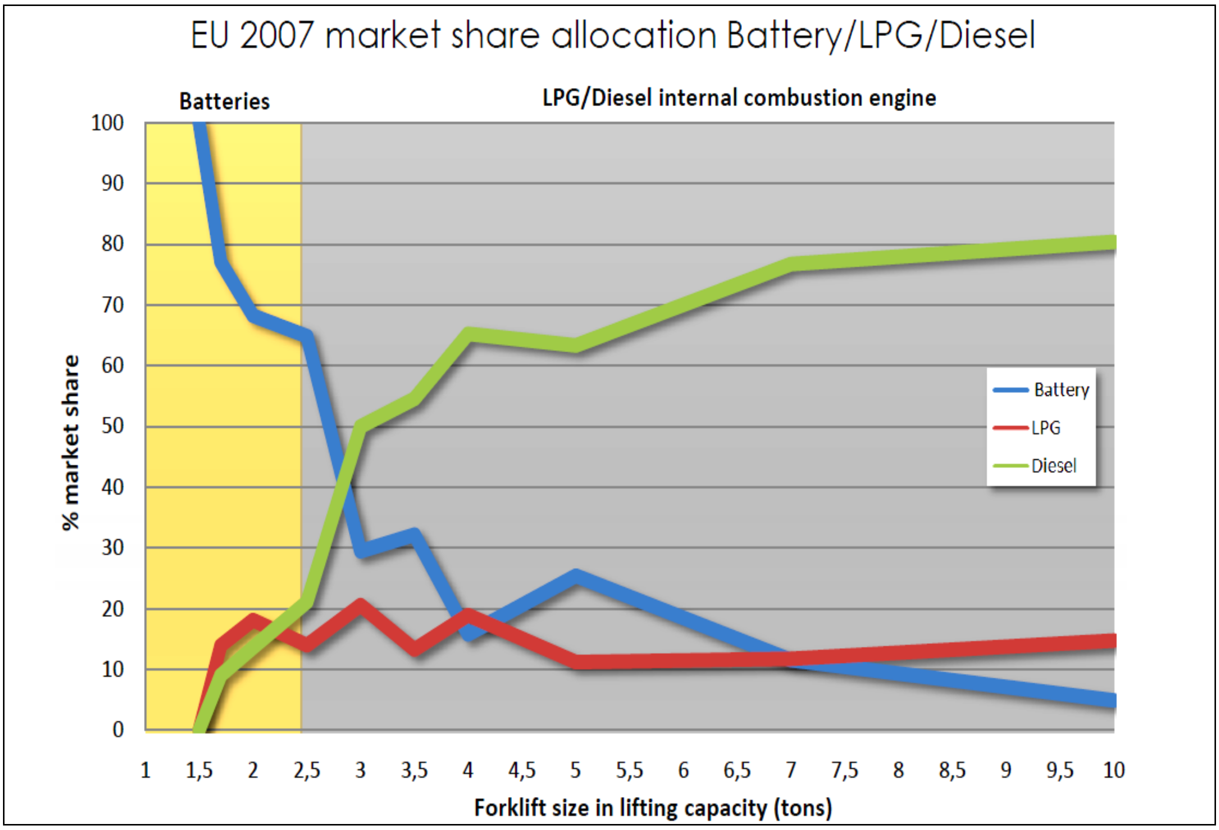

Figure 37: Propulsion technology in material handling[47]

[47] European Federation of Materials Handling, www.fem-eur.com

It is obvious is that in the lower load area batteries are very popular. The higher the load the more energy is needed. Therefore ranges of battery vehicles are not an option any more and diesel engines get popular.

5.1.3 Usage Behavior of Forklifts

Vehicle Lifetime

Maximum lifetime of forklifts is 20.000 hours.[48]

Use in shifts

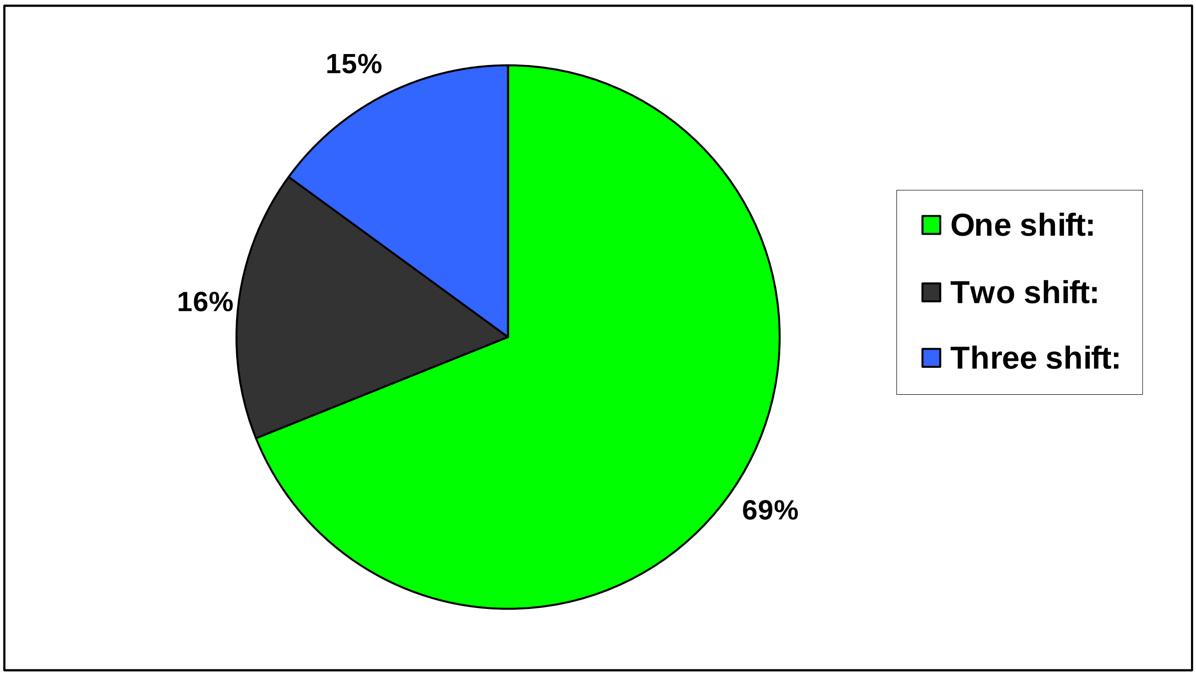

Figure 38: Usage of forklifts in the US[49]

Typical Capacities for Forklifts

No manufacturer provided this data. Some phone calls with salesmen and service workers leaded to following result:

Capacities vary from 300 to 7600 h per year.

In average a forklift is about 1000 h per year in use. If a forklift is used the whole shift and has a separate driver about 1200h /shift can be seen.

With an average of about 1750 h/a (1200/1750= 68% of the drivers time) this value seems reasonable.

[48] Telephone research: Linde Material Handling

[49] Cf. Barttelle/DOE (2007), p.80ff

5.1.4 Prices for the Vehicle[50]

Prices for Material Handling vehicles vary very much. Therefore we chose the Linde-MH E25/30 as a representative vehicle for a Class 1 forklift. The E25/30 is a high volume model, has a maximal load of 2,5/ 3 tons and is already in the demonstration phase at Linde Gas Munich. The current battery forklift does not have to be changed a lot. Just the display for the FC Unit has to be integrated in the interior of the forklift.

Prices:

Vehicle:	€ 30.000 - 35.000
Lift pole:	€ 3.000 - 10.000
Other mandatory parts:	€1.000-2.500
TOTAL Vehicle:	€34.000- 47.500 and more

Lifetime depends on the use as well, but can be assumed with 20.000 to 30.000 hrs.

Price development of H_2-vehicles:
The vehicle, the lift pole and other mandatory parts will not change significantly in the next years.

5.1.5 Fuel Cell Systems and Prices

Current Systems sold in Europe for 3 tons forklift have about 10kW continuous power.
Beside Plug Power, Hydrogenics is one of the leading fuel cell power pack manufacturers in the world. Almost all material handling demonstrations in Europe use this system. The system has the dimensions like the lead acid battery and can be directly substituted. Because weight is welcomed at forklifts steel plates have to be placed under the power pack to get the necessary counterbalance weights.
A display is placed in the view of the driver and a wire has to be connected to the power pack.
This power pack is shown in the following picture.

[50]Confidential source

The Hydrogenics HyPX™ 1-855 system used in the Linde E30 H_2:

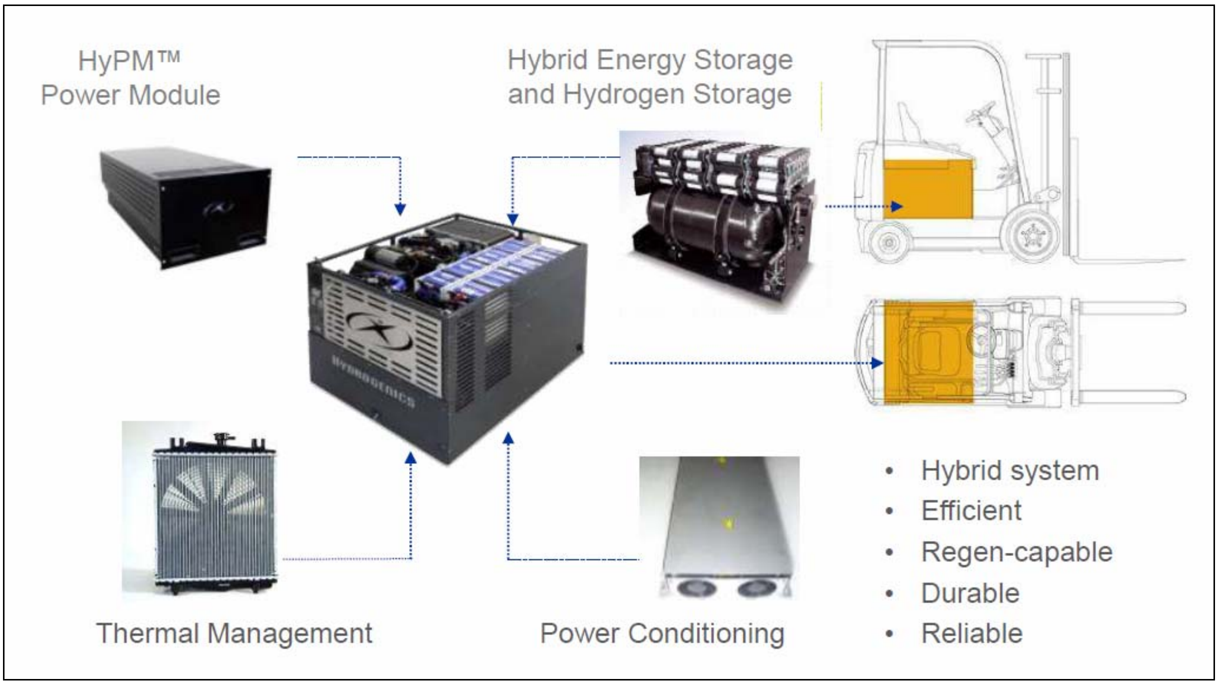

Figure 39: Hydrogenics system[51]

Technical Data:

Net Power Output (Continuous):	10 kW
Max. Power Output – Peak :	30 kW
Available Electrical Energy:	25 kWh
Weight:	1150 kg
H2 Fuel Storage Capacity:	1.6 kg
H2 Fuel Storage Pressure 15°C:	350 bar

Price: €50.000

This price is as high because so few pieces are produced. Important to mention is that price targets are less than 40% of today's prices. With high volume production and further research lower prices can be realized.

Manufacturers confirmed that space for bigger tanks is available but this tank size was enough for all demonstrations so far.

[51] Email: Hydrogenics

5.1.6 Battery Prices

Currently lead acid batteries are the standard. Due to the requirements on the weight of the batteries there is no need to change to other technologies. Lead is a market regulated price, so the costs of the batteries vary with the lead market price.

Current prices depend on the capacity:[52]
Battery: depending on capacity €6.000- 8.000
E.g.: 80V 625Ah €6500.-
Battery charger: depending on charging speed €1.000- 4.000
E.g.: To load 80V 625Ah in 8h €3200.-

The durability of one battery varies with the use. In average batteries have to be changed once a shift. This change is quite a problem currently (see chapter 4.5.5).
Lifetime of a battery is about 1200 charging cycles, with 8 hr per cycle every battery has to be replaced after 9600hrs. [53]

5.2 Cost Calculations

In this chapter the costs are shown. For the calculation a static cost comparison is chosen. First the pure costs for one vehicle are calculated. All the costs together lead to the operating costs for one vehicle.
In the total project comparison infrastructure purchase and maintenance are additional to the vehicle costs included in the calculation.

5.2.1 Investment Costs for One Vehicle

	Battery		Fuel cell		Diesel	
Forklift:	40000	€	40000	€	40000	€
Power pack:			50000	€		
Battery(2#)	12000	€				
Sum:	**52000**	**€**	**90000**	**€**	**40000**	**€**

Table 12: Purchase costs of vehicles

In all the further comparisons Battery vehicles are calculated with 2 Batteries. Applications where the vehicles are used one shift, thus two shifts are available for charging, are neglected.

[52] Source confidential
[53] Values from LindeMH

Battery vehicles are as shown in chapter 4.1 from €34.000 upwards. The fuel cell vehicle is the same vehicle with some small changes (display, etc.).
Diesel vehicles are about €40.000 as well. The advantage here is that no battery costs occur.
In all calculations it's assumed that no selling price, nor disposal fees occur.

5.2.2 Rental for Material Handling Vehicles[54]

Another option is to rent the vehicles. Almost all OEMs offer rental packages for common vehicles.
Example for a 3 ton battery forklift (5a, 1000h/a):
Rental: 700-800 €/month
Service: 200-250 €/month with 1000h/a
The service includes not always the same. Sometimes battery and tires are included as well.
Example for a 3 ton diesel forklift (5a, 1000h/a):
Rental: 600-700 €/month
Service: 100-150 €/month with 1000h/a

5.2.3 Pure Energy Costs

Comparison of a 3ton forklift:

Energy:	**Battery**		**Fuel Cell**		**Diesel**	
Price:	0,1	€/kWh	6	€/kg*	1,2	€/l
Consumption:	6,25	kW	0,4	kg/h	3,4	l/h
Energy costs:	**0,625**	**€/h**	**2,4**	**€/h**	**4,08**	**€/h**

Table 13: Calculation chart of fuel prices[55]

[54] Source confidential
[55] http://www.haschcon.com/2010/07/nachrichten-diesel-preis-in-deutschland-unter-eu-durchschnitt/, 15.07.2010

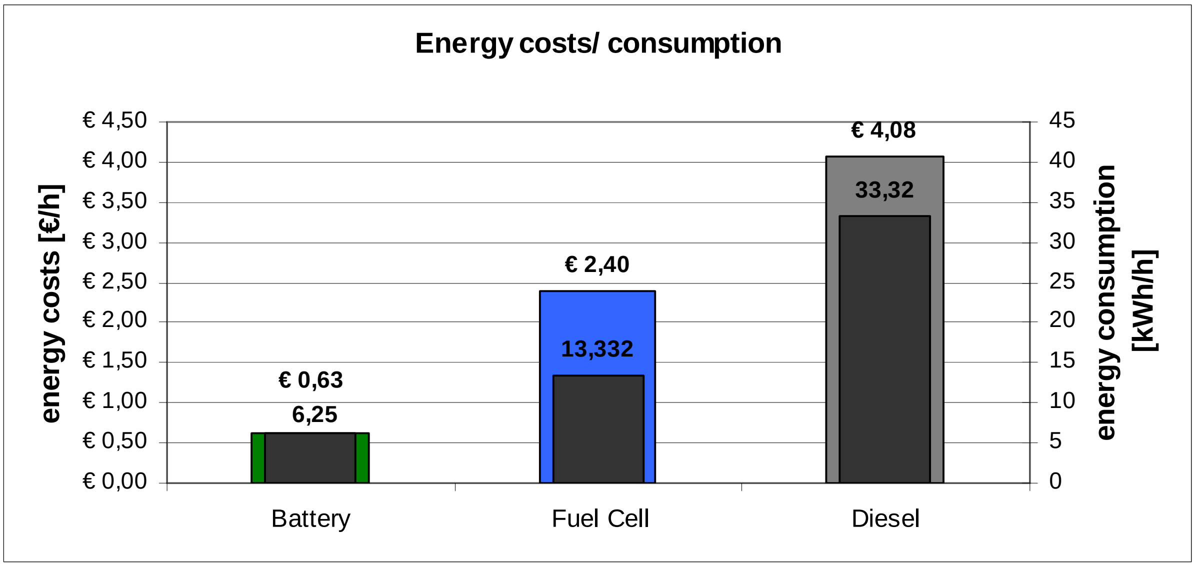

Figure 40: Comparison of taxed energy costs of a 3ton forklift in €/h.

In order to get the same energy price per hour as a battery forklift, hydrogen has to be sold with €1,6 at pump, if consumptions and energy price stay the same. (6,25 kWh/h*0,1 €/kWh/0,4 kg/h= 1,6€/kg)

5.2.4 Pure Maintenance Costs[56]

Data from Industry partners showed that about 1 €/h for battery and diesel appears. Research showed that hydrogen maintenance costs are about 2-3 times higher. So in the following calculations €2,5/h were considered. Maintenance costs sometimes are split in fix and variable costs. Here, all maintenance costs are considered as variable.

5.2.5 Pure Productivity Costs

Productivity Costs due Persons

If a machine needs maintenance time and in this time a person is this maintenance, more persons are needed to get the same work done. Typical labor rates are €30-40 per hour. E.g.: with a labor rate of €40/h a 20 minute battery change costs €13,33 because the person has to be substituted from another person in its main activity, or has to work 20 minutes longer.

[56] Source confidential

Productivity Costs due Machines

At a machine it is quite similar. If a machine has an availability of 80%, 125% of the machines are needed to get 100% of the workload done.

E.g.:

Opportunity 1: 10 Machines with 100% availability

Opportunity 2: 13(12,5) Machines with 80 % availability

Leads to: 30% more investment costs

These costs are just legitimate if operation of around 100% is given. Thus, in the following example this is neglected.

Considered are machine costs, which means that the annual machine costs are divided by the hours of use multiplied by the hours for refueling.

Battery/ Fuel Cell Productivity Costs

Productivity costs depend on several factors and can be calculated with numerous methods.

Assumptions:	Refueling time:	20 min Battery change	5 min FC-Refill
	Personal costs:	40€/h.	40€/h
	Costs per Event:	**13,33€/change**	**3,33€/refill**

Machine costs for one event are machine costs per year/ hours per year * refill time

Machine costs/a:	€12.000	€21000
Hours per year:	1000	1000
Refill time:	20 min	5 min
Costs per event:	3,6 €/change	1,75€/refill

So in total battery change/ H_2-refill is **€19,93** and **€5,08**.

It depends on the range how often a change/refill occurs.

With a range of 8h for the Battery and 4h for the hydrogen vehicle machine costs are:

2,49€/h for Battery and **1,27€/h** for FC vehicles.

Assumed with about 5 minutes for a refill and a similar range the Diesel forklifts have the same productivity costs like the fuel cell vehicles.

5.2.6 Total Operating Costs

Operating costs consider:

- Energy costs
- Maintenance
- Capital costs
- Productivity

Some of these costs are totally linear, like energy costs. Others are pending on the annual operating hours, like capital costs. In the following charts the development of the operating costs for 1200, 2400 and 3600 vehicle hours can be seen in a 5 year project.
Battery is calculated with battery changing station. Which means that the changing time is 5 minutes.

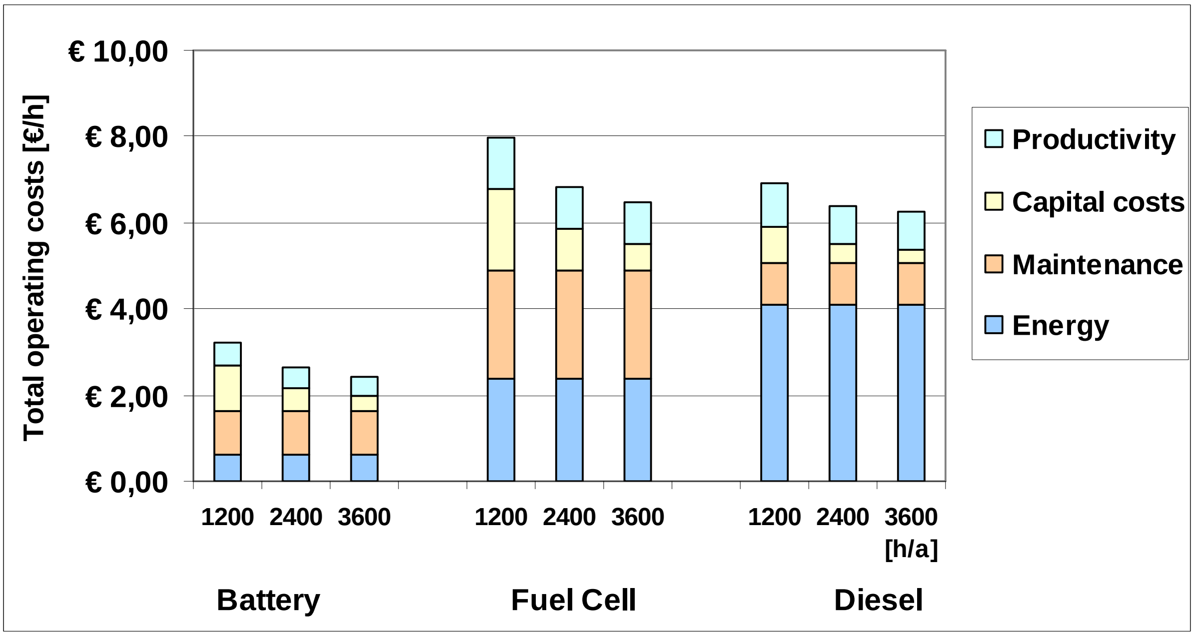

Figure 41: Operational costs per hour for 1200, 2400 and 3600 [h/a]

With in average 1200 hours per shift this three columns mirror a one, two and three shift use.
Accordingly, the following operational costs per hour over capacity can be seen:

Case 1:
In this case the battery is calculated with a battery changing station(5min change), and the Diesel with €1,2 per liter.

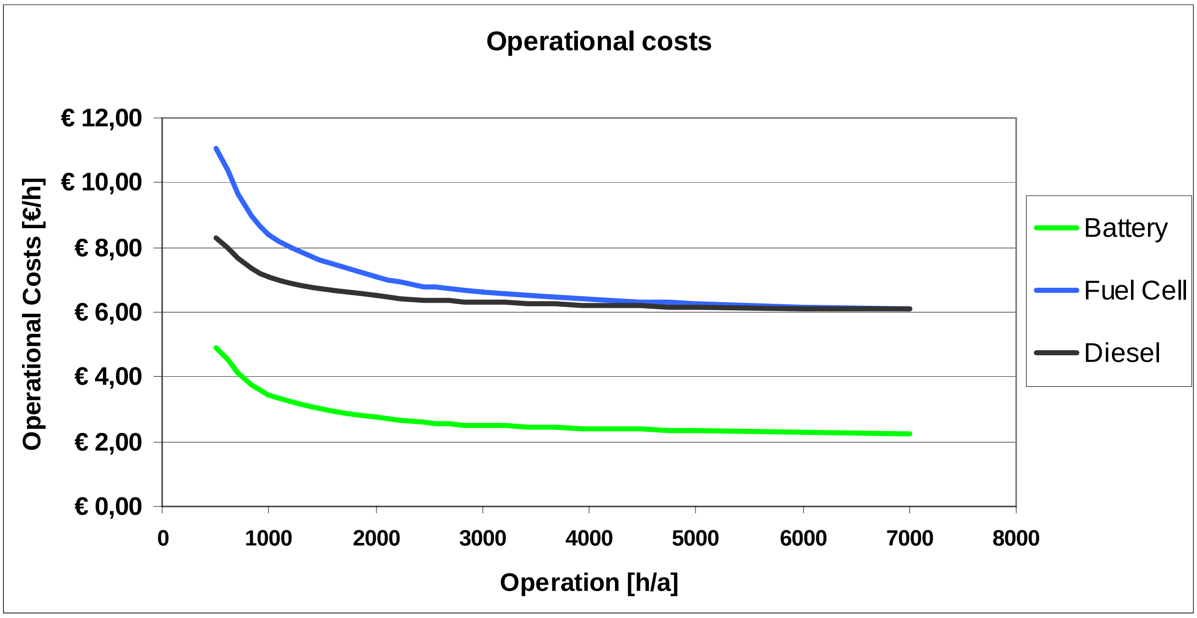

Figure 42: Operational costs per hour over capacity

A theoretical intersection is at 8250h/a.

Case 2:

In the next case the boundary conditions are changed slightly to an application without a battery changing station (20 minutes change). Further the Diesel price is increased to €1,4 per liter. The higher Diesel price is just used for this diagram, in all further calculations it is €1,2 again.

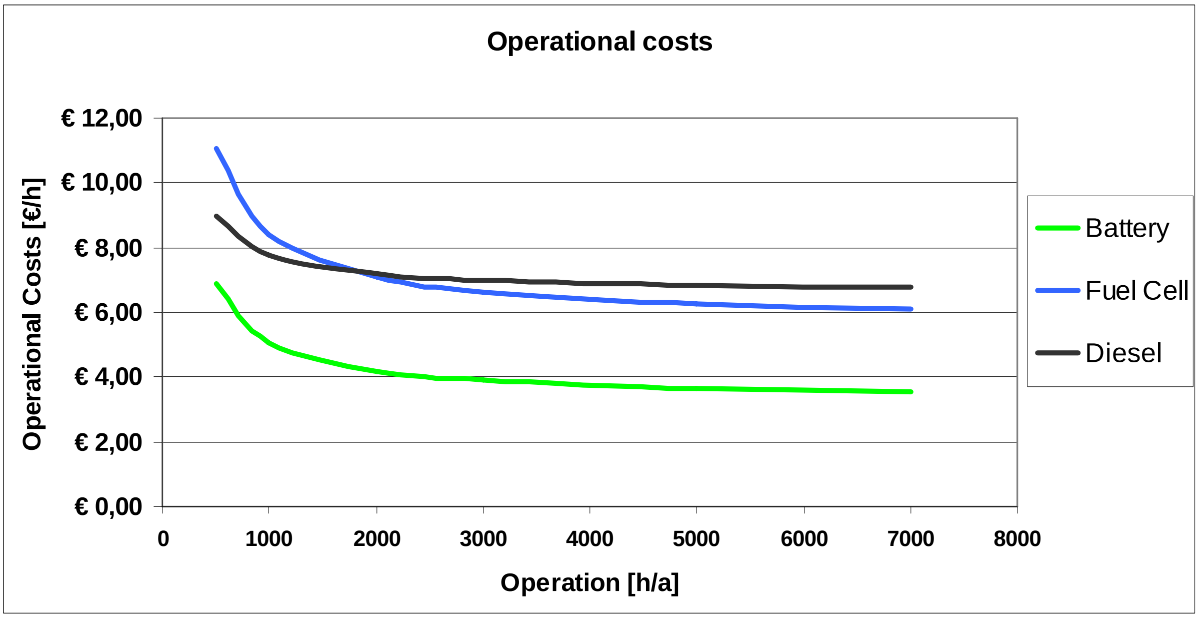

Figure 43: Operational costs per hour over capacity

Now the battery operating costs still can't be reached but the Diesel forklift operation is more expensive with a usage more than 1726 h/a.

The intersection between fuel cell and diesel can come down if diesel price further increases, hydrogen price or hydrogen investment costs decrease.
Battery operational costs can't be underbid, not even with 20 minutes per battery change.
Out of this we have learnt that hydrogen could be an alternative to diesel forklifts with high capacity. Battery solutions are currently operationally cheaper than alternatives.

If a battery changing station is used, the changing time can be reduced to approximately five minutes. So now all refueling events take five minutes.
This again leads to a lower operating costs for battery but has no impact on the intersection diesel/fuel cell.

5.2.7 Total Vehicle Comparison

Case 1: 5a, 1000h/a

This chart is calculated with 5 years and 1.000h/a. Batteries are changed in this case with another forklift (20min). These conditions were chosen because detailed rental data for this case is available.

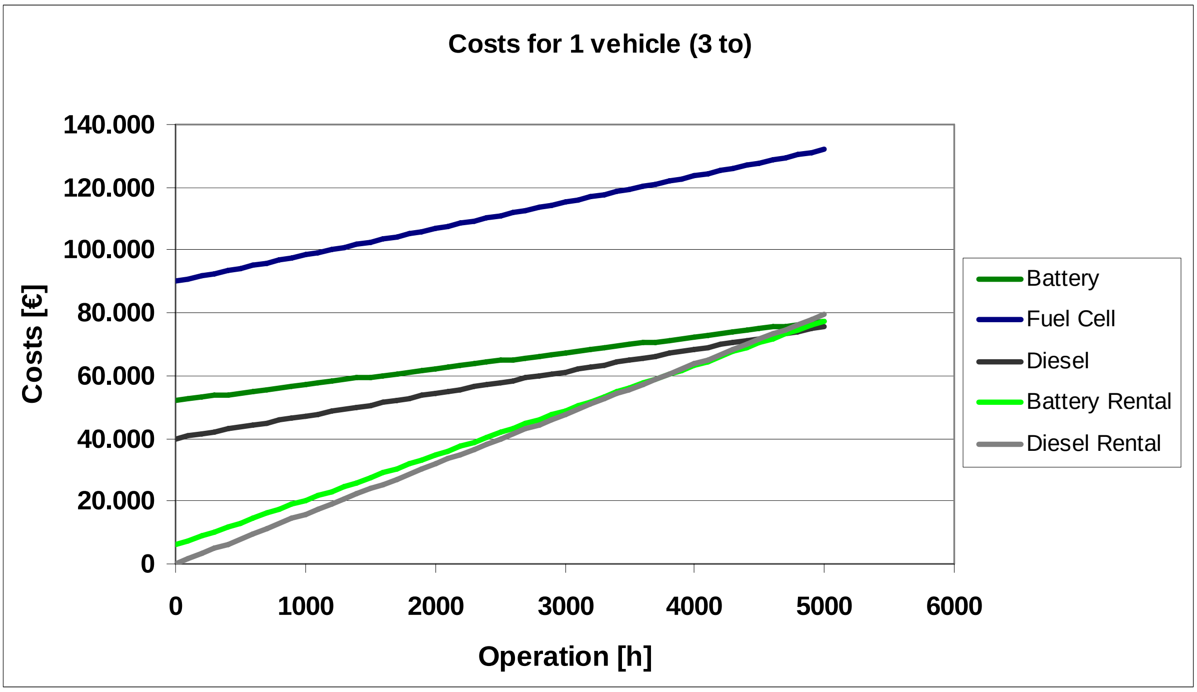

Figure 44: Total vehicle comparison (5a, 1,000h/a)

The total vehicle comparison shows that after 5 years all common vehicles are between €70.000 and €80.000. The hydrogen solution is with €130.000 about 70% more expensive than conventional vehicles.

Because the operating costs for hydrogen are the highest with this capacity, no amortization can be seen.

Case 2: 4a, 5000h/a

The typical runtime for an EU-Project is 2 or 4 Years. The battery change is still assumed with 20 min. In Chapter Total Operating Costs it was shown that with a higher capacity the operational costs change positively to hydrogen. 5000 hours is the maximum for a 4 year project due the vehicle lifetime of 20.000h.

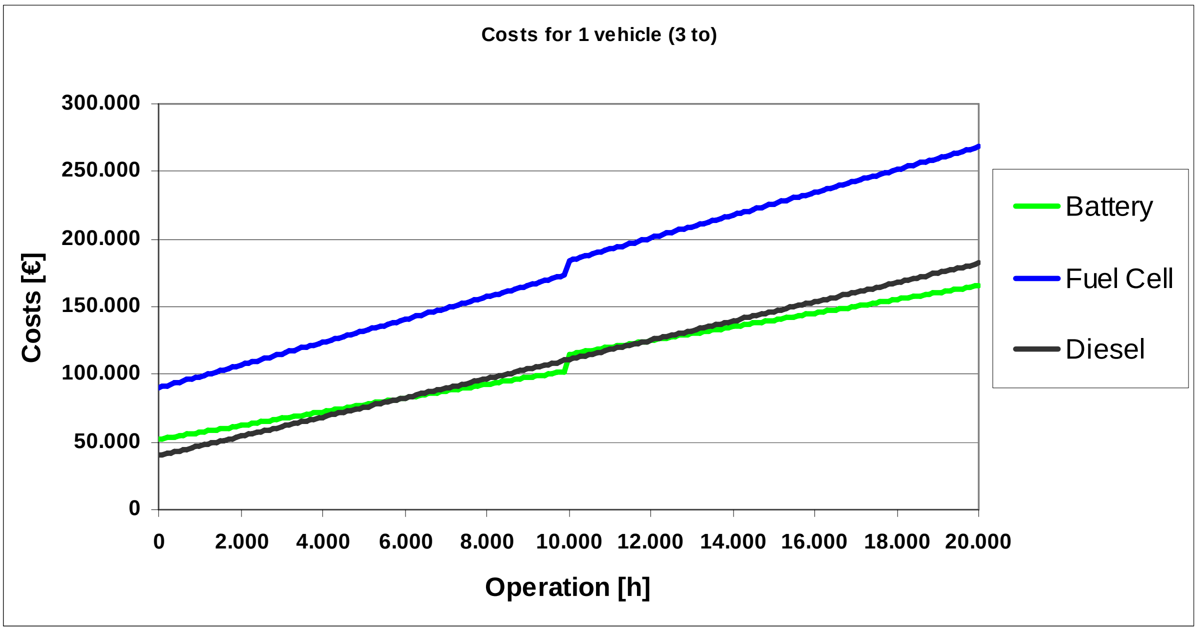

Figure 45: Vehicle comparison (4a, 5000h/a)

As mentioned in the previous chapters the maximum lifetime of the battery is 9600h and of the fuel cell stack 10000h. So, two new batteries are €12.000 and a new FC-Stack is €10.000.

In this chart two intersections between battery and diesel appear. Fuel cell has the highest costs and no chance of amortization in the vehicle’s lifetime.

5.3 Total Project Comparison

In order to calculate a whole project the boundary conditions have to be set.

These major vehicle based boundary conditions are:

- Annual capacity of the vehicles
- Project runtime

And project based:

- Infrastructure investments
- Number of vehicles

Boundary conditions with smaller impact on the result, like interest or labor rate are fix for each calculation.

Hydrogen vehicles are currently EU funded. The funding rate here is 50%. If a project should be funded, a scientific outcome has to be investigated during the project runtime and therefore additional work has to be done. These costs are assumed with €150.000 to €300.000, based on the project size, but are funded as well.

5.3.1 Case 1: Small Company with hydrogen on site (10 forklifts)

Calculation boundary:

- Substitution of 10 forklifts
- Company with hydrogen on site for production
- Infrastructure investments of €200.000 (chapter 3.5.4)
- Batteries are changed by a crane(20 min)
- Average use with 1000h/a
- Project is calculated with 5 years
- Additional costs for a EU project management are expected with €150.000

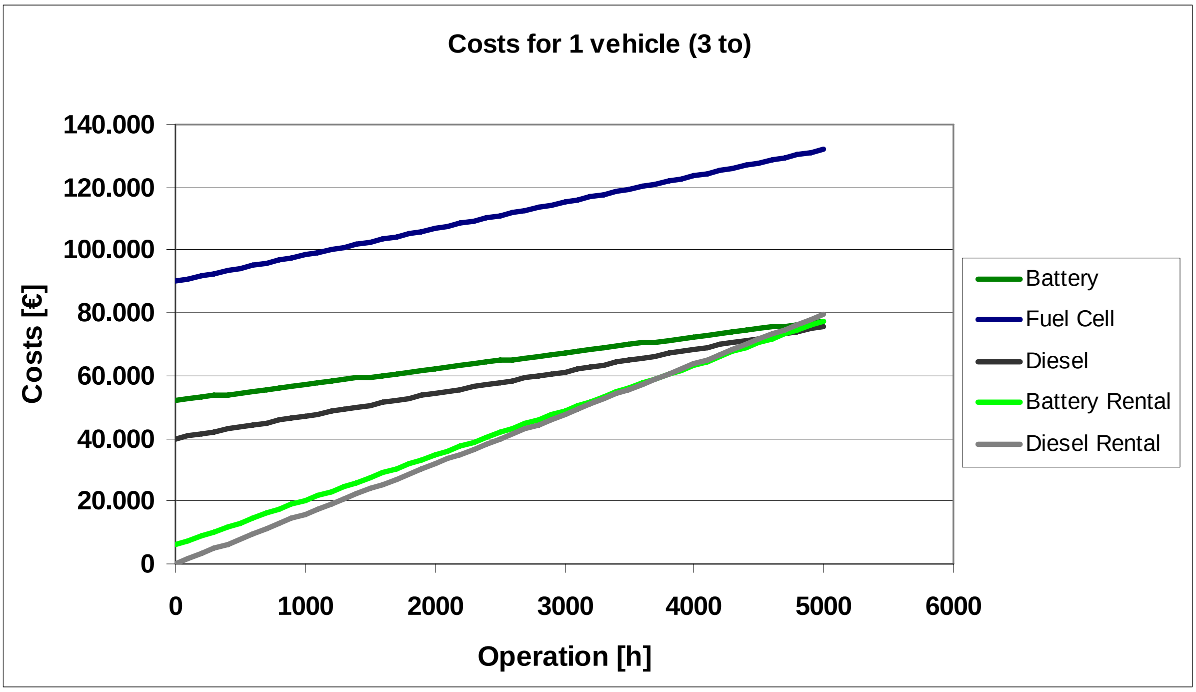

Figure 46: Case 1 one forklift

This case bases on real industry partner data. The name of the partner is confidential. With an average use of 1000 h/a this partner is not the ideal candidate for a demonstration. As a big advantage this partner has already hydrogen on site and so the not the whole infrastructure has to be bought.

The two rental systems (Chapter 5.2.2) are included in the diagram as well. The rental data is directly from the partner and is slightly higher than the calculated investment costs. In this case just one battery was included in the rental system and the other battery has to be bought.

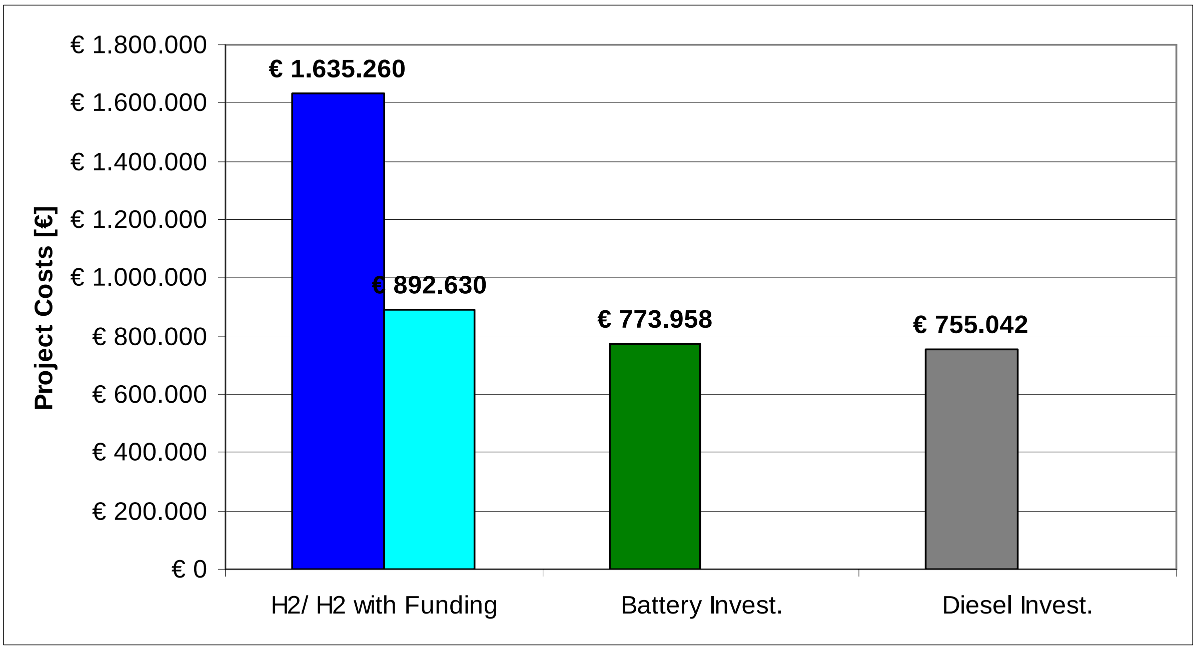

Figure 47: Case 1 total project

The total project costs in this case are about 1.6 million Euros. The funding rate is this case is 50%. The additional costs for an EU project include costs like the establishment of the application, data gathering and data preparation over the whole project and writing of other reports.

Even with the funding in this case the hydrogen solution is the most expansive one.

5.3.2 Case 2: Big Industry Enterprise

Calculation boundaries:

- Substitution of 50 forklifts to fuel cell
- One Hydrogenics refueling station with 120kg/day 350 bar for €1.000.000
- Two shift use with 1200h/shift and year
- Project time of 4 years

Almost all US demonstrations have more than 50 vehicles. This scenario a big industry enterprise substitutes 50 similar forklifts. A new infrastructure has to be installed and hydrogen is produced on site by electrolysis with a hydrogen price of 6 [€/kg]. In a two shift use and a 4 year runtime each vehicle will have 9600 hours. So in this project no fuel cell stack, with a lifetime of 10.000 hours, will be changed. No battery changing station is available. To gather data of 50 forklifts increases the EU project coordination costs to €300.000.

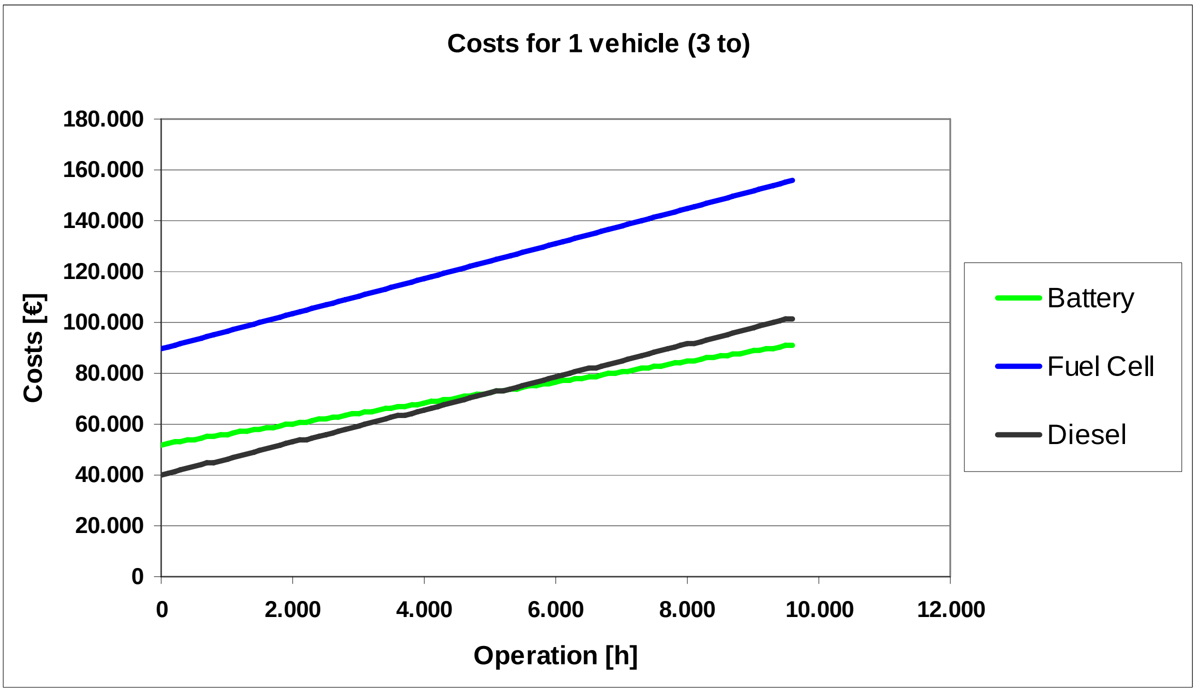

Figure 48: Case 2 one forklift

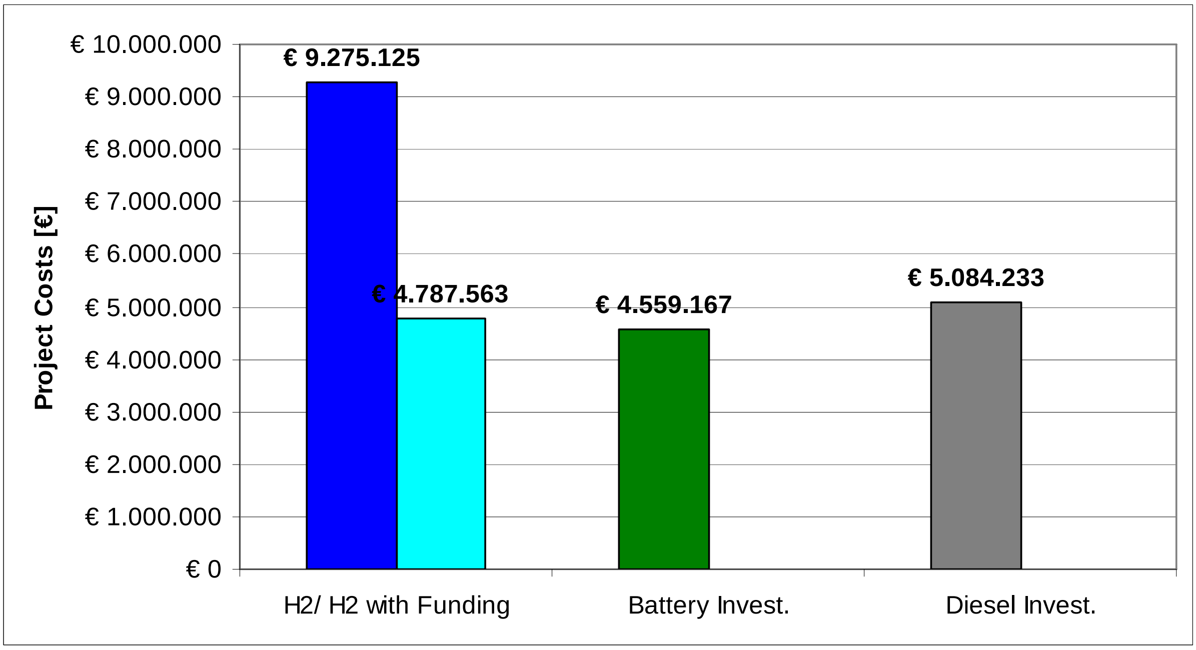

Figure 49: Case 2 total project

The fuel cell project costs are about 9.3 million Euros. A possible funding would decrease the project costs to about the half. The fuel cell with funding is cheaper than the diesel solution. It is almost cheaper than the battery solution.

5.3.3 Case 3: Big Industry with Hydrogen on Site

Boundary conditions like in case 2 but:

- Substitution of 50 forklifts
- Three shift use with 1200 h/shift and year
- Company with hydrogen on site
- Infrastructure investments of €400.000 (assumed, not confirmed)
- Battery changing station is considered (€ 270.000)
- 5 year project (more than 10.000 hrs per vehicle means battery and fuel cell stack change)

This case is the ideal candidate for a hydrogen demonstration. In a three shift use and a five year project almost the whole vehicle lifetime can be investigated. This company has already hydrogen on site and needs just a compressor and a dispenser. In this case a battery changing station is installed.

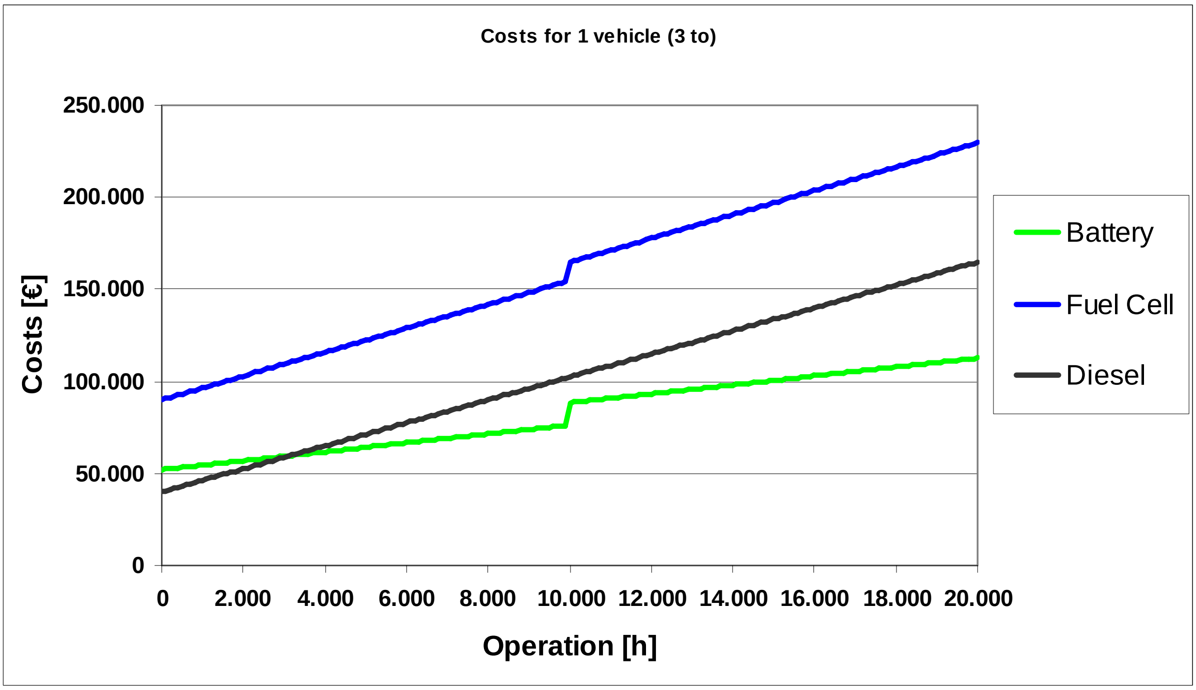

Figure 50: Case 3 one vehicle costs

The two steps at around 10.000 hours is the change of the fuel cell stack and the batteries.

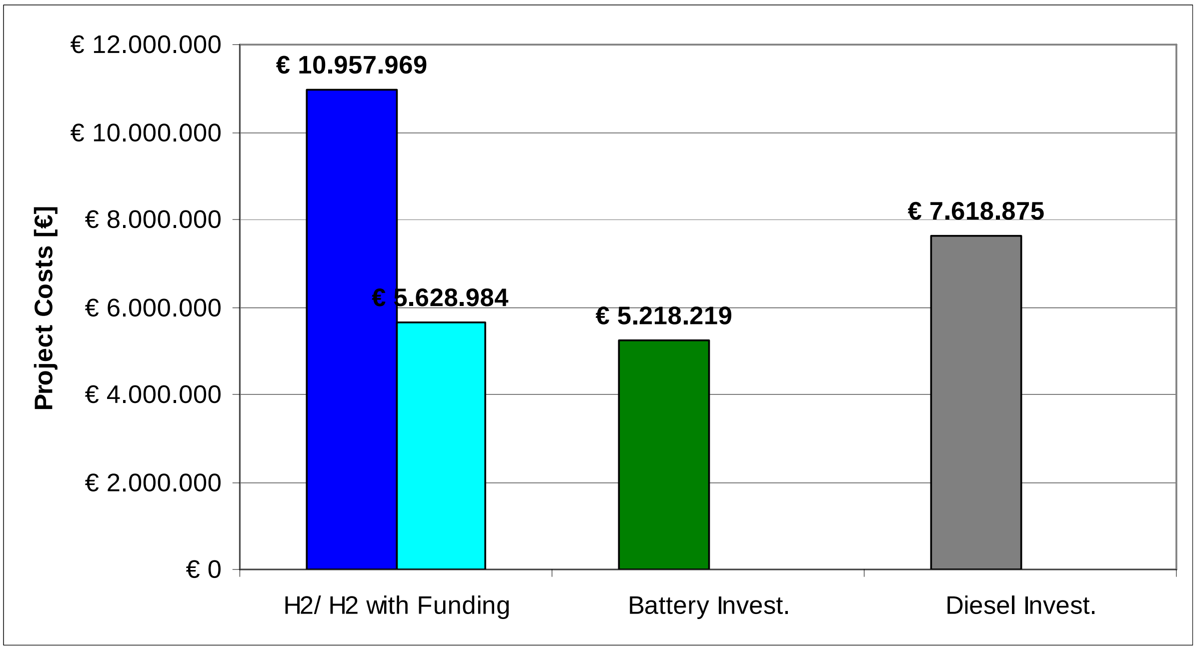

Figure 51: Case 3 total project costs

The diesel solution is very high in this case. If a company has a very high usage and hydrogen on site a funded demonstration project is just slightly higher than the battery solutions.

So even for best candidates the hydrogen systems are too expansive. A further reduction of the costs is absolute essential. Where a cost reduction has the most impact on the demonstration costs can be seen in the following chapter.

5.4 Sensitivity Analysis

The following sensitivity analysis shows the impact of a 10 % decrease of the mentioned data on the total project costs for the demonstration. The calculation is based on the ideal candidate like in chapter 5.3.3.

Basis (chapter 5.2.3):

Power pack: €50.000	→	€45.000
Hydrogen price €6/kg	→	€5,4/kg
Hydrogen maintenance €2,5/ h	→	€2,25/ h
Interests 5%	→	4,5 %
Labour rate €40/h	→	€36/h

E.g.: With a 10 percent cheaper hydrogen price, means €5,4 instead of €6, the whole project is 2% cheaper.

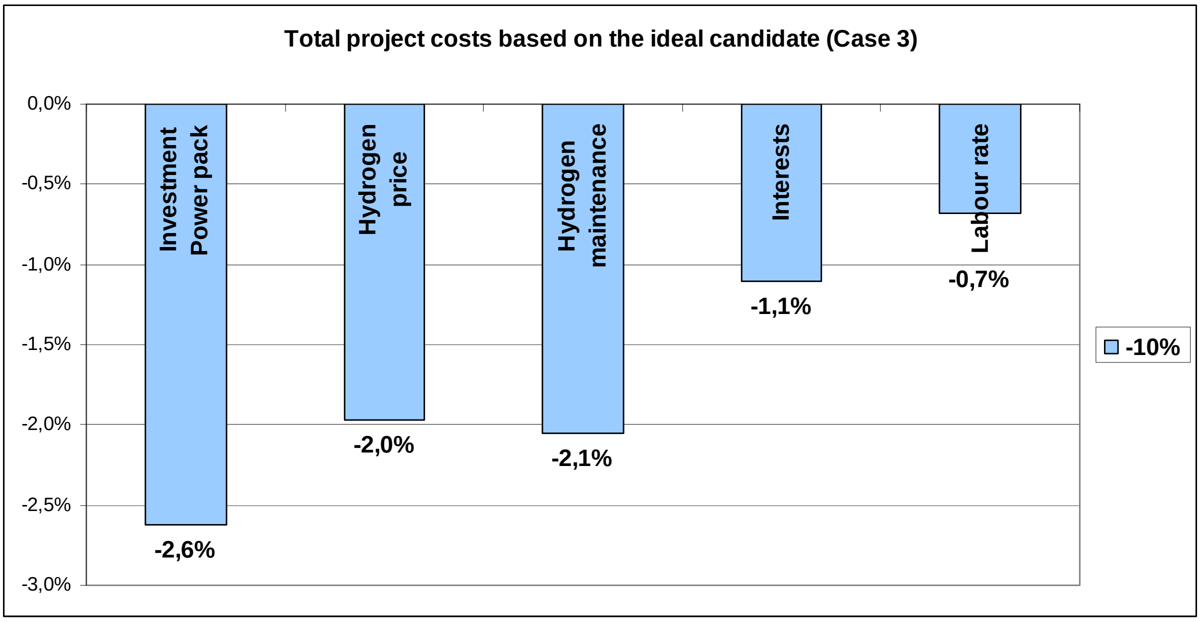

Figure 52: Sensitivity of selected attributes

Out of this chart the most influencing attributes can be shown. Investment costs have a high impact on the whole project. A 10 % reduction leads to 2,6 % cheaper project costs.

Power pack investment, hydrogen price and maintenance are very effective for improvements on a project costs perspective.
Of course these figures work the other way round as well. Means if interests are 10 % higher the whole project costs 1,1% more.

5.5 Possible Project Timescale

NextHyLights was applied one year before the project actually started. So, one year is predicted as period for funding confirmation from European Union. Based on telephone research Infrastructure could be set up within 12 month from ordering. The longer period of time is needed for manufacturing of the power packs. Almost independent of the ordering volume one year is the delivery time.

The forklifts are common electrical machines as for battery, thus there are no long delivery times expected.

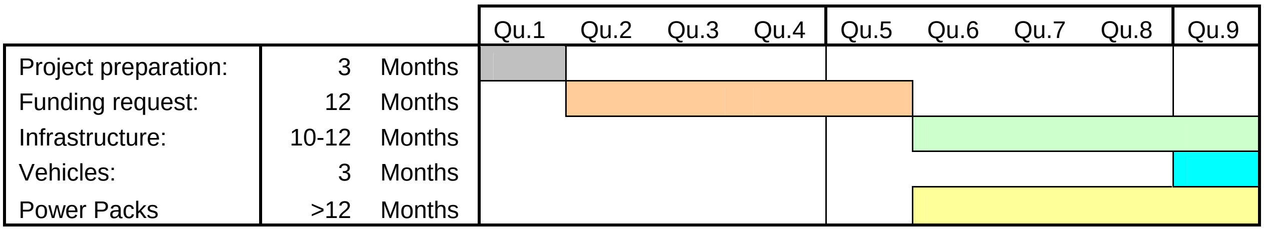

Figure 53: Timescale for a project preparation

The total project preparation time is expected with 2 years and 3 months.

5.6 Other Mandatory Success Factors

This survey was done by Bartelle in the US in 2007. Assumption is that the requirements on material handling vehicles are the same, or do net change significantly in Europe. 13 users of forklifts were ask, which three of the following factors would most influence their decision to purchase a vehicle powered by an alternative technology. E.g. all respondents identified that reliability is important.

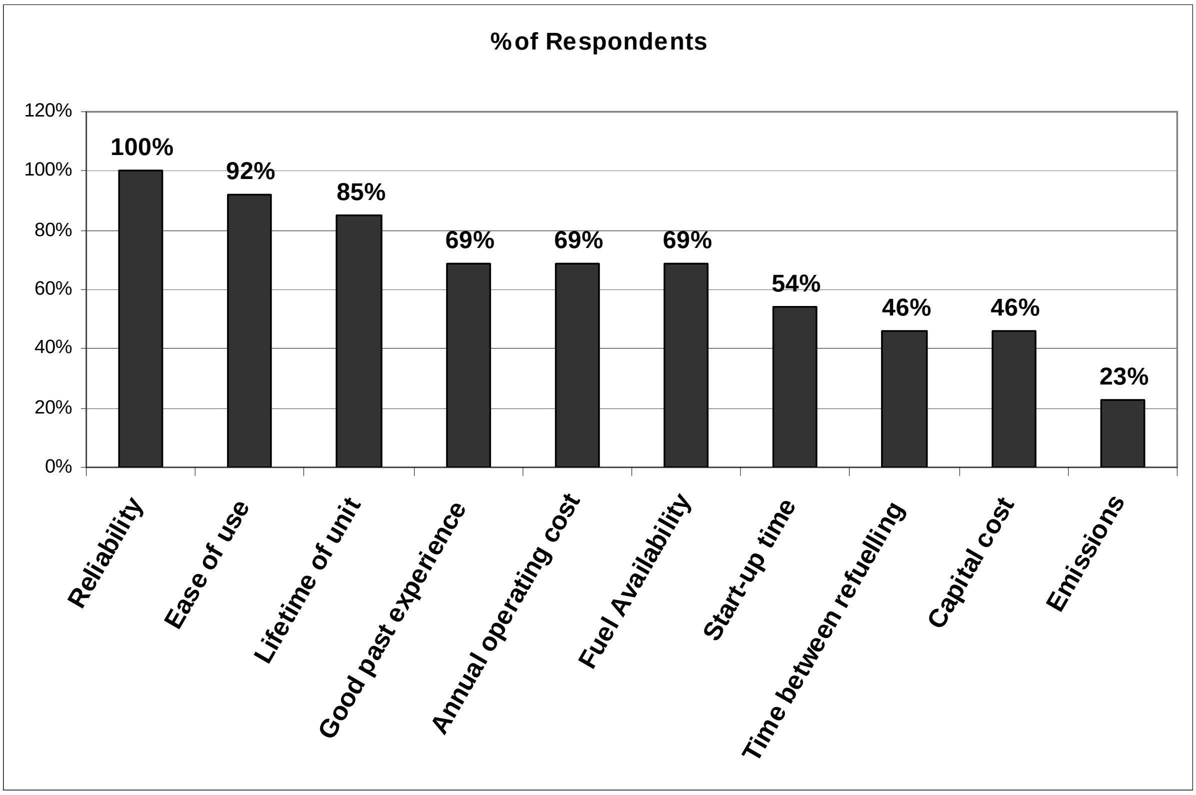

Figure 54: Factors that most influence purchase decisions[57]

Reliability is one of the most important points for customers. Therefore the reliability of fuel cell forklifts has to be secured. Not a lot of data is available about reliability. If a fuel cell forklift is going to be demonstrated, backup solutions, like changeable power packs or batteries as alternatives are recommended. For gathering data power packs should be preferred.

Due to the power pack no more tasks should have be taken over to the driver. Current power packs fulfill these requirements.

Current stack lifetimes are targeted with 10.000 hours. If these figures can be reached a stack has to be changed once in a vehicle lifetime, the lifetime of the vehicle itself is not influenced by the power source.

Because “Good past experience” is one of the most important points for the operators it is recommended to puplish data about current single demonstrator use as soon as possible.

Delectable for fuel cell systems is that most of the operators see the annual operating costs as more important than the investment costs.

“Fuel availability” is for 9 of 13 respondents a very crucial success factor. For customers who use hydrogen from the production process, production breaks or shutdowns have to be considered.

[57] Cf. Barttelle/DOE (2007), p.92f

If buffer batteries or hybrid systems are used start up time should be the same as for battery forklifts. Battery forklifts have a sufficient quick start-up time.
The time between refueling is with the current Hydrogenics power pack about four hours. Manufacturers confirmed that a bigger tank would not be hard to change.
Good for new technologies is that just 46% say that capital costs are important.
Just 3 of 13 material handling users see emissions as a important factor.

5.7 The Ideal Demonstration Enterprise

If the big advantages of hydrogen vehicles are:

1. Emission free operation, therefore applicable for indoor use.
2. Quick and safe refueling
3. Continuous stable power output during the whole operation

And the main targets of a demonstration:

From manufacturers:

4. Collect data from real life use
5. Collect these data quick and over the full vehicle lifetime (capacity, runtime)

From Operator:

6. Secure availability (with batteries or reserve power packs)
7. Not many more costs than existing fleet
8. Predictable costs

From European Commission:

9. Use existing infrastructure
10. Avoid emissions
11. At least ten vehicles

The ideal demonstration enterprise uses the vehicles indoor or partly indoor with a capacity of at least 3600h/a, which can be reached with a three shift use. To gather enough data the enterprise employs at least ten vehicles for at least 4 years. So a minimum of 144.000 hours of operation data will be gathered. Each vehicle will run for 14.400 hours which is about three quarter of the whole vehicle lifetime.

To avoid emissions diesel vehicles should be substituted. Additionally diesel vehicles are more expensive than batteries at high capacities.

It is task of the manufacturers to secure the availability of the systems. Quick repairs and maintenance, which includes a fast supply of service quantities, are crucial success factors. Warranties have to be offered by manufacturers.

The high investment costs and the unknown maintenance costs often irritate customers. Rental systems from manufacturer side, like available for the battery or diesel systems, are highly recommended. Higher predicted costs are more welcomed than lower insecure efforts.

6 Forecast and Recommendation

The triangle, Infrastructure providers, vehicle manufacturers and customers have to be set up and strengthened accordingly. The material handling sector is a very convenient sector to do so and introduce fuel cells. It is big enough to achieve reasonable scales to reduce prices, and the infrastructure hen-egg problem does not exist either. In the end it is just a question of prices. In the next years the customer, and his willingness to pay more, funding systems and motivation of the producers will decide about the European material handling vehicles. In the US an early commercialization is expected. It will be decided by the same three parties weather this commercialization is sustainable.

For the next phase, the high volume demonstration of vehicles, enterprises should be found where hydrogen is on site. The infrastructure providers should jump on this

train and provide more and thus cheaper compressing and dispensing solutions. To get as much data as quick as possible the vehicles should be operated very intensive. Ideally some high volume demonstrations are installed at the same time or even at the same order, to probably reduce the investment costs already for the demonstration.

Currently all hydrogen MH vehicles in Europe are based on a conventional battery vehicle. Understandably, is the direct change of batteries against fuel cell systems very convenient for customer and OEM.
Forklifts for loads of more than three tons are primary Diesel powered, because the energy consumption for battery vehicles is very high. Thus, electrical forklifts offered by the biggest European manufacturers end at five tons load. At this load most forklifts are diesel driven.
The emission free indoor operating advantage together with the high energy consumption of these vehicles are good reasons why the fuel cell systems manufacturers should create a system big enough to power 5 to 10 tons forklifts. Calculations showed that generally highly used diesel forklifts are quite expensive due high operating costs.
A new model, the Toyota TraigoHT is a 6 to 8,5 ton forklift in a high capacity application is an ideal candidate for further hydrogen investigations.

Discussions with OEMs lead to the awareness that totally new MH-vehicle concepts are possible with hydrogen as energy source. The direction to a sustainable future is already chosen and many alternatives are under research. Energy shortness will come, main task is to actuate the gears now and straighten the way for new technologies, to be prepared when oil production is getting lower. The future will stay exciting.

7 Table of Figures:

8 Table of Tables

9 Bibliography

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10 Appendix

10.1 Appendix: European Manufacturers and Technology Providers

Still GmbH (GER)	Material Handling Vehicle Manufacturer	www.still.de
Linde MH GmbH (GER)	Material Handling Vehicle Manufacturer	www.linde-mh.de
Intelligent Energy (UK)	System integrator bikes	www.intelligent-energy.com
Hydrogenics (CAN,GER)	Stacks, Power Packs and Infrastructure	www.hydrogenics.com
Hoppeke (GER)	System integrator	www.hoppecke.de
Nuvera Fuel Cells (US,I)	FC Manufacturer	www.nuvera.com
Proton Motor GmbH (GER)	FC Manufacturer	www.proton-motor.de
Air Liquide/Axane	H2 gas supply and refilling stations, FC systems	www.airliquide.com www.axane.net
H2 Logic A/S	FC Systems and H2 refilling stations	www.h2logic.com

10.2 Appendix: US Manufacturers and Technology Providers

Crown (US)	Material Handling Vehicle Manufacturer	www.crown.com
Hyster (US)	Material Handling Vehicle Manufacturer	www.hyster.com
Plug Power (US)	Power Unit Provider	www.plugpower.com
Hydrogenics (CAN,GER)	Hydrogen Solutions	www.hydrogenics.com
Ballard (US)	FC Manufacturer	www.ballard.com
Nuvera Fuel Cells (US,I)	FC Manufacturer	www.nuvera.com

10.3 Appendix: Data Form

Company:
Contact Person:
Phone:
Email:

Name of the H2-vehicle:

Vehicle is a

Forklift:	☐	max. load:	[to]
Tow tractor:	☐	capacity:	[kN]
Passenger boat:	☐	passengers:	Persons
Other Boat	☐		
Scooter	☐		
Other vehicle			

H2-Vehicle bases on a common vehicle platform?	Yes	☐	Which?
	No	☐	

Technical data of the H2-Vehicle:

Fuel cell type:	(PEM,AFC)
FC-Power:	[kW]
Vehicle power:	[kW]
Size of the Fuel cell:	[dm^3]
Durability of Fuel cell:	[hr]
Tank:	(liquid, CGH2 350, …)
Tank size:	[kg]
Range:	[hr, km]
for which cycle:	(NEDC, real life, …)
Efficiency(Tank to wheel):	[%]

Technical data of comparable/common Vehicle:

Power:	[kW]
Tank:	(Batterie, Benzin,Diesel,…)
Tank size:	[kWh, Liter]
Range:	[hr, km]
Efficiency (Tank to Wheel):	[%]
Emissions:	NOx (g/km,g/h)
	CO (g/km,g/h)
	HC (g/km,g/h)
	CO2 (g/km,g/h)

Is or was the H2-Vehicle already in use as a demonstrator?

Yes ☐ Where?

How many?

Demonstration start: End:

No ☐

Economical data regarding the H2-vehicle:

Investment costs for 1 demo-vehicle: [€]

Operating costs for 1 demo-vehicle: [€/hr, €/100km]

The operating costs consider:

Is your company able to manufacture a bigger demonstration fleet of 100 to 1000 vehicles?

Where are in your opinion the obstacles why hydrogen fuel cells are still not used in series vehicles?

What should the European Union do to promote hydrogen?

10.4 Appendix: Excel Sheet Factor Calculation

Linde Stapler E30

Comparison to period costs
Linde E30

Declaration	**H2**	**Battery**		**Detail**	**Factors**
Investment	90000	42000	€	eine Batterie(Schöbel: Faktor 5 FC/Batt)	**2,1**
Liquidation returns			€	Batterie € 6.000	
Lifetime	6	6	a		
Insurance			€/a		
Maintenance			€/a		
Operating hours/a	1000	1000	h/a	1 shift use	
Interest	3,00%	3,00%	%		
Fuel costs			€/h		
Total operating	300	80	€/h		**3,8**
Personal costs are not considered.					
Calculation					
Depreciation	15000	7000	€/a		**2,1**
Opportunity costs	1350	630	€/a		**2,1**
Insurance			€/a		
Maintenance			€/a		
Fuel costs			€/a		**3,2**
Total operating	300000	80000			
SUM	**19550**	**8630**	**€/a**		**2,3**
Cost factor Investment	2,1				
Cost factor total	**2,3**				
Financial gap	**10920**	**€/a**			

Technical comparison

Performance	16	16	kW	**1,0**
Performance FC	10			
Size FC			dm3	
Tank Size	1,6	50	kg, l	
Range	3,5	6	h	**0,6**
Durability	10000	9600	h	
max. Lifetime	10,0	9,0	a	**1,1**
Efficiency			%	

Advantage due fueling time:	Yes
Advantage due restrictions:	Yes

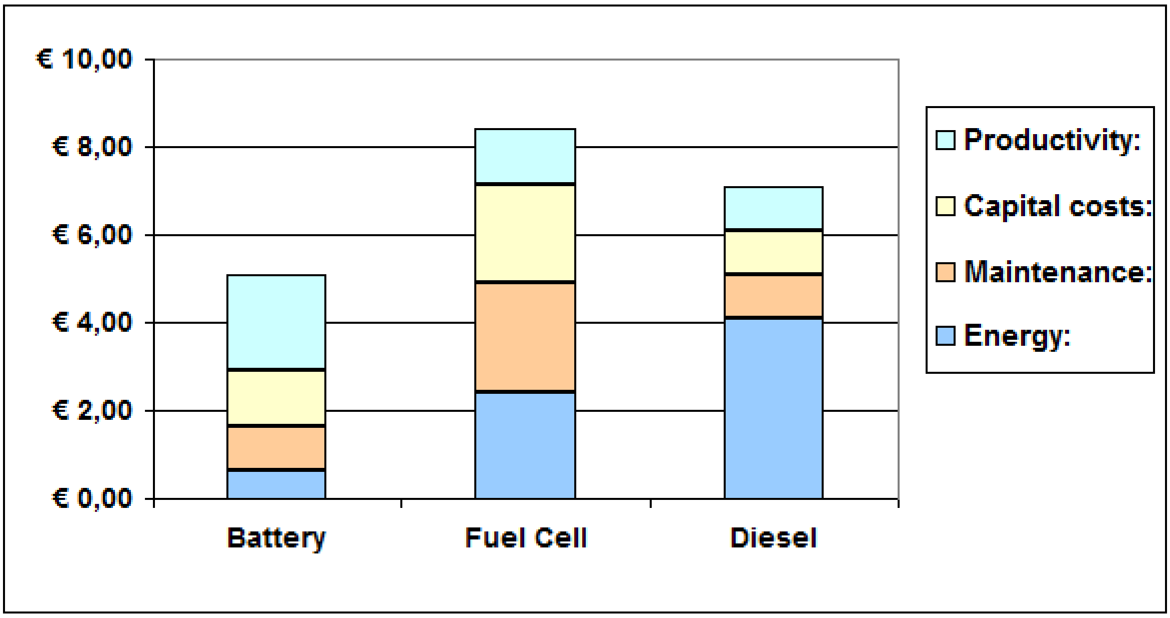
10.5 Appendix 5: Calculation one Truck Case 1

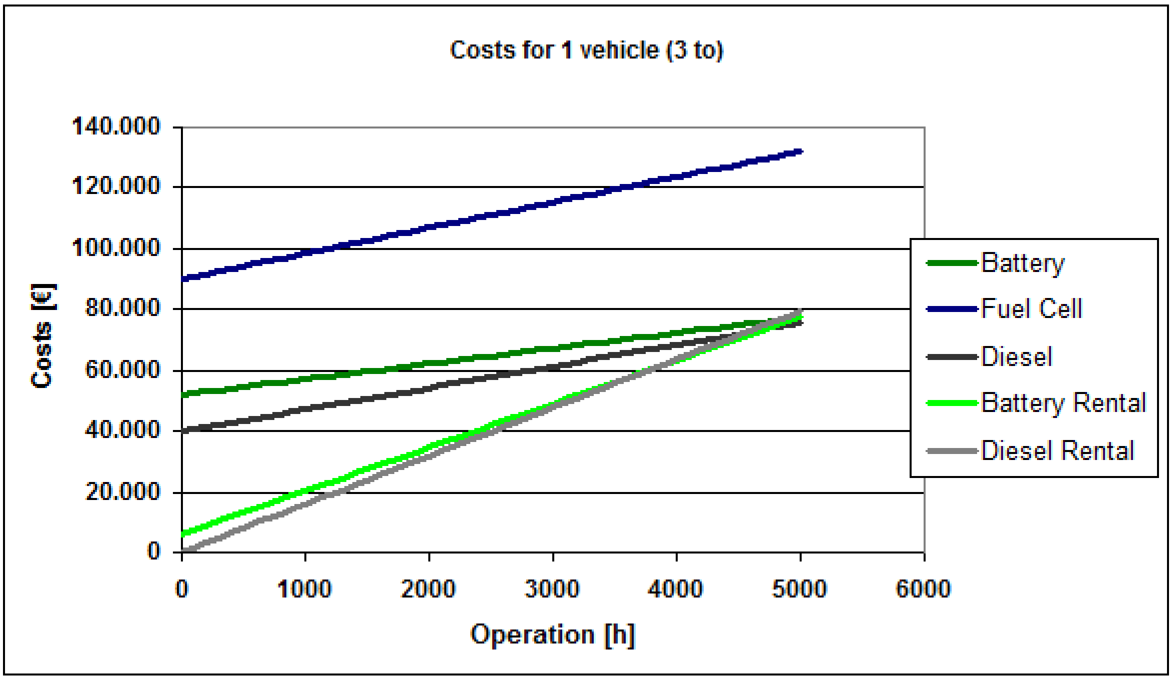
Example 1: Comparison of 1 truck (Infrastructure neglected)

Project runtime	5	Years						
with	1000	h/a						
means	5000	h						
INVESTMENT								
		Battery		**Fuel cell**		**Diesel**		
Forklift:		40000	€	40000	€	40000	€	
Power pack:				50000	€	0		
Battery(2#)		12000	€					
Sum:		**52000**	**€**	**90000**	**€**	**40000**	**€**	
Depreciation/a		10400	€	18000	**€**	8000	**€**	
Capital costs/a		1300	€/a	2250	€/a	1000	€/a	
Costs/a		**11700**	**€/a**	**20250**	**€/a**	**9000**	**€/a**	
		11,7	€/h	20,25	€/h	9	€/h	
OPERATION								
Energy:								
Price:		0,1	€/kWh	6	€/kg	1,2	€/l	
Consumption:		6,25	kW	0,4	kg/h	3,4	l/h	
Energy costs:		**0,625**	**€/h**	**2,4**	**€/h**	**4,08**	**€/h**	
Maintenance:								
Maintenance costs:		**1,0**	**€/h**	**2,5**	**€/h**	**1,0**	**€/h**	
Capital costs:								
Interests:	5%	/a						
Capital (average):		26000	€	45000	€	20000	€	
Annual Capital costs		1300	€/a	2250	€/a	1000	€/a	
Capital costs:		**1,30**	**€/h**	**2,25**	**€/h**	**1,00**	**€/h**	
Labour rate		**40**	**€/h**	**40**	**€/h**	**40**	**€/h**	
Productivity:								
Time Refill		20	min/event	5	min/event	5	min/event	
Range		8	h	4	h	4	h	
less productivity:		4,17%	of h	2,08%	of h	2,08%	of h	
less productivity machine:		0,49	€/h	0,42	€/h	0,19	€/h	
less productivity driver:		1,67	€/h	0,83	€/h	0,83	€/h	
Costs due productivity:		**2,15**	**€/h**	**1,26**	**€/h**	**1,02**	**€/h**	

10.6 Appendix: Total Operational Costs Case 1

TOTAL OPERATING:	Battery		Fuel Cell		Diesel	
Energy:	€ 0,63	€/h	€ 2,40	€/h	€ 4,08	€/h
Maintenance:	€ 1,00	€/h	€ 2,50	€/h	€ 1,00	€/h
Capital costs:	€ 1,30	€/h	€ 2,25	€/h	€ 1,00	€/h
Productivity:	€ 2,15	€/h	€ 1,26	€/h	€ 1,02	€/h
TOTAL OPERATING:	**€ 5,08**	**€/h**	**€ 8,41**	**€/h**	**€ 7,10**	**€/h**





10.7 Appendix: Rental Systems

Battery Rental (5 Years):

Rental:	740	€/month		
Full service:	220	€		(=0,22€/h)
Investment:	6000	€ for 1 Battery		One Battery in the rental service included.
Rental:	8880		8,88	€/h
Full service:	2640		2,64	€/h
Energy:	625		0,63	€/h
Productivity:			2,15	€/h
TOTAL:			**14,30**	**€/h**

Diesel Rental (5 Years):

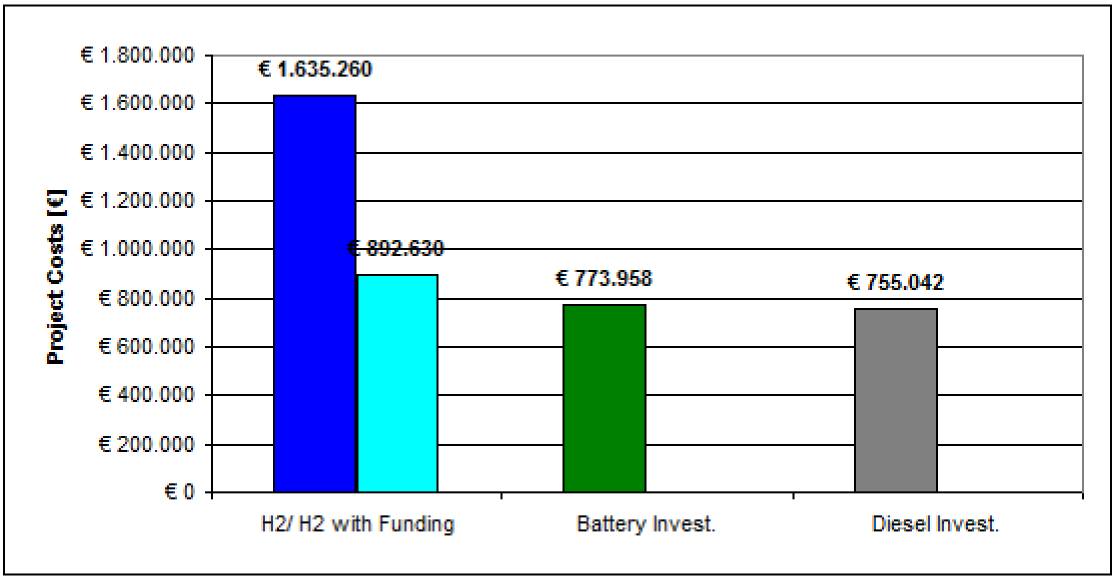
Rental:	650	€/month		
Full service:	230	€		(=0,23€/h)
Investment:	0	€		
Rental:	7800		7,8	€/h
Full service:	2760		2,76	€/h
Energy:			4,08	€/h
Productivity:			1,26	€/h
TOTAL:			**15,90**	**€/h**

10.8 Appendix: Total Project Comparison

Total Project Comparison (with infrastructure):
Battery rental

		Hydrogen:	Battery Invest:	Diesel Invest:
Infrastructure acquisition		200000		
Infrastructure maintenance	10%	100000		
Infrastructure capital	5%	15000		
Infrastructure		315000		
Number of vehicles:	10 #			
Invest. price for 1 vehicle:		90000	52000	40000
Investment Vehicles:		900000	520000	400000
Additional investments (Batteries/FC):		0		
Operational costs per vehicle and year:		8405	5079	7101
Operational costs total(all vehicles whole project):		420260	253958	355042

	H2/ H2 with Funding	**Battery Invest.**	**Diesel Invest.**
Total costs of project:	**€ 1.635.260**	**€ 773.958**	**€ 755.042**
Additional project costs:	€ 150.000		
Possible funding:	50%		
Total costs of project:	**€ 892.630**		
% H2 more to …		111,3%	116,6%



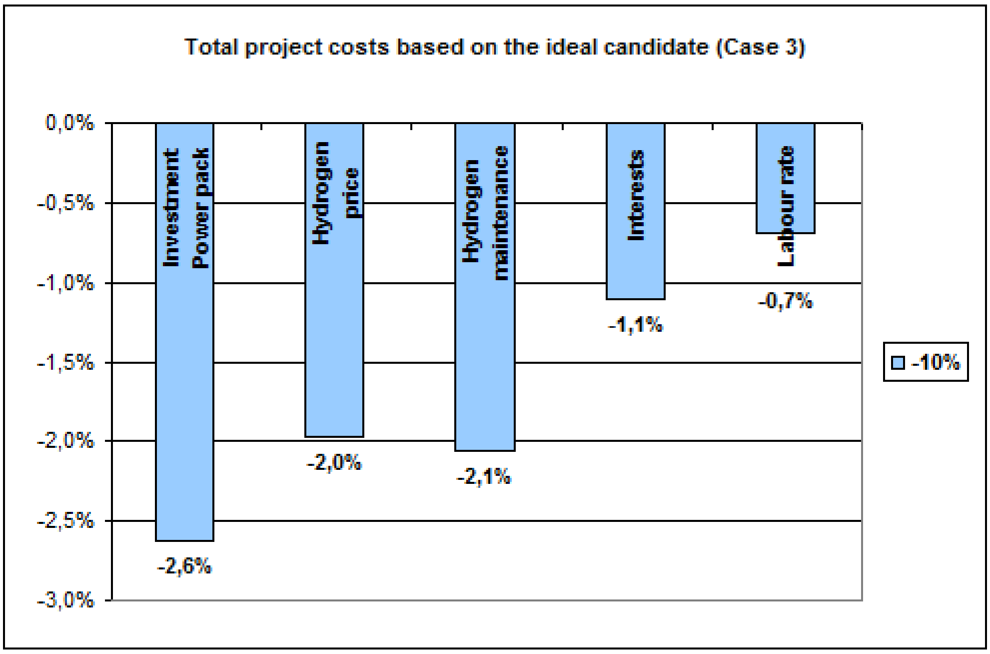
10.9 Appendix: Sensitivity Analysis

Total project costs based on the ideal candidate (Case 3)

	Normal figures	
Investment Power pack	50000	€
Hydrogen price	6	€
Hydrogen maintenance	2,5	€/h
Interests	5	%
Labour rate	40	€/h
Range		Hr
Infrastructure	400000	€
Vehicles	50	
Total project	10957968,	

Update Data

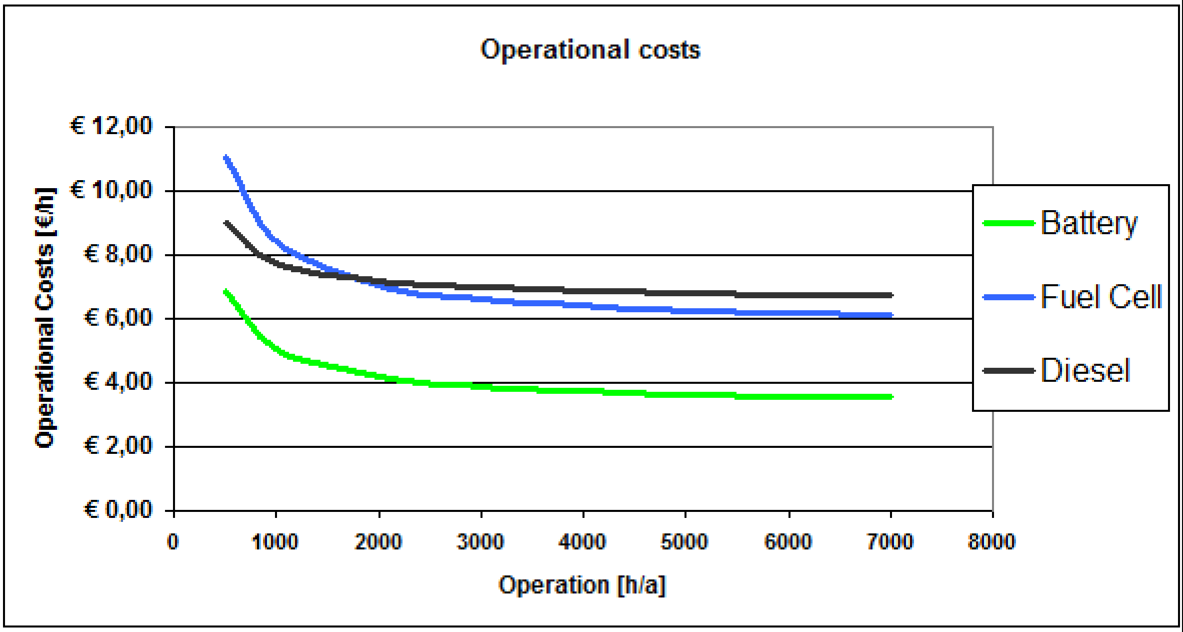
Low(-10%)	high(+10%)			low(-10%)	high(+10%)
45000	55000	-2,6%	2,6%	**€ 10.670.859**	**€ 11.245.078**
5,4	6,60	-2,0%	2,0%	**€ 10.741.969**	**€ 11.173.969**
2,25	2,75	-2,1%	2,1%	**€ 10.732.969**	**€ 11.182.969**
4%	6%	-1,1%	1,1%	**€ 10.837.125**	**€ 11.078.813**
36	44	-0,7%	0,7%	**€ 10.882.969**	**€ 11.032.969**



10.10 Appendix: Diagram Generation

	Battery	Fuel Cell	Diesel
500	€ 6,87	€ 11,08	€ 8,97
1000	€ 5,08	€ 8,41	€ 7,78
2000	€ 4,19	€ 7,07	€ 7,19
3000	€ 3,89	€ 6,62	€ 6,99
5000	€ 3,65	€ 6,27	€ 6,83
7000	3,6	€ 6,12	€ 6,76

Update



TOTAL OPERATING:	Battery			Fuel Cell			Diesel		
	1200	2400	3600	1200	2400	3600	1200	2400	3600 [h/a]
Energy	€ 0,63	€ 0,63	€ 0,63	€ 2,40	€ 2,40	€ 2,40	€ 4,08	€ 4,08	€ 4,08
Maintenance	€ 1,00	€ 1,00	€ 1,00	€ 2,50	€ 2,50	€ 2,50	€ 1,00	€ 1,00	€ 1,00
Capital costs	€ 1,08	€ 0,54	€ 0,36	€ 1,88	€ 0,94	€ 0,63	€ 0,83	€ 0,42	€ 0,28
Productivity	€ 0,52	€ 0,47	€ 0,45	€ 1,18	€ 1,01	€ 0,95	€ 0,99	€ 0,91	€ 0,89

All 5 minutes.

Update