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Parallel Sessions Book 6:
- Stationary Applications
- Transportation Applications

Editors: Detlef Stolten, Thomas Grube

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Book 6: Stationary Applications | Transportation Applications

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TA TRANSPORTATION APPLICATIONS

ST Stationary Applications

High-Temperature Fuel Cells in Decentralized Power Generation

Robert Steinberger-Wilckens and Niels Christiansen

Abstract

Decentralised power generation (DG) can contribute to increases in efficiency of the entire power generation and distribution network. It reduces grid losses by moving the generation closer to the customer, thus also allowing the use of the waste heat generated in electricity production. At the same time it offers competitive advantages to industrial customers in supplying cost effective peak production, grid stabilisation and uninterruptible power supply. Total power generation efficiency, and subsequently also CO_2 balances, though, is only increased if the DG electrical efficiency meets minimum standards. These are defined by the grid characteristics within which the DG is operated. High temperature fuel cells offer a high value due to their high electrical conversion efficiencies of above 50%, reaching up to over 60% with the Solid Oxide Fuel Cell (SOFC). High efficiency, though, is only achieved with adequate system architectures. Worldwide, a number of manufacturers and developing groups are working on fuel cells for distributed electricity generation, with increasing success.

Fuel Cell System HotModule: Highest Efficiency and Cleanliness at Sustainable Base Load Supply

Stefan Rolf, **Ursula Paulus-Rodatz**, MTU Onsite Energy GmbH, Germany

Introducing the Company

MTU Onsite Energy, formerly known as CFC Solutions, is a Tognum Group Company with its place of business in Ottobrunn near Munich, Germany. MTU is a supplier of tailor made systems of highest efficiency and cleanliness for cogeneration and trigeneration based on carbonate fuel cell technology.

Applications and Clients

Within the existing market of cogeneration and trigeneration MTU focuses its marketing and sales efforts on industrial and commercial customers. Targeted clients are data centers, the telecom industry, hospitals, the food industry, waste water treatment operators, energy service companies and industrial key accounts.

Introducing the Product Portfolio

HotModule is the registered trademark of MTU`s fuel cell systems. Based on three standardized building blocks, the stack module, the media supply, the inverter & control unit, MTU offers their customers tailor made solutions by complementing the HotModule with heat utilization and specific gas clean up systems as required.

Figure 1

The product range comprises currently single stack HotModules with an electrical output of approximately 250 and 350 kW followed by a 500 kW single stack HotModule in the near term. Based on multi stack HotModules MTU will cover a power range of up to 2 Megawatt.

Ongoing development

To fulfill the requirements of an emerging fuel cell market, today’s gap of the total cost of ownership for an installation over a given time period in comparison to conventional CHP systems, has to be reduced. Besides working on cost reductions related to the process design, the focus is a development program, reducing cost, increasing lifetime and increasing the power density of the fuel cell stacks.

Cost reduction efforts

A great effort has been started in research for alternative powder materials for the electrodes. As a result, we were recently able to substitute the comparatively expensive Anode powder material based on a nickel alloy by a cheaper commercial Nickel material. Simultaneously with the anode cost reduction program a redesign of the anode was carried out, which resulted in an efficiency increased as described below.

In a second step recently investigations were carried out successfully to replace both the anode- and the cathode base material by a 30% cheaper version of Nickel material. Again these substitution efforts are accompanied by a redesign of both electrodes resulting in a further increase of the power output of the electrodes.

Concerning the metal components a complete redesign of the anodic current collector also resulted in considerable material cost savings of approximately 50%.

Efforts to increase lifetime

From mechanistic investigations it is well known that kinetic polarization of both electrodes decreases with increasing temperature. On the other hand corrosion effects tremendously increase with increasing temperature. To address these two contradictory aspects we take great effort to homogenize the temperature distribution of a full scale cell (increase of the minimum cell temperature to decrease kinetic polarization and reduction of local temperature peaks to decelerate corrosion effects).

In order to describe the actions concerning heat management, first the state of the art cell conditions are introduced. Within the cell the electrochemical reaction is producing electrical current and heat on the one hand. On the other hand due to the system conditions including the internal reforming reaction, the cell is cooled. The amount of cooling and the temperature distribution over a full scale cell now depends on maximum current density, amount of oxygen and fuel available at different cell regions and on the catalyst distribution within the cell. The present design reveals a delta in temperature of roughly 100°C over the cell area with a maximum cell temperature of roughly 650°C. Simulations revealed that with an optimized catalyst distribution a decrease in temperature delta to approximately 50°C accompanied by a slightly increase of the medium cell temperature by roughly 5°C is possible. This would directly result in an increased cell voltage and cell power. First measurements with full scale electrodes generally confirm these theoretical findings.

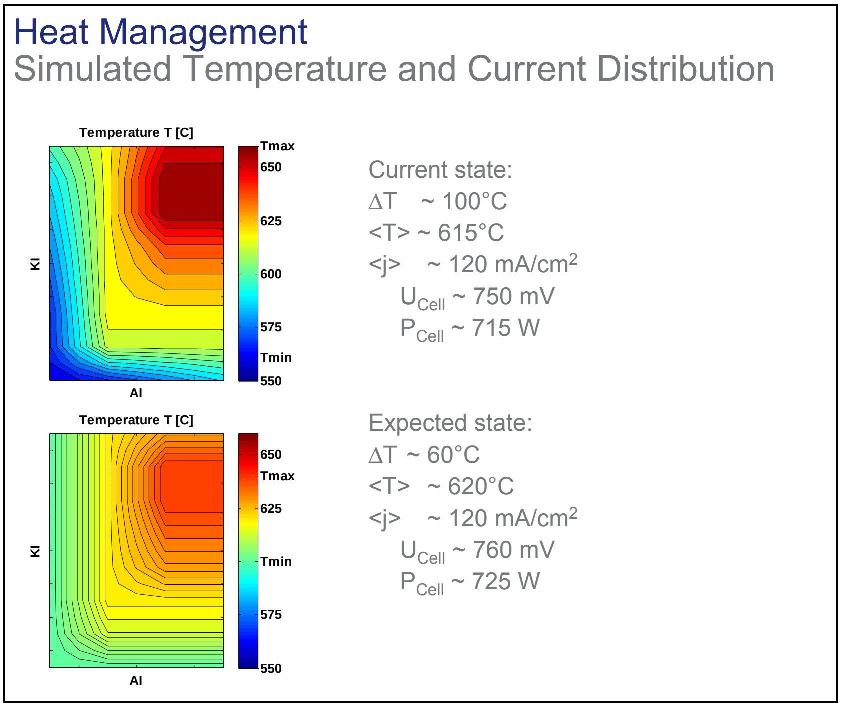

Figure 2

Efforts to increase power density

Major goal in MCFC research and development is to improve the power density and thus the efficiency of the stack. Appropriate electrode design is highly suitable to positively influence both the anode and the cathode reaction kinetics. An elemental base for specific optimization of the electrode design is a detailed knowledge of the reaction mechanism and of the factors of influence affecting the electrode reactions.

In order to find out about details of the overall electrode reaction mechanisms in house developed half cell test benches both for anode and for cathode examinations are used. These half cell test benches allow the cost and time efficient examination of a large range of different electrodes. In addition the application of a broad variety of testing parameters like gas composition, current density, temperature and humidification is possible. Sample size of electrodes applied in half cell test benches is in the range of 10 cm^2. Besides that 250 cm^2 single cell test assemblies are used as well as laboratory scale small MCFC stacks for fundamental investigations in a real fuel cell surrounding. Impedance spectroscopy is applied as main diagnostic tool for mechanistic studies.

Considering the cathode reaction the first aim was to clarify the reaction mechanism by investigating the influence of varying oxygen and carbon dioxide partial pressure, temperature and humidification effects. In order to improve the cathode, the dependency of the cathode reaction on different morphologic electrode properties was investigated.

Trying to increase the efficiency of single electrodes and electrode-matrix-electrode assemblies a variety of measures was investigated like catalytic activation of the electrodes, optimization of the electrode morphology (i.e. the pore size and pore size distribution), optimization of fuel and oxidant composition etc. Based on the results from kinetic half cell studies several generations of high performance MCFC cathodes which are subject to further improvements have been generated. Besides this a new generation of advanced anodes applying active pore design and taking into consideration the interaction between anode and cathode pore structure with respect to capillary forces and electrolyte distribution has been designed.

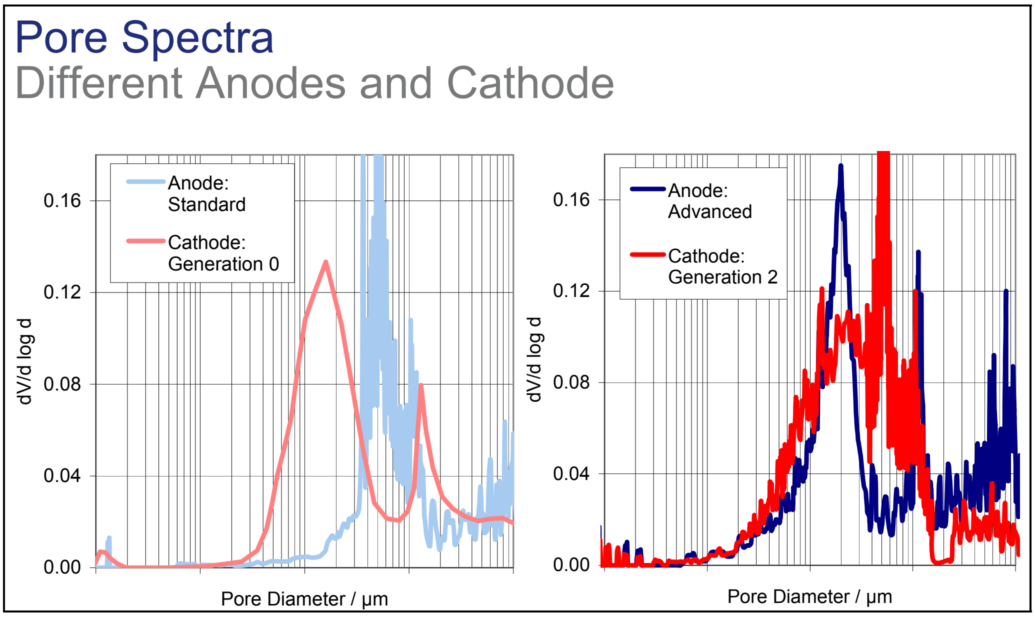

Figure 3

The figure on the left side demonstrates that in case of a standard anode, the pores within the structure of the electrochemical active layer were clearly larger than the ones in the electroactive layer of our generation 0 cathode. In the figure on the right side it becomes clear that in our advanced anode and our generation 2 cathode both active layers have similar pore diameters.

A surprisingly good accordance was found between half cell measurements, findings from lab scale MCFC single cells and lab scale stacks and even observations in full area technology stacks (20 cells with a cell area of approximately 0,8m²). This demonstrates the importance of fundamental kinetic investigations to proceed in electrode design and MCFC power density.

Finally the application of advanced anodes and cathodes compared with formerly used “standard” electrodes in a full scale MCFC-test was demonstrated. By substituting the standard cathode and anode by the respective advanced electrodes an increase in cell voltage of up to 60 mV has been proven. The results shown in the following figure demonstrate the potential of electrode design.

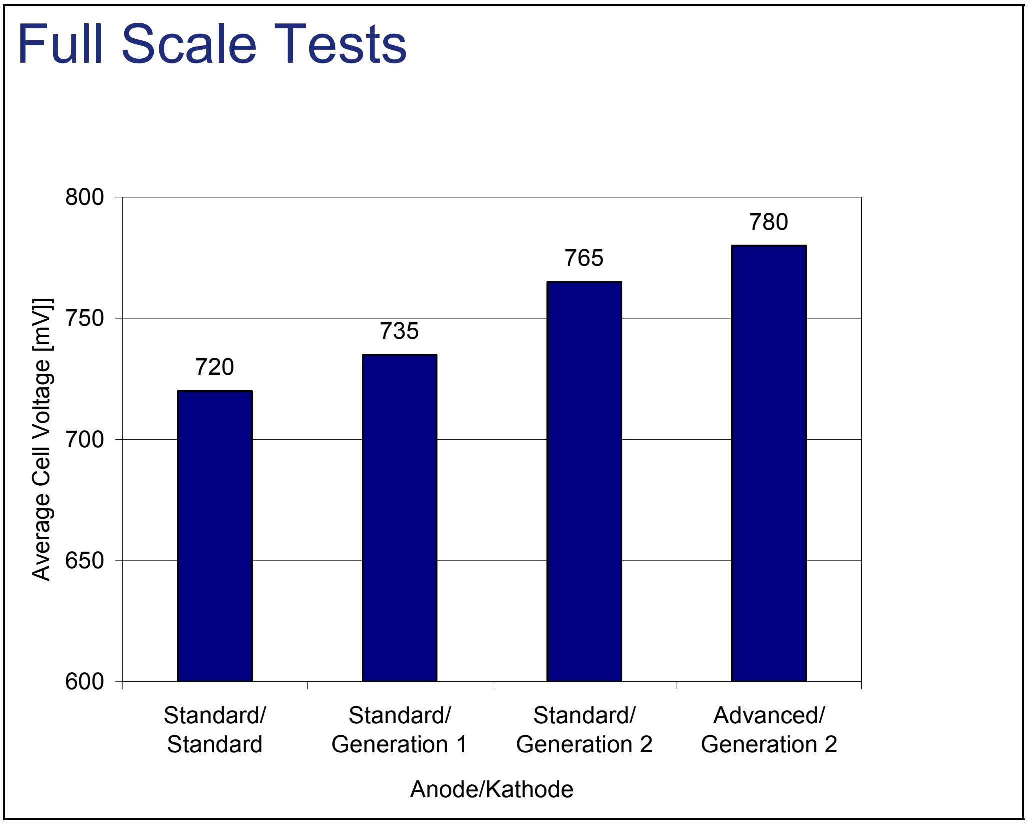

Figure 4

The above figure demonstrates results obtained in full area technology stacks (1000 h runtime, 120 mA/cm2, 70% fuel utilization, medium cell temperature 620°C, system gases). The performance increase is clearly visible. For solely substituting the cathode a voltage increase of 45 mV could be realized. For substituting both the anode and the cathode by the newly developed versions a voltage increase of 60 mV was realized.

Future prospects

Above described activities together with others cover the whole range of cell-, stack- and system development as well as the monitoring of all operational data, the supply chain process and the manufacturing process.

MTU Onsite Energy GmbH performs these ongoing development activities with the aim of cost reduction, efficiency increase and increase in lifetime.

The up so far achieved results are very promising and will be continued in order to pave the way for the commercialization of the molten carbonate HotModule fuel cell system.

Development of a Fuel Flexible, Air-regulated, Modular, and Electrically Integrated SOFC-System (FlameSOFC)

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J. Valldorf, VDI/VDE Innovation + Technik GmbH, Germany

Abstract

The present paper summarizes experimental results from the operation of the SOFC based micro-CHP unit developed within the framework of the project FlameSOFC. The project is co-financed by the European Commission as an Integrated Project within the 6th framework program. The objective is the development of an innovative SOFC-based micro-CHP system capable of operating with different gaseous and liquid fuels and fulfilling the technological and market requirements at a European level. The partners involved in the FlameSOFC project bring together a sufficient number of important European actors on the scientific, research and industry level including SMEs and industrial partners from the heating sector. The presented work concerns the operation of the 2nd phase prototype FlameSOFC system, with a 1 $kW_{el.}$ SOFC stack and natural gas as feedstock.

1 Introduction

The objective of the integrated European project FlameSOFC is the development of a multi-fuel, modular SOFC micro-combined heat and power (CHP) system, which is capable to operate with gaseous and liquid hydrocarbon fuels, fulfilling the relevant technological and market requirements at a European level. The main focus concerning the multi-fuel flexibility lies on different natural gas qualities and LPG but also on liquid fuels (diesel like heating oil). The target nominal net electrical output is 2 $kW_{el.}$, which is expected to represent the future mainstream high volume mass market for micro-CHPs. The advanced planar SOFC stack [1], that constitutes the core part of the unit, enables fuel flexibility as well as a simple and compact system design. The SOFC stack is combined with a novel, compact and robust fuel processor [2-7], which is able to process many different fuels without catalytic components. Apart from the fuel processor, the periphery of the developed system incorporates a multi-purpose off-gas burner [8-13], compact heat exchangers [14], a vaporizer [15] and a soot trap. The integration concept of the components leads to a very simple and reliable system design. The efficiency targets are > 30 % net electrical efficiency and > 90 % total CHP efficiency. The final application is going to be a micro CHP system for single or two-family residential homes with electrical grid connection.

2 Technological Solution

An overview of the technological solutions provided in FlameSOFC and the 3-D drawing of the complete 2nd prototype system is given in Figure 1. The proposed system can generate electrical power from gaseous fuels like natural gas or LPG as well as from liquid fuels like heating oil. The overall system is split up into three main sections: the fuel processing stage, the SOFC stack with power electronics and the BoP section. The entrance section of the fuel processor shows two separate routes for the pre-treatment of gaseous and liquid fuels, respectively.

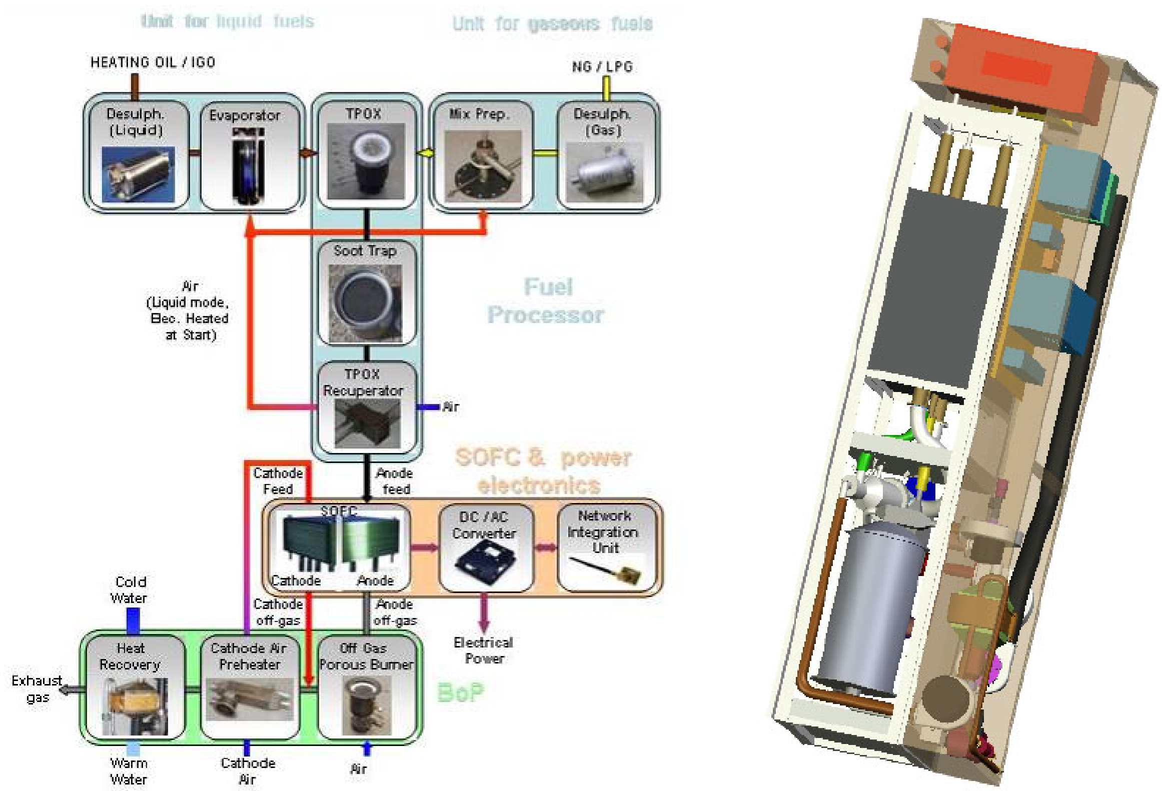

Figure 1: **Schematic diagram of the FlameSOFC micro CHP system and 3-D CAD drawing of 2nd Phase Prototype.**

In both cases the fuels are desulphurised after entering into the system [15]. As the fuel has to be in gaseous phase when entering the reformer, liquid fuels are vaporized in a tailored designed vaporizer [16]. In the TPOX reformer the gaseous fuel flow, mixed with an under-stoichiometric amount of air (λ in the range of 0.42 - 0.45) performs a partial oxidation reaction at temperatures in the range of 1200 °C - 1400 °C. The reformer is based on the porous burner technology, which shows an enhanced heat and mass transport within the reaction zone as well as high heat recuperation against the flow direction. Both effects help to extend the operational range towards low air ratios, which is normally limited by blow off and / or soot production. Low air ratios are essential for the achievement of high hydrogen and CO yields, which comprise the useable fuel components of synthesis gas for utilization in solid oxide fuel cells. In order to obtain sufficient reaction speeds in the TPOX reformer the temperatures in the reaction zone must be high and preferably in the mentioned range of 1200 °C - 1400 °C. The targeted temperature range at low air ratios is only achievable by additional preheating of the educts. Furthermore, before the fuel reformate can be sent to the SOFC stack, it has to be cooled down to temperatures lower than 850 °C in order to prevent overheating and damaging of the SOFC stack. For this reason a heat exchanger (TPOX recuperator) is installed after the soot trap. It preheats the fresh air inlet of the TPOX reformer and cools the fuel reformate down to SOFC operating temperatures. By preheating the air supply of the fuel processor the TPOX reformer can reach the required high operating temperatures at low excess air ratios λ. The preheated air either enters at the evaporator enabling an efficient vaporization and mixing of liquid fuels, or is mixed with the gaseous fuel in the specially designed mixing chamber. After the TPOX reformer a ceramic soot trap is implemented for removing any possible soot traces formed in the reformer [17], which could poison the SOFC anode. The regeneration of the soot trap is a main challenge since anode supported cells do not endure oxygen at elevated temperatures as it would occur in the case of conventional regeneration procedures based on the injection of air. The purified and temperature conditioned reformate fuel (synthesis gas) enters the SOFC stack at the anode inlet. In the stack the H_2 and CO components are reacting with the oxygen transported through the electrolyte from the cathode side and electrical current is generated. Regarding the interconnection to the electrical power network the current is converted with power electronics, showing an overall efficiency (DC/DC converter plus DC/AC inverter) of more than 90 %. The communication of the FlameSOFC unit with possibilities for energy management options is performed in the network integration unit. The hot anode off-gas containing small amounts of unconverted H_2 and CO (during normal operation) is post-combusted in the off-gas burner based on the porous burner technology. The hot cathode off-gas, which consists of oxygen depleted air, is mixed with the off-gas burner exhaust and a large portion of the overall heat content is recuperated in the cathode air preheater by heating up the cathode air supply. The final exhaust gas stream after the cathode air preheater flows to a heat recovery unit (which depending on the heat requirements may be fed also by an auxiliary burner), where hot water for heating purposes is generated.

Two FlameSOFC micro-CHP units, developed at two different stages, were constructed and were tested under laboratory conditions, in order to prepare and assure the functionality of the final prototypes at the demonstration sites. During the first two project years, prototypes of all components were developed, tested and evaluated concerning their functionality for the FlameSOFC unit.

Based on the results and experience of the 1st phase prototype the 2nd phase prototype was designed and manufactured [18-21]. Therefore a highly integrated design has been implemented and the system is based on three main sections (stack, hot BoP and reformer components, cold BoP and electronic devices), see Figure 2.

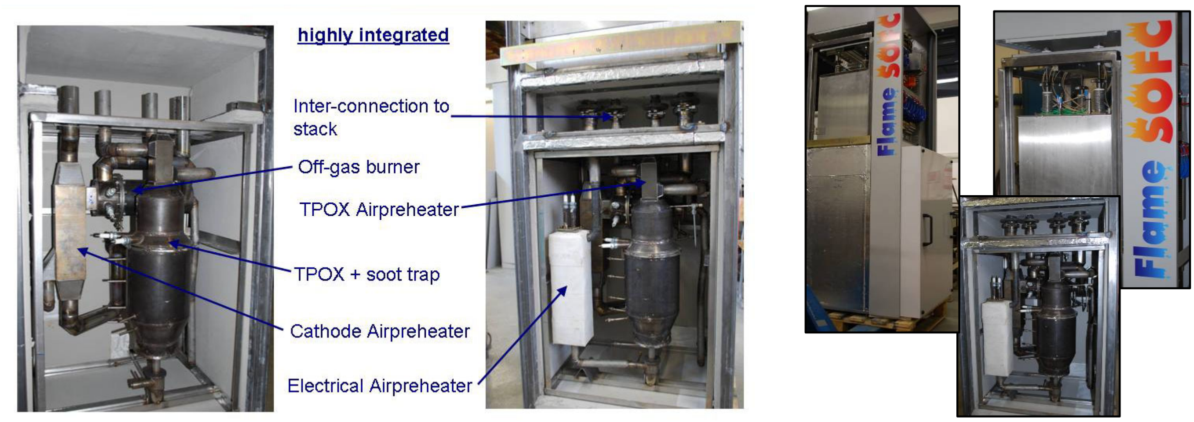

Figure 2: 2nd Phase Prototype of the FlameSOFC micro-CHP system.

3 Experimental Conditions and Results of the 2nd Phase Prototype

The operation of an SOFC micro CHP-system is mainly based on the boundary condition of the stack. Therefore, the boundary conditions for stack operation are summarized in Table 1.

Table 1: Summary of stack requirements.

Parameter	Limit/ target
Thermal gradient stack core material	50 K/min
Temperature difference anode/ cathode/ stack core	100 K
Maximal temperature for oxidizing atmosphere	400 °C
Minimal temperature to draw electric current	700 °C
Pressure difference anode / cathode	≤ 30 mbar

Table 2: Flow rates of gas, air branches according to mass and heat balance simulations for normal operation (natural gas case, u_f = 65 %, λ_{TPOX} = 0.42)

Load	25 %	50 %	100 %
Flow rate natural gas	2.8 l_N/min	5.9 l_N/min	13.3 l_N/min
Flow rate afterburner air	7 l_N/min	10 l_N/min	53 l_N/min
Flow rate cathode air	162 l_N/min	297 l_N/min	631 l_N/min
Flow rate TPOX air	11 l_N/min	14 l_N/min	44 l_N/min
Fuel power related to the lower heating value	1.7 kW	3.5 kW	8 kW

The thermal gradients together with the allowed temperature differences between the cells and interconnectors form the main obstacles for a fast heat-up rate of the stack. However, it should be noted that these values have mainly the sense of being "on the safe side" of stack operation, since statistically credible data is not available due to high costs. Table 2 shows a summary of the flow rate for the different streams that are based on simulation results for the natural gas case for representative operational parameters, a fuel utilization of 65 % in the stack and a TPOX air ratio of 0.42. For start-up and load rejection operation the afterburner had to handle the reformate gas from the reformer without electrical conversion in the stack. This affected of course the amount and composition of the anode off-gas and consequently the heat and mass balance of the system. The operational results of the 2nd phase prototype are presented in Figure 3. It can be seen, that after ≈ 16 hours of preheating the system in start-up mode (the first 20 min. in this mode an electrical preheating is needed) a stable operation can be achieved. The current collection was performed with an electronic load in contrast of the inverter of the final system. The results of the operation is summarized and presented in Table 3.

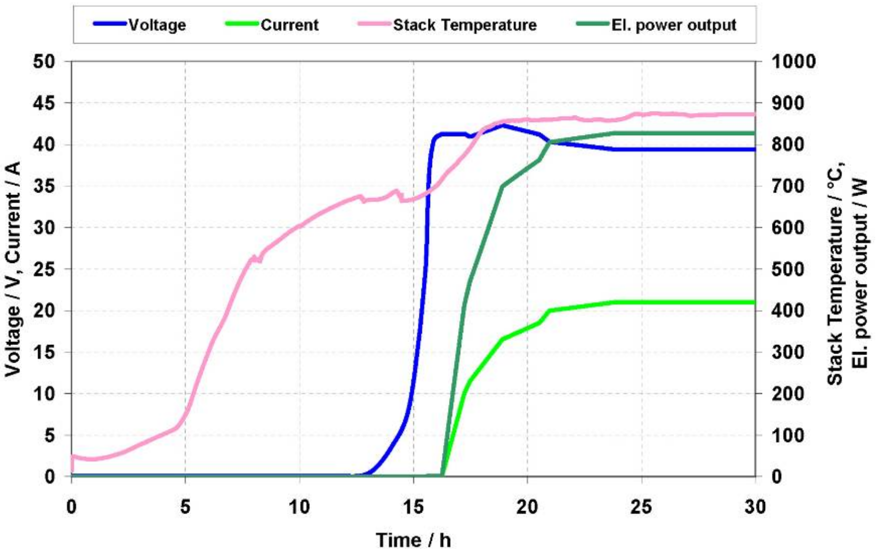

Figure 3: Operational results of the 2nd Phase Prototype FlameSOFC with 1 $kW_{el.}$ SOFC stack.

Table 3: Overview of the operational results of the 2nd Phase Prototype FlameSOFC (1 $kW_{el.}$ stack).

Temperature anode in	676°C	Cathode inlet pressure	28 mbar
Temperature anode out	798°C	Stack core temperature	858°C
Anode inlet pressure	24 mbar	Voltage	39,4 V
Temperature cathode in	748°C	Current	21,0 A
Temperature cathode out	823°C	Power output	827 W

4 Summary

The 2nd Phase Prototype of the FlameSOFC micro-CHP unit has been operated successfully with a 1 $kW_{el.}$ stack. All main components like TPOX reactor, heat exchangers and afterburner operated successfully in combination and fulfilled their specifications. It has been shown that the system achieved 830 $W_{el.}$ and operated stable.

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[1]TU Bergakademie Freiberg, Germany, [2]VDI/VDE Innovation + Technik GmbH, Germany, [3]MTS GROUP (Merloni TermoSanitari SpA), Italy, [4]Fagor Electrodomesticos S. Coop, Spain, [5]EBZ GmbH, Germany, [6]HTceramix SA, Switzerland, [7]PROMEOS GmbH, Germany, [8]Stobbe Tech Ceramics A/S, Denmark, [9]Ikerlan S. Coop., Spain, [10]ECN, Netherlands, [11]OWI gGmbH, Germany, [12]University of Erlangen-Nuremberg, Germany, [13]Ecole Polytechnique Fédérale de Lausanne, Switzerland, [14]Politecnico di Torino, Italy, [15]National Technical University of Athens, Greece, [16]Instituto Superior Tecnico, Portugal, [17]Imperial College of Science Technology and Medicin, UK, [18]Budapest University of Technology and Economics, Hungary, [19]EC BREC Instytut Energetyki Odnawialnej, Poland, [20]ELCO/ELCO Shared Services GmbH, Germany

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Cogeneration in Single Family Homes with Fuel Cell Heating Appliances

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Andreas Mai, **Thomas Doerk**, Hexis AG, Switzerland

1 Fuel Cell Manufacturer Hexis

Since beginning of the year 2006 Hexis Ltd. is working as an independent company on the further development of SOFC heating appliances for the environmentally sound and cost-effective energy supply of single family and small multi family homes. Hexis restarted its business with the background of more than 20 years experiences in solid oxide fuel cells (SOFC) ranging from materials to systems development as well as field trials. In 2007 Hexis started its new business in Konstanz, Germany. A Swiss foundation in Winterthur funds this effort as a 100 percent owner of the company.

Figure 1: Galileo 1000 with domestic hot water tank in a single-family home.

Hexis has an extensive laboratory and test infrastructure. The company experienced the operation of more than 100 fuel cell systems from the first system generation. As a result of this effort the new fuel cell system called Galileo 1000 N has been developed. In the mean-time it showed already good results. All that and an extensive knowledge for the integration of the stack in a fuel cell module and a system makes Hexis confident to progress with its 18 member team, mainly scientists and researchers on the development of the SOFC based micro-CHP (Combined Heat and Power) unit Galileo 1000 N. As such this device will substitute the gas boiler and, in addition, produce electrical power. Generation of electricity will be shifted from the central power plant to the fuel cell system in a household.

2 Fuel Cell System for Single Family Homes

This fuel cell heating appliance is developed to cover both the entire heat requirements and the basic requirements for electrical power of a single-family home. Galileo 1000 N works efficiently, with lowest emissions and virtually silently.

Fuel cell heating appliance Galileo 1000 N	
Fuel cell	
Electrical Output	1 kW_{el}
Thermal Output	2 kW_{th}
Type	Solid oxide fuel cell (SOFC)
Fuel processing	Catalytic partial oxidation (CPO)
Electrical $efficiency_{ACnet}$	30 % (Target 35 %)
Overall efficiency	> 90 % LHV
Operation mode	Modulating, steady operation, switch-off in summer
Emissions	NOx < 22 mg/kWh, CO < 20 mg/kWh
Integrated back-up burner	
Output	4-20 kW_{th}
Operation mode	Condensing boiler, modulating 1:5, DHW in summer
Entire system	
Overall efficiency	90-105 % LHV
Fuel	Natural gas
Dimensions	550 x 550 x 1600 mm
Mass	170 kg

Figure 2: Specifications of the fuel cell heating appliance Galileo 1000 N [1].

Galileo 1000 N basically consists of two parts. In the upper part is the fuel cell module with insulation which is easily accessible in the case of maintenance. In the lower part are the components for power transformation, the heat transfer and the supply of the additional heat. This fuel cell system is compact and light because functions and components have been combined and simplified, and it is easy to service and suitable for series production and so, Galileo 1000 N combines high-tech with user friendliness.

The fuel cell supplies an electrical power of 1 kW and a thermal capacity of about 2 kW. If heat requirements of the building exceed this value, an integrated back-up gas burner will provide another 20 kW of heating energy. Overall efficiencies of more than 90 % and electrical efficiencies of more than 30 % have been demonstrated in the field. About 47 systems are currently in service, approximately 43 Galileo 1000 N and some less of its predecessor. Galileo 1000 N is significantly smaller and lighter than this predecessor. Its manufacturing costs have been significantly reduced and the system is easy to operate and fully integrated. It operates directly on natural gas which is converted by an integrated partial oxidation catalyst. The integrated SOFC stack consists of circular electrolyte-supported planar cells and metallic interconnectors. The post-combustion zone is located around the open stack, minimizing sealing demands and simplifying the thermal management of the system.

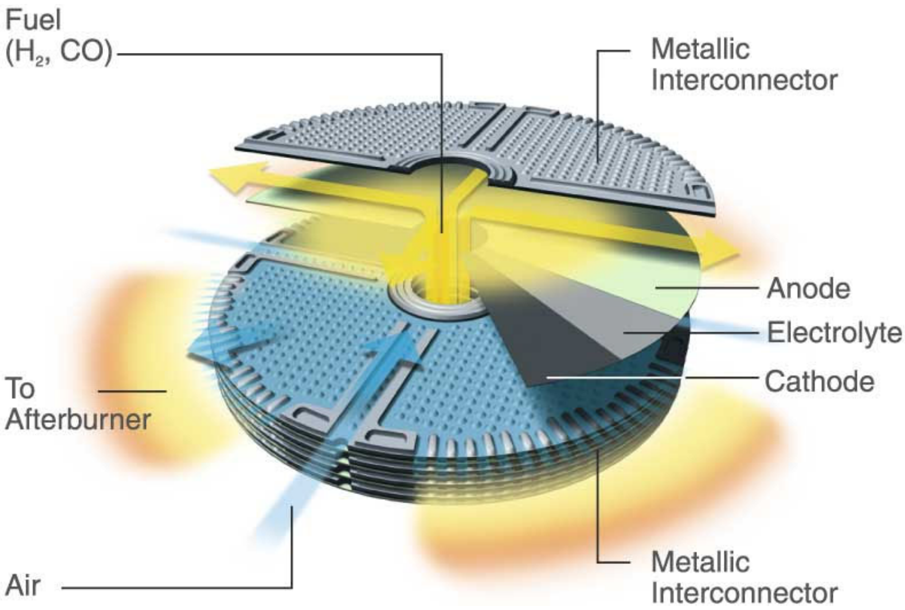

Figure 3: Hexis fuel cell stack and its basic principle.

A double chamber heat exchanger serves as the central supporting component. The additional burner with blower and gas-air ratio control as well as the heating circulation pump are integrated in there. By means of a hot water circuit the waste heat of both the fuel cell and the additional burner can be used for the supply of space heat and domestic hot water. The exhaust gas flows are combined in a condensate collecting pan. The induced draft fan of the fuel cell integrated here provides the air for the electrochemical reaction in the fuel cell.

The system operates in low air pressure which means that it is inherent safe against leakage. The transformation from direct in alternating current of 230 V is carried out by an inverter. Energy management software makes the system to run during the entire year. When the heat demand of the building becomes too small in summer the system switches off. Domestic hot water will be provided by the back-up burner during that time. In autumn when average outside temperature becomes lower, the fuel cell itself will be started again automatically.

Within the fuel cell itself the pre-reformed gaseous mixture of hydrogen and carbon monoxide oxidizes at the anode. On this occasion electrons are released that are then conducted on the cathode by an electrical conductor outside the fuel cell. At the cathode a part of the air oxygen is reduced with the released electrons which produce oxygen ions. At an operating temperature of between 800 and 1000° centigrade these are carried through the now ion conductible electrolyte. At the anode end these ions recombine with the oxidized fuel to water vapour and carbon dioxide. The electrons that are conducted from the anode to the cathode are used as electrical power on that occasion.

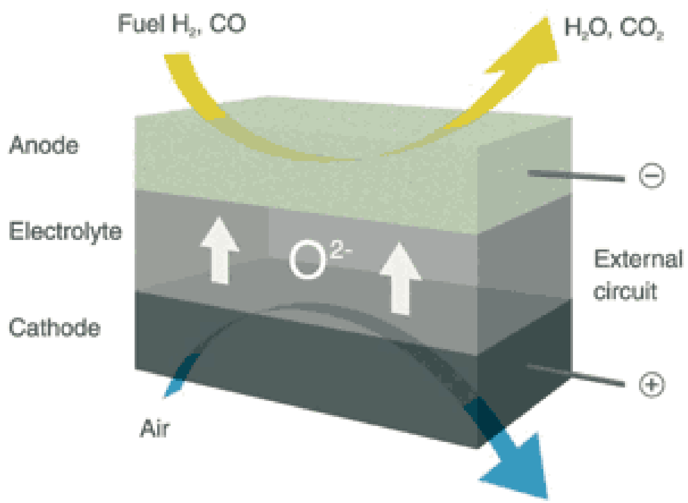

Figure 4: Electrochemical process.

3 Experience from the Laboratory and the Field

In the laboratory overall efficiencies of approximately 95 % and electrical efficiencies of more than 35 % have been demonstrated [2]. A significant reduction in primary energy consumption and therefore in carbon dioxide emissions is possible. Both emissions of pollutants and noise are extremely low. Very low noise emissions of 30 dB (A) have been measured in front of the system [3]. Stack lifetime of more than 24’000 operating hours in the laboratory and more than 9’000 hours in the field have been showed. Those systems are still in operation.

Figure 5: Single-family home in Mülheim/Ruhr, Germany, with Galileo 1000 N [Source: T.B.E. GmbH, Duisburg].

Systems tests are being conducted especially in the field to gather experience under real operation conditions and feedback for further improvements. So, field systems will be operated together with field test partners in the energy industry. The picture on the left shows a single family home in Mülheim/Ruhr, Germany next to the WHEC’s venue where Galileo 1000 N will be operated until end of April 2010.

4 Micro CHP Market

Target market of Hexis' fuel cell heating appliance is the building refurbishment market in Europe. All houses which provide a sufficient heat demand, a connection to the grid and natural gas supply as well have a central heating system can be equipped with such a CHP device.

Hexis plans to introduce the fuel cell system Galileo 1000 N from 2012/2013 into the European market. After comprehensive field test the company expects to achieve reach the technical and economical qualification for a successful market launch. Until than the good technical status regarding stack lifetime and system reliability will be improved so that customer requirements can be fulfilled.

In future end customer will either buy a fuel cell system – analogue to a conventional gas boiler today - and operate it self dependently, or provide in the context of a energy service contract an operation site for that fuel cell system and just pay for the supplied heat and electricity. Everything else, from financing, planning, installation, commissioning, operation and service until billing will be done by the energy service company.

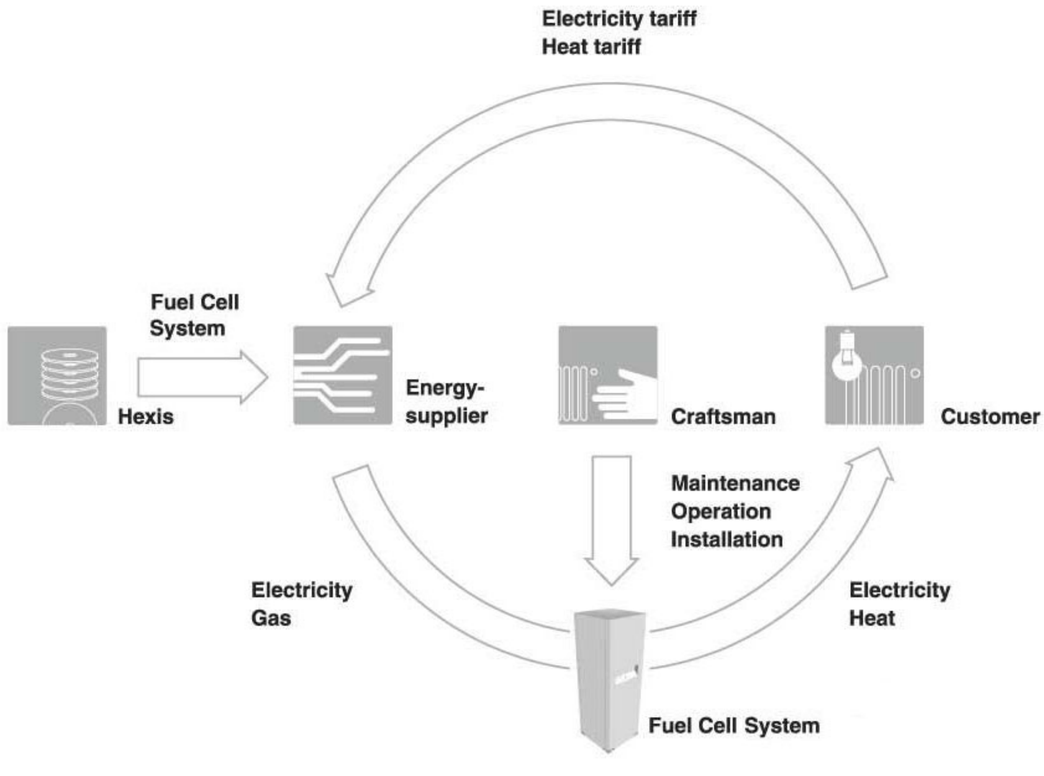

Figure 6: Business Model Energy Service with fuel cell systems.

The other option is: The end customer will buy a fuel cell system via the installer. The latter will deliver, install, commission and maintain if needed the system. The customer will operate it on his own responsibility. To access this sales channel Hexis started a sales and service cooperation with two well established companies in the heating market. These are Stiebel Eltron, Holzminden in Germany, and Hovalwerke, Vaduz in Liechtenstein [1].

5 Summary

The presentation will not be an announcement of a tomorrow market launch, but it will show clear perspectives of a micro CHP solution based on fuel cells made by Hexis. Although, most steps to improve the fuel cell system and its core component, the fuel cell stack, are well known and understood, its further development is time consuming. By-and-by, those steps will be transformed into system technology in order to make Galileo 1000 N being a product, not a prototype.

Long term successful and broad execution of laboratory and more than ever the field tests represents the next challenge on the road to marketing these systems. Statistically firm data of field test operation will be one crucial basis to make Hexis sure to be ready for the market with Galileo 1000 N from 2012 approximately. Additionally, the callux project of the German “National Innovation Programme for Hydrogen and Fuel Cell Technology” pushes the technology forward to improve and enables the manufacturers to head for the market.

The manifold advantages provided by the fuel cell system Galileo 1000 N make Hexis to work hard and to create a marketable and an outstanding product. The experience and knowledge the team gained already makes us confident to continue the Hexis track record.

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ST Stationary Applications

ST.1 High-Temperature Fuel Cells

ST.2 Fuel Cells for Buildings

Fuel Cells for Buildings

John F. Elter

Abstract

Buildings account for about one third of the primary global energy demand, and as such, a major source of energy related greenhouse gas emissions. In this chapter, fuel cells are considered as an alternative and more efficient source of electricity and heat for building applications. Starting with a discussion of the importance of the customer's perspective, a brief overview of the different types of fuel cells applicable to buildings is given. These include those based upon polymer and solid oxide electrolytes. Newer alternatives including alkaline polymer and solid acid systems are mentioned. A in-depth discussion of the recent advancements made in low temperature and high temperature PEM electrodes and membranes is provided as a context from which fuel cell systems for buildings is discussed. A brief discussion of some aspects of fuel reforming and system control is provided, with relevant references, along with some examples of nearly commercial fuel cell systems.

Fuel Cell Systems in Extended Duration Emergency Backup Power Applications

Christopher Guzy, Ballard Power Systems, Canada

1 Introduction

In this presentation, we will cover how the deployment of clean energy, zero-emission fuel cell backup power modules seamlessly handles extended power interruptions. Fuel cell powered backup power products have:

- Extended runtimes, while delivering a high level of reliability in an affordable package;
- High durability with minimal maintenance;
- Longer lifetime than batteries;
- Fueling flexibility, since reformate-capable fuel cell products permit flexible installation where natural gas or methanol is available.

Various aspects of the business will be reviewed in this presentation, including a market and technology overview, followed by examples and experiences from current deployments along with information regarding the commercialization of Ballard Power Systems' fuel cell technology.

2 Market Overview

There are currently two commercially viable telecom applications where extended duration power solutions are being used: emergency backup power and supplemental power.

Emergency backup power is widely required in areas where the grid is reliable and the requirement for backup power is infrequent. Events such as the Northeast U.S. Blackout of 2003 and the Hurricane Katrina disaster of 2005, led to increased focus on availability and reliability of telecommunications services. A key differentiator of telecom systems, whether wireless or wireline, is the ability to provide continuous, reliable service to customers at all times and, in particular, during extended power outages. The choice of backup power technology has a direct impact on the availability of services to end-users and contributes significantly to a telecommunication company's market success. Deployment of fuel cell systems in this application is a practical alternative to lead-acid batteries for telecom service providers.

Supplemental power solutions are required in regions where the grid is unreliable and the need for power is robust and growing. Fuelled by the transition from an agricultural to an industrial base, newly industrialized countries are experiencing economic growth and rapidly expanding market demand. In many of these countries, however, the lack of widespread and reliable electrical power is a real bottleneck to smooth running and efficient economic activity. Urban areas can, and do, experience frequent power outages of over six hours that interrupt daily life, especially for businesses relying on electricity to power critical devices. Companies in high tech industries, such as telecom network operators, long familiar with the unreliability of grid power, have invested in private distribution generation systems. As a result, diesel generators and batteries are most often used to provide supplemental power, though each has its own limitations.

3 Technology Overview

At the heart of Ballard's backup power solutions is our FCgen^{TM}-1020ACS fuel cell stack. The FCgen^{TM}-1020ACS is an air-cooled hydrogen fuel cell that has been engineered to incorporate advanced open cathode technology and state of the art self-humidifying membrane electrode assemblies. These features completely eliminate the need for humidification systems and simplify system integration. The result is a simple, low-cost design delivering reliable operation over a wide range of challenging conditions. With no moving parts and high efficiency, the FCgen^{TM}-1020ACS produces clean DC power with a low thermal and acoustic signature. The fuel cell stack can be scaled to meet power requirements from 300W to 3kW.

The next generation of technology that Ballard is introducing is our FCgen^{TM}-1300 fuel cell stack. The FCgen^{TM}-1300 is a reformate-capable liquid-cooled fuel cell that has double the durability, as well as lower cost, than the FCgen^{TM}-1020ACS. The FCgen^{TM}-1300 has been engineered for state of the art high volume manufacturing. It has the ability to provide from 2kW to 11kW of power suitable for use in applications such as supplemental power.

4 Fuel Cell Deployments

Ballard has several deployments of backup and supplemental power solutions in the marketplace. Two examples will be reviewed in this presentation:

> **(i)** Deployment of fuel cell backup power systems by our partner, Dantherm Power, for use in European TETRA emergency networks, ensuring reliable power-on-demand. This environmentally friendly, fuel cell based backup solution provides mission-critical operations with continuous secure communication across the nationwide SINE network in Denmark, the first network of its kind in the world.
>
> **(ii)** Deployment of our partner IdaTech's fuel cell supplemental power modules by ACME TelePower in India, where the rapid growth of telecom networks and poor grid infrastructure create the need for a more reliable and flexible supplemental power solution. Future deployment of natural gas and methanol reformate fuel cell products to support telecommunication networks in India – and other developing economies – will be a major step forward in providing clean continuous power.

5 Field Experiences

Using the above two examples, the presentation will review the technical challenges that we have faced, including environmental factors (such as high altitude operations and air pollutants) as well as cell degradation due to frequent start/stop cycles. Also a challenge was non-operational performance loss (NOPL) in backup power stacks due to the infrequent operation. Strategies to mitigate NOPL had to be developed and will be reviewed. In addition, we will cover the analysis selected field operational data provided by Dantherm and IdaTech/ACME and the path forward for these deployments.

6 Commercialization

We will conclude with a summary of how Ballard is “putting fuel cells to work” by bringing PEM fuel cell costs down, while leveraging the advantages of the technology, including scalability, safe designs, fuel flexibility, fast start-up, and low-temperature operation. Fuel cells are delivering reliability, durability, and efficiency gains…leading to compelling savings relative to incumbent technology and ensuring their place in the future clean energy landscape.

High Temperature PEM FCs Based on Advent TPS® Technology

Nora Gourdoupi, Advent Technologies, Greece
M. Geormezi, Advent Technologies, S.Neophytides-Institute of Chemical Engineering and High Temperature Chemical processes
J.K. Kallitsis, University of Patras, Advent Technologies

High Temperature PEM Fuel Cells (130˚C-200˚C) offer the distinct advantages of high CO tolerance, enhanced kinetics on both electrodes, easier thermal management and the ability to use cell stack waste heat to boil water for the fuel processor increasing electrical efficiency substantially compared to conventional PEM Fuel Cells. The selection of the components of a fuel cell stack is very critical for the efficiency and durability of the final product. Especially for stationary applications-for example distributed CHP (combined heat and power) systems-a lifetime of at least 40,000 hrs with minimum degradation, is required.

Fuel cell components such as electrocatalyst, catalyst support, microporous layer, membrane, gaskets, bipolar plates are of great importance. The MEA is the core part of the stack and should have specific properties to withstand the strong conditions during the fuel cell operation. The polymer material should possess good mechanical, thermal, chemical and oxidative stability, high glass transition temperature and high proton conductivity while the MEA should possess good mechanical stability, long term chemical stability under continuous operation and cycling conditions and small voltage drop [1-3].

Advent Technologies has developed high temperature polymer membranes based on aromatic polyether polymers and copolymers bearing pyridine units based on the idea of creating acid-base interactions so as to acquire high proton conductivity (~10^{-1}S/cm) at temperatures ranging between 150° and 200°C [4-6].

The aromatic polyether backbone was chosen for its high mechanical, thermal and chemical stability while the incorporation of polar pyridine groups aids in the retention of phosphoric acid. High temperature polymer condensation polymerization is used while the insertion of pyridine groups into the polymer backbone was accomplished using pyridine containing diols which are designed and synthesized for this purpose.

Advent Technologies technical team has succeeded in developing different kinds of high temperature electrolytes, combining different monomers that result in tailor-made polymeric materials. All polymer characteristics are pre-screened in terms of their compliance to the desired properties and then MEAs are studied under cell conditions. At the same time, much work has been done towards the optimization of the electrode and the enhancement of electrode electrolyte interface. So far, Advent TPS® MEAs count two generation products which are the outcome of this chemistry and electrochemistry development efforts.

First generation Advent TPS® MEAs use main chain pyridine polymer as electrolyte.

These MEAs show excellent performance and chemical and mechanical stability at operating conditions for temperatures up to 200°C using oxygen or air as the cathode feed gas. A power output of 0.125 W/cm^2 was measured at 0.2 A/cm^2 at 180^{o}C with H_2/air. In addition, excellent tolerance to 2% CO present in the hydrogen feed was also found.

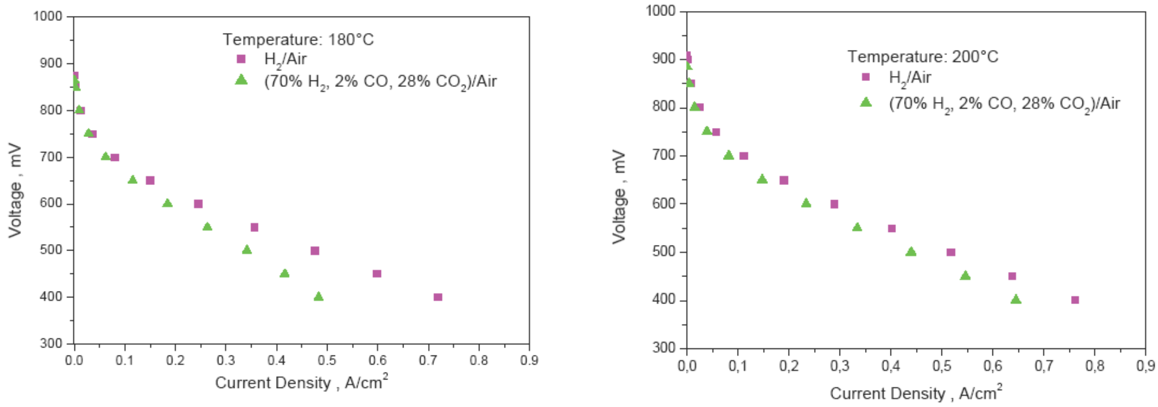

Figure 1: Polarization curves of first generation Advent TPS® at 180^{o}C and 200^{o}C with H_2 or reformate gas and air, under ambient pressure.

Finally, initial long term stability tests have shown extremely stable performance to more than 4000 hrs and 100 thermal cycles.

In the next generation Advent TPS® MEAs, side chain pyridines are inserted in the polymer backbone while optimized electrodes have been used.

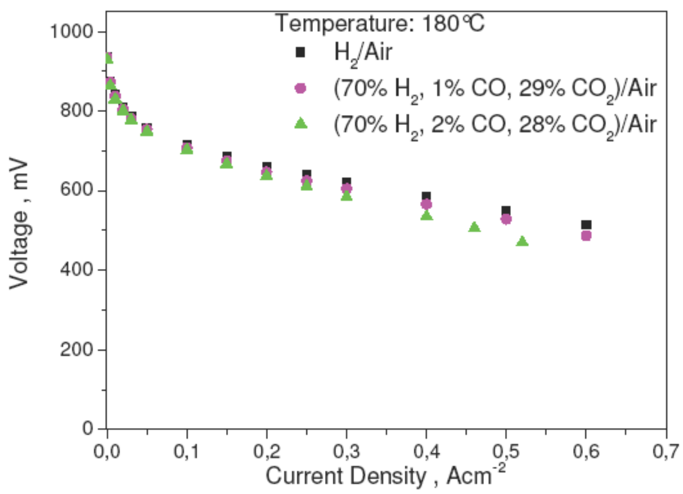

Figure 2: Polarization curves of next generation Advent TPS® at 180^{o}C with H_2 or reformate gas and air, under ambient pressure.

The presence of side chain pyridine has resulted in higher amount of H_3PO_4 retained in the membrane, while new electrodes improve the electrode/electrolyte interface. Those MEAs show decreased ohmic and polarization resistances that result in higher performance compared to the first generation products. A power output of 0.136 W/cm^2 was measured at 0.2 A/cm^2 at 180^{o}C with H_2/air.

Long term stability tests have shown equally stable performance to first generation Advent TPS® and over 130 thermal cycles.

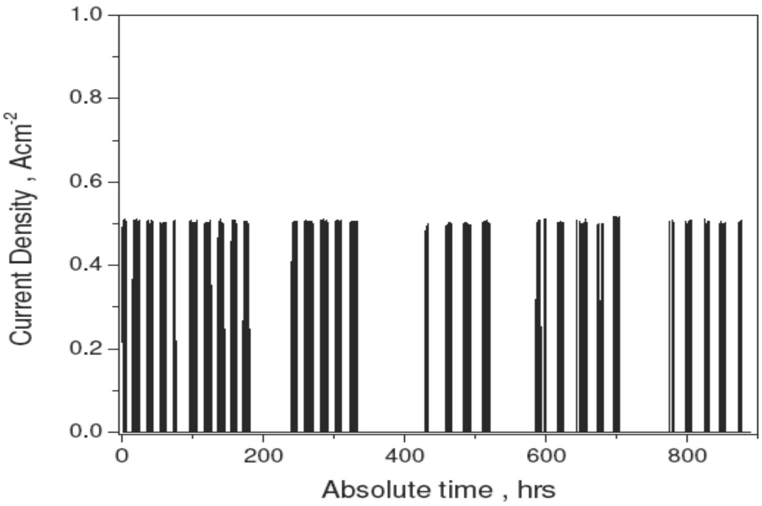

Figure 3

Additional alterations have been also made to the MEAs so that they meet the requirements of different reformate streams and applications. As an example, the absence or the percentage amount of humidity strongly affects the electrode and MEA performance. So custom made MEAs are designed and tested in order to fulfil the feed specification and be compatible with the stream coming from the fuel processor in each case.

Overall, Advent TPS® products show certain advantages compared to the competition due to the high mechanical integrity of the polymer membranes, their oxidative stability as well as the relatively low acid doping level proving them to be a reliable solution for HT PEM stacks for CHP applications.

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Development of Stationary PEFC Co-generation System in Panasonic

Kouichi Kusumura, Soichi Shibata, Akira Maenishi, Hideo Ohara, Panasonic Corporation, Japan

1 Introduction

Panasonic has set "Coexistence with the global environment" as one of its business visions for the 21st century to promote environmental sustainability management. We have defined fuel cells as the most important key business in the Panasonic Group and are promoting the commercialization of household fuel cell cogeneration systems.

Since the introduction of 1 kW-class fuel cell cogeneration systems to the market in 2005, we have installed and operated approximately 500 systems as of the end of March 2009, as part of the large-scale field test project. In May 2009, the systems were released to the general market. We expect to sell 1,000 systems or more in the first fiscal year and will adopt various strategies to encourage full-fledged distribution.

In this report, we describe the development status of Panasonic's household fuel cell cogeneration systems and the product specifications.

2 Concept behind the Development of Fuel Cell Systems

Asthe basic concept for full-fledged distribution of household fuel cell cogeneration systems, we believe that it is necessary to establish safety and quality first, to improve the efficiency and cost reduction for enhancing the advantages of the systems to be purchased by customers, while improving their durability and reliability.

The fuel cell system is a complex aggregate of materials and devices, so system technologies and "integration of technologies" is the key. Not only major device technologies such as fuel processors, stacks, inverters, etc., but technologies and expertise that have been built up by Panasonic during our development of home appliances have been used for overall system optimization.

Panasonic has been developing fuel cell systems by integrating the technologies available at its laboratories and business domain companies and integrating its own technologies.

3 Development Status of Fuel Cell Stacks

The key issues in the development of stacks are to achieve a power-generating lifetime of 40,000 hours and a durability of 4,000 start/stop operations. To achieve such a high durability over a short period of time, we have advanced our development by focusing on identifying degradation factors. With regard to the membrane-electrode assembly (MEA), the most important component in the stack, our study of degradation factors has revealed that the voltage drops due to the following three factors.

1. Damage of the electrolyte membrane due to deterioration (degradation of the gas separation function)

2. Degradation of electrochemical activity due to loss of capability of the platinum catalyst
3. Clogging of generated water due to the degradation of gas diffusion layers

In view of these degradation factors, the development was pushed forward from the viewpoints of material development, stack design, and forecast evaluation technologies. As a result, we could see the way ahead for improving system durability. Some of the durability test results are shown in Figure 1.

During the 24,000-hour durability test, the voltage dropped only by approximately 3.5% from the initial value. This was within our expected level of degradation. A durability of more than 4,000 start/stop operations was also achieved.

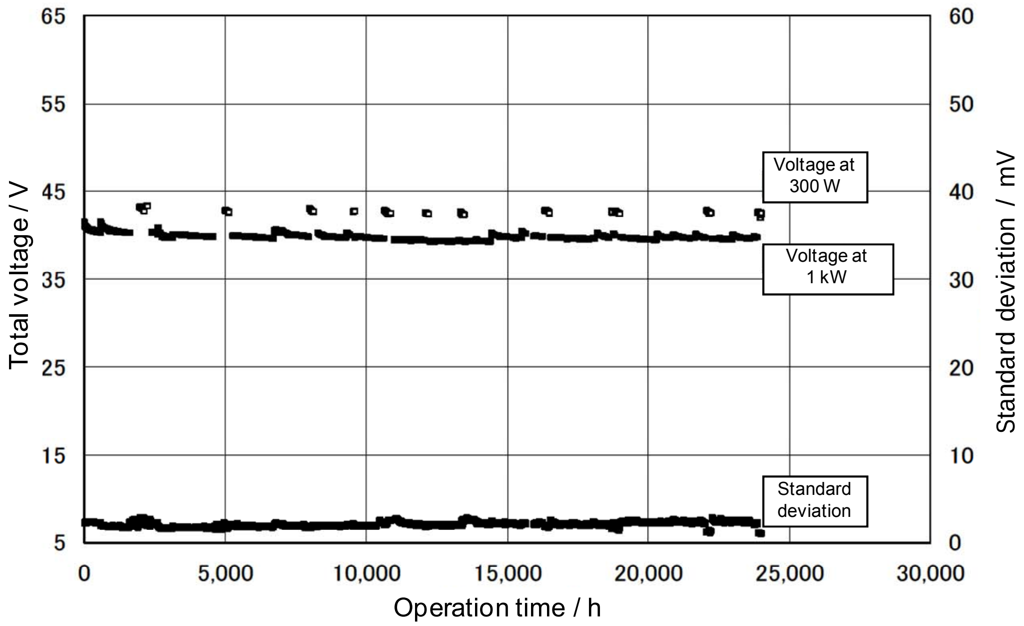

Figure 1: Full-stack durability test conditions.

4 Development Status of Fuel Processors

For fuel processors, what is required is better reforming efficiency to improve the power generation efficiency, better stability of hydrogen supply to the stacks, and a durability of 10 years or more. Improved reforming efficiency is of particular importance, since a household fuel cell is energy-generating equipment. The reforming efficiency is the ratio of the calorific value of the hydrogen used for power generation to the calorific value of the supplied raw materials.

In our conventional fuel processors, the reforming, denaturation, and preferential oxidization processes were independently controlled to stabilize performance. On the other hand, to achieve high efficiency by using heat effectively, thermal fluid simulations, in which reactions are taken into consideration, were used to study configurations that can optimize the reactions and fluid flow. As a result, we have developed integrated small multi-walled coaxial cylindrical fuel processors, on which evaporation, reforming, denaturation, and preferential oxidization devices are circularly located around the burner.

The heat from burner combustion is used in 'downhill' from the high-temperature device (for reforming) to the low-temperature device (for evaporation). Also, the heat of the generated gas is transferred from the high-temperature device to the low-temperature devices to ensure its most effective use.

Figure 2 shows the efficiency of reforming with reference to the operating conditions of the integrated fuel processor. The efficiency of reforming was 77% (Lower Heating Value, LHV) during the rated operation and 69% (LHV) during low-load operation (while generating 1 kW of power). The efficiency was significantly better under medium and low-load operating conditions than in conventional fuel processors.

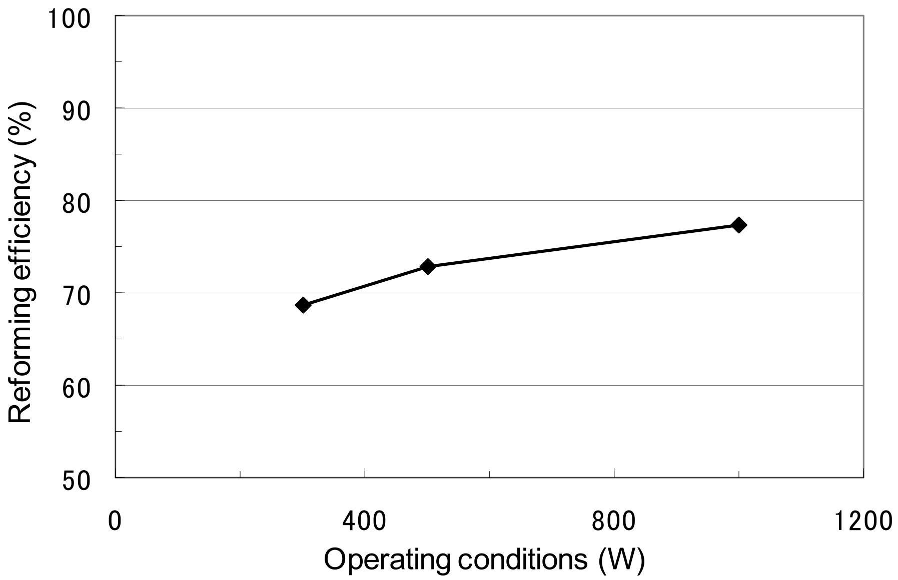

Figure 2: Reforming efficiency.

5 Development Status of Household Fuel Cell Cogeneration Systems

5.1 Product overview

The appearance of the newly developed fuel cell cogeneration system is shown in Figure 3, the product specifications in Table 1, and the outline of performance in Table 2.

With regard to performance, efficiency in the actual usage range of 500 W to 1 kW has been improved to achieve a high degree of energy saving. In addition, a durability of 10 years or more, necessary for a household equipment item, has been ensured. We adopted the following strategies to improve the equipment's energy-saving performance and durability.

Figure 3: Appearance of the fuel cell cogeneration system.

Table 1: Specifications of the fuel cell cogeneration system.

Item	Specifications
Fuel type	City gas
Electrical output range	300 to 1,000 W
Operational control system	Automatic power generation (with demand learning function), hot-water reserving-based power generation, timer-controlled power generation, or manual power generation

Table 2: Performance of the fuel cell cogeneration system.

Item	Performance
Power generation efficiency	38% (LHV) at 100% output 39% (LHV) at 75% output
Heat recovery efficiency	55% (LHV) at 100% output 50% (LHV) at 75% output
Hot-water temperature	Equal to or greater than 60 ˚C

5.2 Strategies used to improve energy-saving performance

Fuel cell cogeneration systems generate hydrogen from city gas in the fuel processor and, in the fuel cell stack, react the hydrogen with oxygen taken from the air to generate electricity and heat. The generated electricity is then converted to usable alternating-current power via an inverter, and the generated heat heats up water held in a hot-water reservoir. The hot water is supplied as is or for heating purposes. Therefore, to achieve a high overall efficiency, it is necessary to improve the efficiency of the fuel processor, stack, and inverter. In our developed fuel cell system, we targeted achieving efficiency improvements in the actual usage range of 500 W to 1 kW. We worked on developing the above-mentioned high-efficiency integrated fuel processor and low-loss inverters.

The inverter consists of a boost converter that boosts low DC voltages and a utility interactive inverter that converts DC output to 200 V AC and interacts with the commercial power supply. The conventional hard switching system has a large overlap loss of "current x voltage" when switching at low voltage (large current) and its efficiency is significantly lower in the low to medium output ranges. In the newly developed inverter, the voltage change timing is controlled by software switching over the entire operating range to eliminate the "current x voltage" overlap loss, and the thermal losses from power transistors have been significantly reduced. As a result, the efficiency in the 300- to 750-W output range has been significantly improved. As shown in Figure 4, the new fuel cell cogeneration system achieves its highest power generation efficiency of 39% (LHV) at 750 W output, and 38% or higher (LHV) over the entire output range (500 W to 1 kW), at which the system is most often operated, due to the adoption of a more efficient fuel processor and a low-loss inverter.

Learning control software, based on a neuro-algorithm, is incorporated to save even more energy by optimizing the operation conditions. The predictive control to which the energy management technologies are applied has achieved the optimum system operation in accordance with the actual usage conditions in each household.

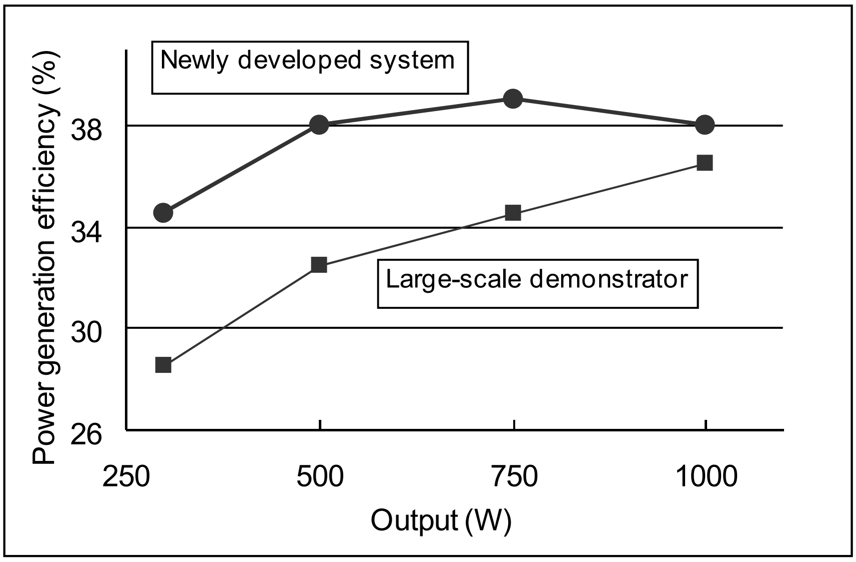

Figure 4: Power generation efficiency of the fuel cell cogeneration system.

6 Future Directions

Following the large-scale field test project, which lasted for four years starting in 2005, the systems were released onto the general market in May 2009. Panasonic is adopting various strategies for the full-fledged distribution of the system. The chief problem is naturally cost.

The cost must be reduced for full-fledged distribution of the system. We plan to focus our development efforts towards achieving a market price of 600,000 yen. We will need to develop unique technologies, such as system simplification, etc., to unify the basic specifications and component standardization in the industry; and also reduce the cost by means of economies of scale. We plan to positively promote the blending of technical capabilities by collaboration with two or more national projects.

Definition and Analysis of a Hydrogen Integrated Building in Andalucía, Spain

Beatriz Alzueta, **Gabriel García**, **Raquel Garde**, **Mónica Aguado**, National Renewable Energy Centre (CENER), Ciudad de la Innovación, 7, 31621 Sarriguren, Spain

1 Introduction

If we want to achieve the commitments adopted by the European Commission in order to reduce the CO_2 emissions [1] and to increase the energy produced by renewable sources, it is necessary to make an important effort in all sectors.

Residential sector could contribute to achieve these targets making a more efficient use of the energy and increasing the use of renewable energy.

Hydrogen and fuel cells could be introduced in this sector considering their high efficiency, small size, reliability and general performance.

The owners of households, who are generating electricity for their own needs, could feed surplus electrical power into the grid constituting a small distributed generation system.

If hydrogen is obtained from renewable sources, fuel cells can increase the contribution of renewable sources in the electricity grid and reduce the dependence on fossil fuels.

In this paper, the results obtained in the project carried out by CENER “Definition and analysis of a hydrogen integrated building in Andalucía” are presented. This project has been financed by the Planning and Technology Department of the Consejería de Obras Públicas y Transportes of Andalucía Goverment, Spain.

Different configurations for this system are analyzed to determine the best option from different points of view: technical, economical and environmental.

2 System Description

CENER has analyzed the feasibility of building a 16 flats building block in Sevilla, Spain, using hydrogen to cover the electrical demands. At the beginning, the aim of the project was to achieve self-sufficiency for the whole building, but due to the high cost of this systems and the space required, this target has been discarded and 4 new configurations have been analyzed using HOMER [2] (Figure 1).

The necessary hydrogen could be produced on site with photovoltaic electricity, purchased to an external gas company, or even reformed from natural gas.

As we can see in Figure 1, in some of those cases the fuel cell is connected to the DC bus, but this does not mean that a DC/AC converter is not necessary. In those cases, both converter costs and the lost of efficiency related are included within the fuel cell cost and efficiency.

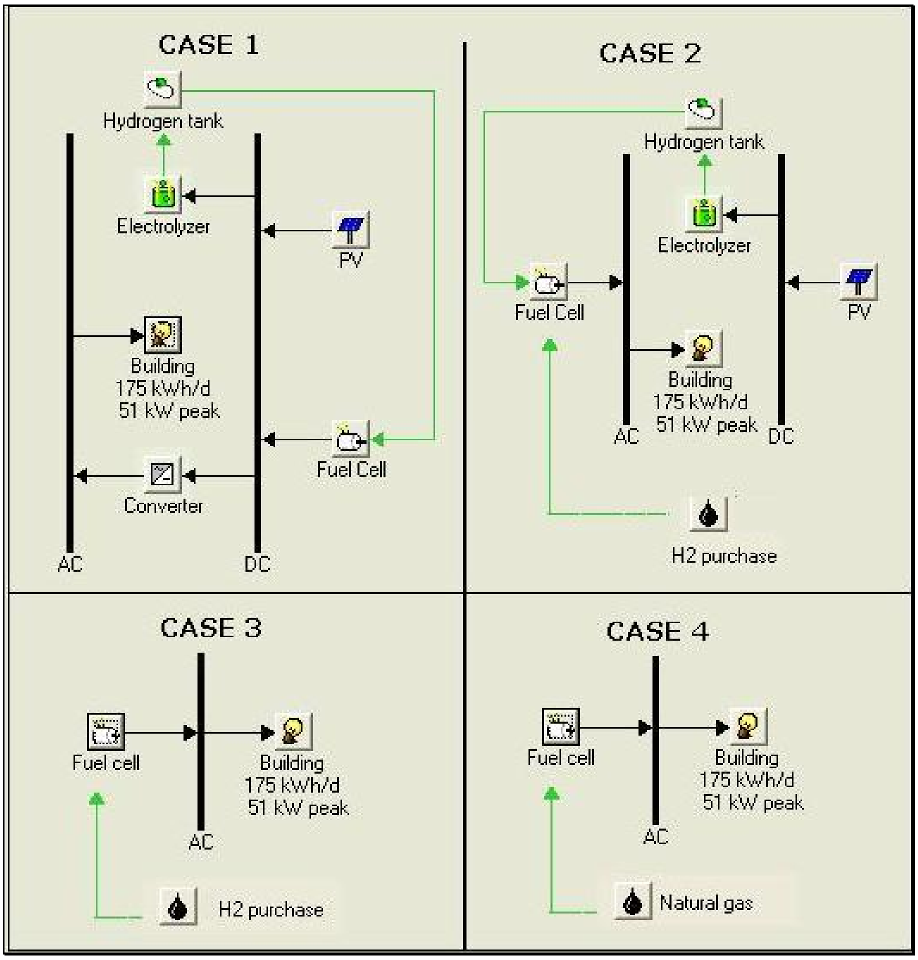

Figure 1: Four different scenarios analyzed with HOMER.

In case 1 the photovoltaic system produces electricity to cover part of the electrical demands, at the same time that produces hydrogen when there is surplus electricity.

To simulate this system, photovoltaic panels, electrolyser, and fuel cell are connected to the DC bus (Figure 1). In this way, HOMER could select the best option between a) to generate electricity from the photovoltaic panels and to consume it directly by the building, or b) to produce hydrogen and to use it when electrical demand exists but photovoltaic generation is not available.

Some simulations have been carried out reducing the self-sufficiency of the building. If all the electrical demand was to be covered, just for the photovoltaic system more than 100 kW will be necessary, so much as for a 600 m^2 building, when there is only enough space on the roof to install 40 kW aprox. Therefore, the CASE 1 has been developed for 70% self-sufficiency.

The next cases analyzed seem more feasible, because they need less space in the building to install all the components and the system is more cost competitive.

In CASE 2 the fuel cell covers 100% of the electrical demand, thus covering all the power peaks in the building, taking into account the simultaneousness factor. In this case the fuel cell will be oversized, because most of the time it works below its total capacity, as we can see in Figure 4.

In this case hydrogen has two different origins: a small part of the hydrogen is produced on site the building through electrolysis from photovoltaic electricity, and the rest of the hydrogen needed is provided by a specialized company. If this company produces hydrogen from renewable sources as solar thermoelectric, a possible option in Andalucía, the hydrogen will still be renewable even though it is not produced in the building.

To simplify the installation, two different cases have been analyzed.

In CASE 3, instead of producing the hydrogen in the building, it will be totally provided by a specialized company. As we mentioned before, this company could produce the hydrogen from renewable sources leaving fuel free of emission.

In CASE 4, the difference lies in the fact that a natural gas fuel cell has been used. In this case, it is only necessary the natural gas pipelines connected to the building and the hydrogen will be produced within the fuel cell with a reformer.

Under this last option, as well as covering the electrical demands of the building there exists the possibility to use the residual heat from the fuel cell to cover part of the DHW demand and/or the heating demand. The only drawback of this system is that the source of the hydrogen is not renewable.

3 Features of the Components

To analyze the different cases described in the previous section, the software HOMER has been used.

In Table 1, the economical and technical features of the components used in the different simulations are shown. The investment costs of each component are shown in this table, as well as the replacement and O&M costs. In the same way, the lifetime of the photovoltaic modules and electrolyser, the number of operation hours per year of the fuel cell and the electrolyser efficiency are shown.

Table 1: Features of the components.

	Photovoltaic modules	Electrolyser	Fuel cell	H_2 storage
Investment costs	6,000 €/kW	5,400 €/kW [3]	6,000 €/kW[1] 3,000 €/kW[2]	1,445 €/kg
Replacement costs	4,000 €/kW	2,000 €/kW	4,000 €/kW[1] 1,500 €/kW[2]	1,445 €/kg
O&M costs	300 €/ year	216 €/year	5.5% of the investment costs	0 €/ year
Operation hours			15.000	
Lifetime (year)	35	25		25
Efficiency		65%		

[1] For 1 kW fuel cell, estimated from [4]

[2] For 20 kW fuel cell, estimated from [4]

In Figure 2, the H_2 fuel cell and NG fuel cell efficiency curves calculated by HOMER are shown. Those curves are calculated according to the fuel consumption and production parameters introduced in the model.

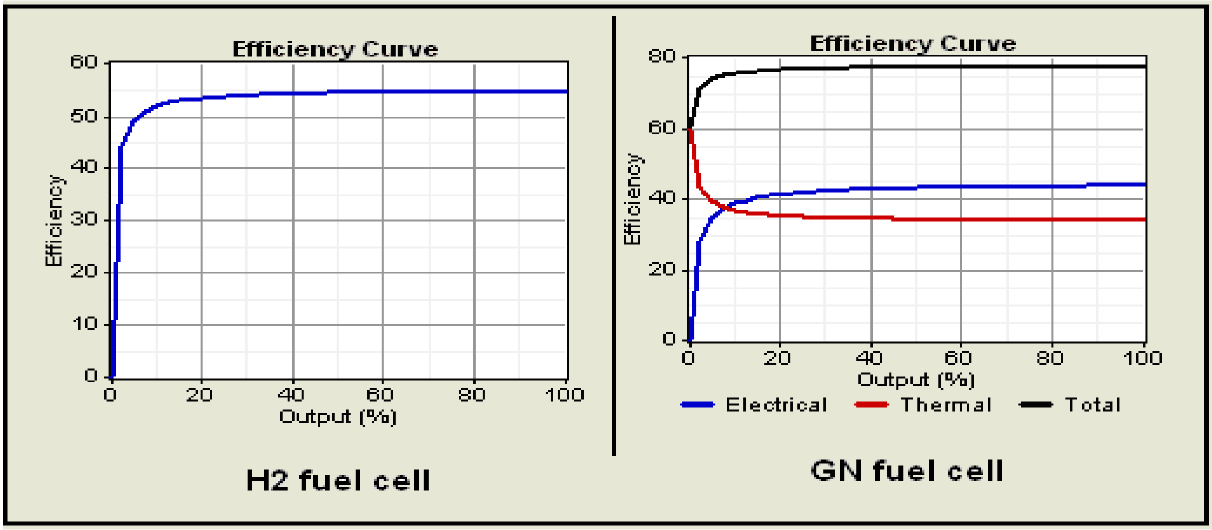

Figure 2: H_2 fuel cell (Left) and NG fuel cell (Right) efficiency curves.

4 Analysis of the Results Obtained from HOMER

The sizes of the equipments used in each case are shown in Table 2, as well as the amount of hydrogen or natural gas purchased when an external supply it is necessary. In this table, we can also see the cost of energy per kWh and the whole system cost for each case.

Table 2: Summary of different cases analyzed.

	P.V. (kW)	F.C. (kW)	Electrolyz (kW)	H_2 storage (kg)	H_2 purchase (kg)	Natural Gas (m^3)	COE (€/kwh)	TOTAL (NPC)	CO_2 emissions avoided (ton)
CASE 1	45	4	30	15			0.8723	829,549	20.3
CASE 2	10	40	9	2.5	3,482		0.977	967,922	29
CASE 3		40			3,810		0.894	804,409	29
CASE 4		40				15,739	0.835	750,938	

P.V.= Photovoltaic array; F.C.= Fuel Cell; COE= Cost Of Energy; NPC=Net Present Cost

According to the results shown in Table 2, the most feasible case from the economical point of view is CASE 4. This case is also the most easy to install and it uses the most reliable technology, because natural gas fuel cells have a longer lifetime than hydrogen fuel cells have. However, in this case the origin of the hydrogen is not renewable.

Among the rest of the cases, CASE 3 is the most the most suitable from the technical and economical point of view. Finally, CASE 1 is more cost-competitive than CASE 2, because in

CASE 1 30% of the electrical demands are covered by the grid and this fact makes the system cheaper.

The operation mode of the main components in CASE 1 (photovoltaic system, fuel cell, hydrogen storage) is shown in Figure 3, reaching a 70% of self-sufficiency.

As shown in this figure, the photovoltaic system works during the day, whereas the fuel cell works during the night or when the solar contribution is not enough. The black colour shows the hours of the day in which fuel cell or photovoltaic modules do not work.

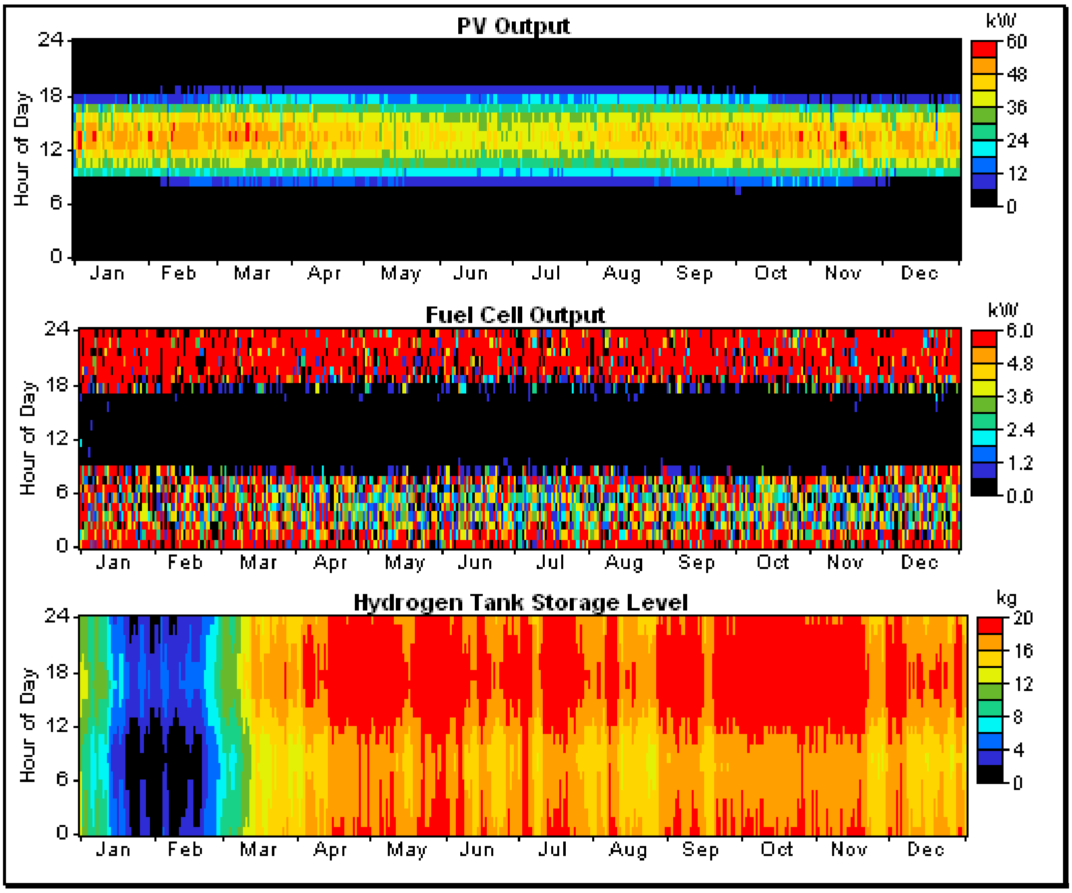

Figure 3: Photovoltaic system, fuel cell and H_2 storage operation mode.

In relation with the hydrogen storage, the following restriction has been made: at the end of the year the level in the hydrogen tank has to be, at least, at the same level as it was at the beginning of the year. In this way, a year is representative of the rest of the period (25 years in all). Therefore, in Figure 4 we can see how the tank is sometimes full during the summer months, while in January and February there is a reduction in the hydrogen storage.

As we have seen before, 45 kW of photovoltaic system are necessary in CASE 1, but this option takes a huge space in the roof. CASE 2, which is a combination of CASE 1 and CASE 3 could clear this problem up.

In CASE 3 and CASE 4 the fuel cell could cover practically 100% of the building demand, but this option is not the most appropriate since the building is connected to the grid, and to cover the peak power with the grid avoiding to oversize the fuel cell is more reasonable.

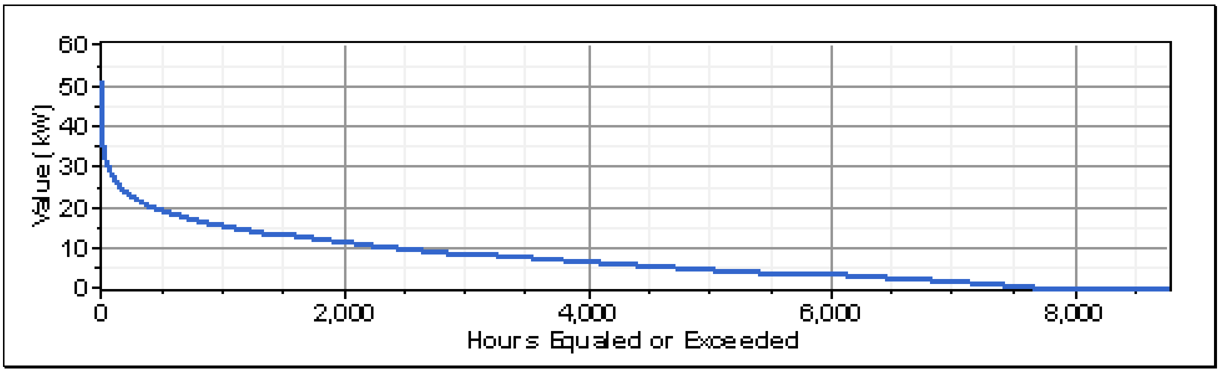

Figure 4: AC primary load duration curve.

In Figure 4, we can see that the power is higher than 40 kW (maximum fuel cell power) only during 7 hours per year. This means that the power grid will need to cover the 0.05% of the whole year demand. A 30 kW fuel cell will be used in order to reduce costs, and in this case the grid will have to cover 60 hours a year.

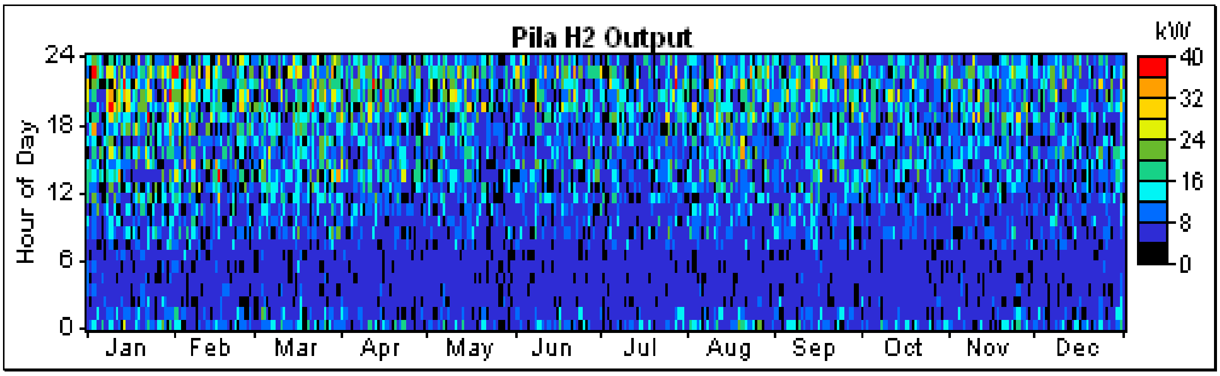

Figure 5: Fuel cell operation mode.

This fact is also shown in Figure 5, where we can see the fuel cell operation mode in CASE 3 and CASE 4. The fuel cell is working below its maximum power during most of the time, and therefore the system costs could be decreased quite a lot if the power peaks were covered from the grid.

5 Conclusions

Different configurations have been analyzed to study the feasibility of a 16 flats building block using hydrogen to cover the electrical demands. Hydrogen could be produced on site through water electrolysis from photovoltaic electricity.

The 100% self-sufficiency is the most restrictive option, as this option is really expensive, has a lot of technical restrictions and takes a lot of space in the roof to install all the components. Therefore other options have been studied.

The fist option is to increase the contribution of the grid to cover part of the electrical demands reducing the size of the systems. The second option analyzed is to produce part of the hydrogen on site and to purchase the rest of the needed amount to a specialized company. In the third option all the hydrogen is purchased, and in the last option a natural gas fuel cell with a reformer is used.

Analyzing all these options the conclusion is that currently the election of most feasible option, taking into account all the barriers related to physical space, lack of technological maturity and regulation, depends on the amount of electrical demand required to be covered from a renewable source to avoid CO_2 emissions, and depends as well on its economical cost.

Hence, the two most feasible options could be the option of using a natural gas fuel cell and the option of purchasing the hydrogen if a free emissions system is preferred.

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Hybrid Installation to Cover Isolated Electrical Consumptions with Hydrogen Storage (IH2 Project)

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1 Introduction

The continuous need of energy supply to a dwelling requires reliable generation sources; one of the most important concepts is the no interruption of the energy. Moreover, the society demands clean energy sources to care the environment. One possible solution for this topic is the combination of electrical storage with renewable energy. This storage provides an amount of energy for periods in which we cannot produce energy from renewable sources.

There are several alternatives to storage energy: in the form of electromagnetic energy, kinetic, electrostatic potential... [1]. Among them we can highlight the chemical energy of hydrogen by their unique characteristics. Hydrogen is the most abundant element in the universe. It can be produced from the electrolysis of water with electricity, or biomass for thermal or biological decomposition, as well as from the fossil fuels like gas, oil or coal.

Between all methods, we can notice the electrolysis as a method to get hydrogen from renewable way, at any scale of production, and a possible housing facility. Once produced, hydrogen is an energy carrier. Hydrogen can be used in stationary applications (power generation) and / or cogeneration systems, and also for mobile applications, i.e., vehicles that run on hydrogen.

The Aragon Hydrogen Foundation launches IH2 like a demonstrative project for the technical integration of renewable energy with hydrogen as energy vector. It was decided to undertake a small project for possible integration into real small power applications , such as communication systems, houses, mountain huts, and in general, small installations where the power supply is not feasible.

The targets have been met by performing the system design, equipment selection, integration and assembly equipment, studies and other patterns that are described in more detail below:

1. Design and development of the plant balance, to supply electricity to a house to meets the demand, using photovoltaic as the main source of energy, a small support wind generator and hydrogen like energy vector.
2. Survey of the different connections types for the hydrogen production with photovoltaic and his storage. Integration, installation and implementation of the project.
3. Equipment testing and evaluation
4. System development of control and data acquisition [2,3].
5. Analysis and processing data acquired with varying levels of production consumption in order to extrapolate results to different power systems.
6. To develop criteria to improve the efficiency, reliability and security of the project

2 IH2 Project Installation

The following figure shows the installation scheme:

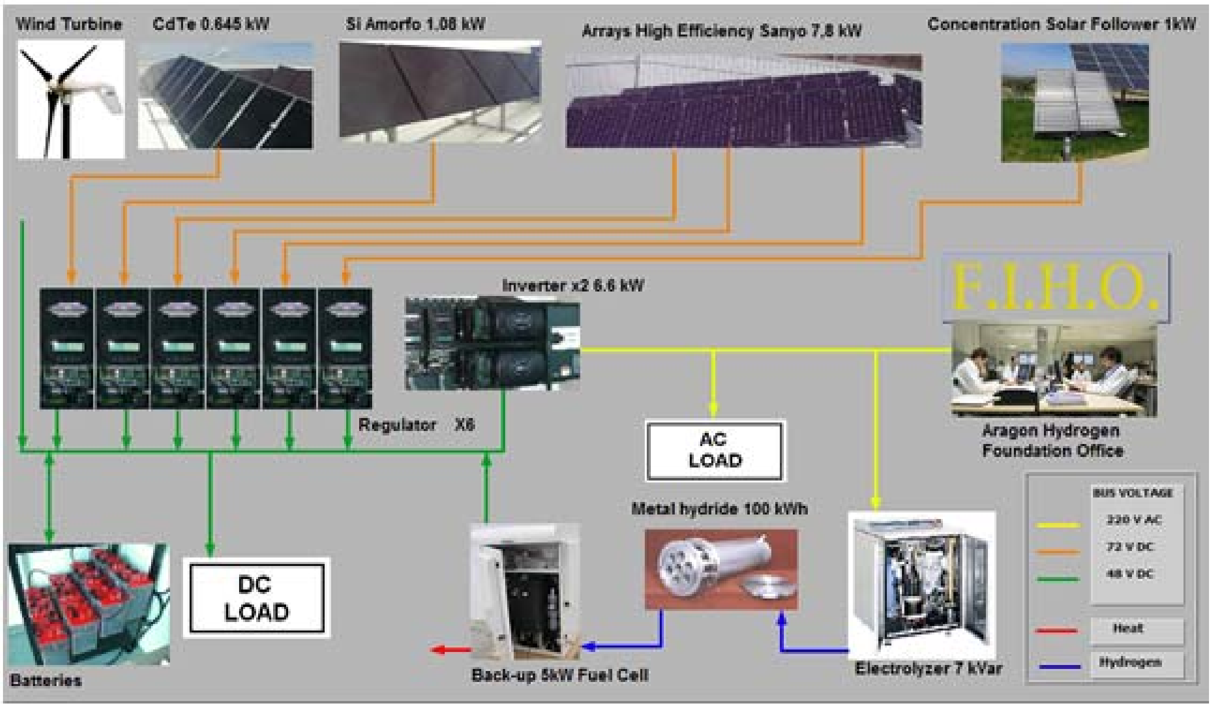

Figure 1: Installation scheme.

Electrical installation consists of a solar system that is placed around the Foundation's building. It is composed of fixed photovoltaic panels on the roof and solar concentrator at the front) and a micro wind turbine. The detailed generator list is:

1. 7.6 kW high efficiency panels. Divided in three arrays.
2. 1 kW sun concentration tracker with tree layer photovoltaic technology.
3. 0,7 kW thin film (TeCd) photovoltaic panels.
4. 1 kW amorphous silicon photovoltaic panels.
5. 400 W, Air X wind turbine

All electrical generators produce direct current (DC), the photovoltaic panels work in the optimum point coupled with Pmp regulators. A small bank of batteries is coupled to be actuated as an energy buffer. Two inverters transform DC it into AC to feed powering electrical charges and electrolyser.

1. Electrical equipment:
2. Regulators (Outback MX60),
3. Charger/inverters (Outback VFX3048E),
4. Batteries (Exide OPZ 460 Ah)

Hydrogen produced by the is stored in metal hydrides with a maximum pressure of 14 bar. During periods of lack of energy sources or at night, a 5kW fuel cell runs to power the system. The detailed hydrogen component list:

1. Electrolyze (HOGEN 0.5m^{3}N/h) and water treatment

2. Fuel cell PlugPower SB48 Power: 5kW
3. Labtech Metal-Hydride 15m^{3}N, 5m^{3}N per bottle of 3 installed. The amount of energy can be approximate to 66kWh

In order to use the amount of energy produced, the office of the Aragon Hydrogen Foundation has been connected to the installation acting as an electric load.

3 Monitoring Program

A comprehensive monitoring system has been developed [4]. It is combined with the research orientation to opens the door to many behavioural studies of the plant: under different load profiles, response with the weather conditions, system failures etc. The monitoring system has been developed in LabVIEW. It is flexible enough to be implemented in other applications with only minor modifications.

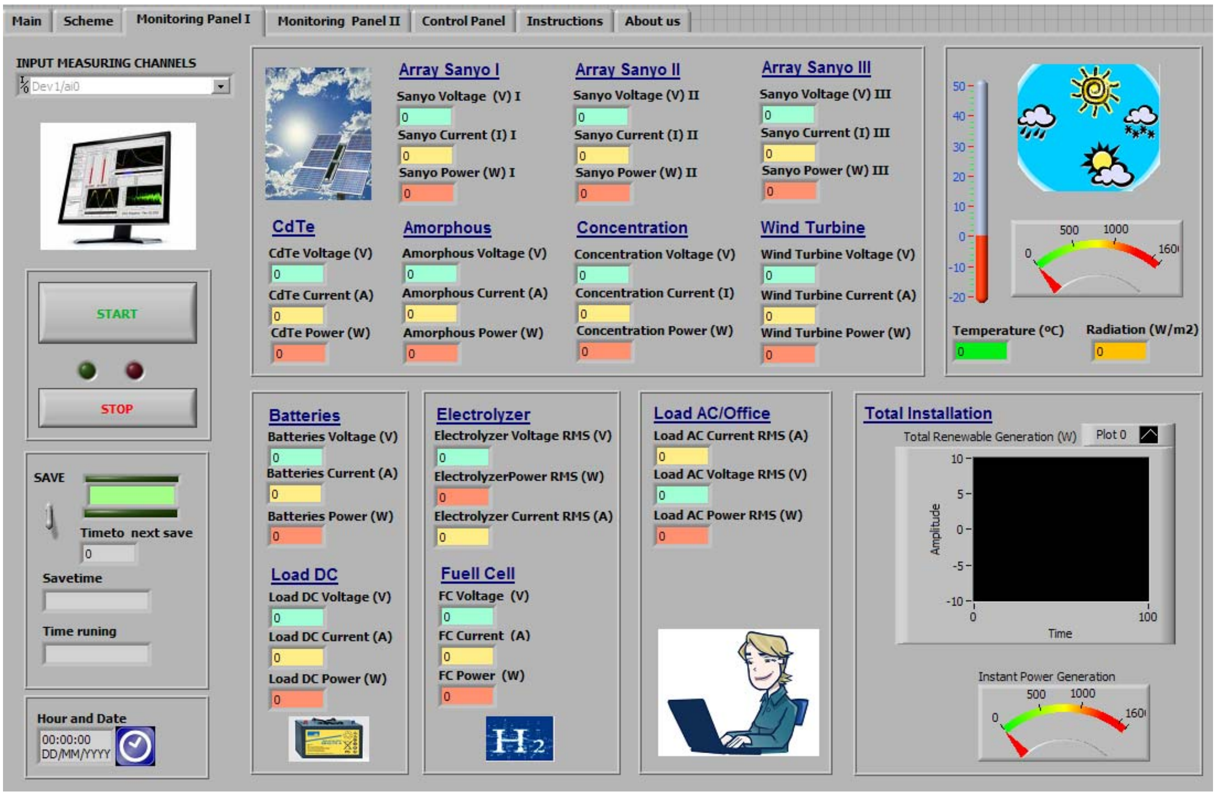

Figure 2: Screen capture of monitoring program.

Figure 2 shows that at electrical installation it has been measured the following variables: Voltage, Intensity Power, Temperature and Radiation. It allows to analyze the installation response with weather variability. At the hydrogen part the following measures have been developed: Temperatures, Pressure, Flow in order to obtain PFT graphics to characterize capacity, load and unloading operations.

A control panel and a hardware have been installed and developed in order to control electric loads. The main purpose is to probe different control systems and algorithms.

4 First Test

During the first part of the experiments, all equipment has been tested individually to verify the right work, as in the case of wind turbine, photovoltaic panels and electrolyze. The next part of the work plan is on the way, and the first results have been processed. They consist of different tests between many devices connection topologies and the energy supplied by the different generators. Furthermore these measurements allow to compare different technologies to choose the most efficient.

The next graphs show the results feeding the Aragon Hydrogen Foundation Office during a week. The first graph shows renewable energy generation by the different technologies installed. Next chart shows the energy balance during this test.

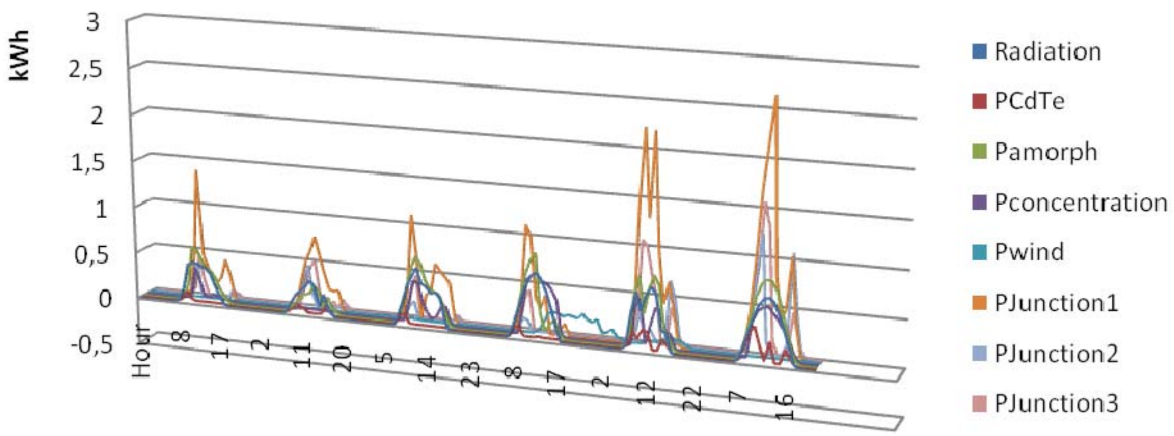

Figure 3: Renewable generation.

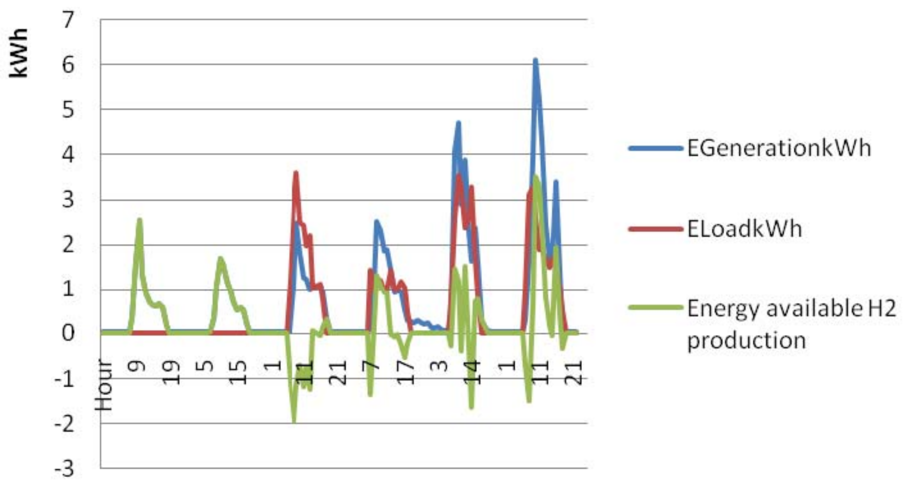

Figure 4: Energy balance.

Last chart involve Hydrogen generation and the real amount of energy available to store it in metal hydrides [5,6].

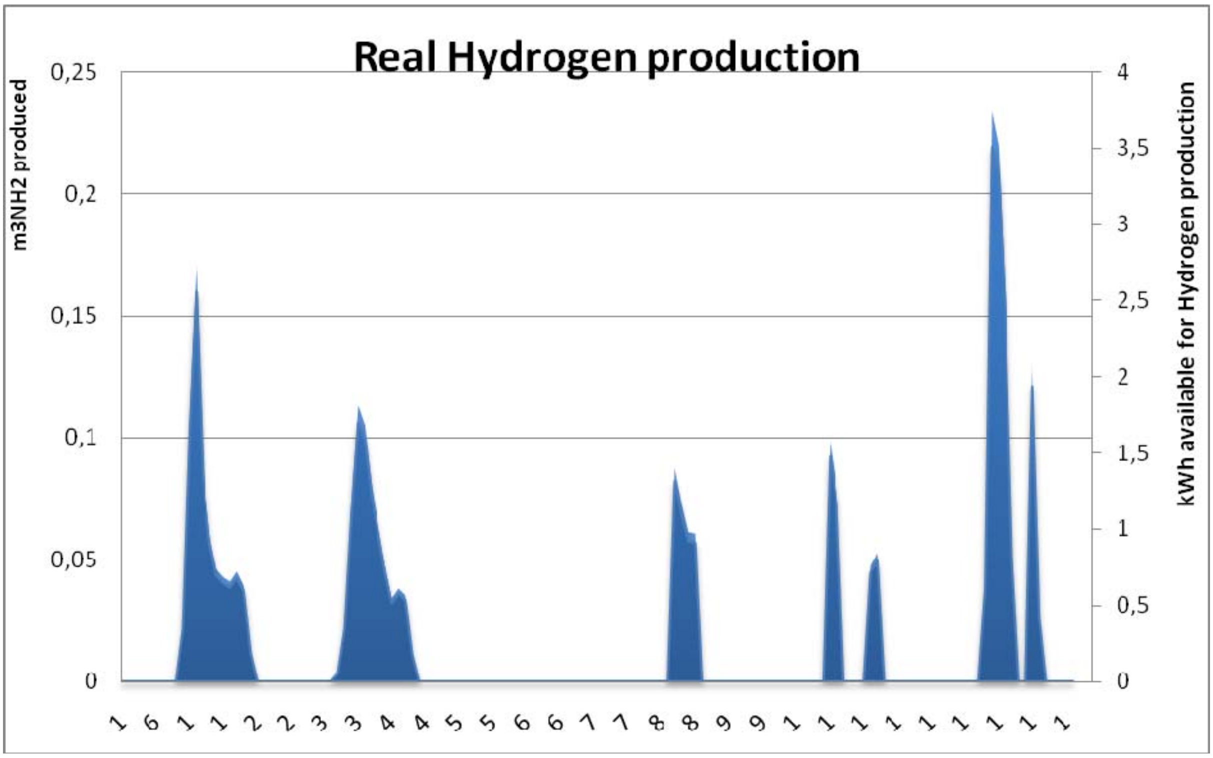

Figure 5: Real Hydrogen production.

5 Conclusions

A real installation and a complete monitoring system have been developed to analyse the system under different conditions. It has been checked that the installation works correctly. Besides the feasibility of producing green hydrogen from photovoltaic and wind energy in a real isolation conditions has been demonstrated. On cloudy days and nights, the small bank battery is used. If it is not sufficient the main support of the hydrogen fuel cell feed the load using the hydrogen generated by renewable energy when the weather conditions make it possible.

Real tests are in progress and the first results are shown in this paper. Moreover, it is important to realize, that the energy produced in the installation is being consumed by the Aragon Hydrogen Office.

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Thermodynamic Efficiency of Geothermal Plants with Hydrogen Steam Superheating

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Abstract

Results of the thermodynamic analysis of using hydrogen for steam overheating in geothermal power plants are presented. It is shown that increase of parameters of wet geothermal steam leads to increase in power station efficiency at 3-6 % taking into account expenses of the electric power for hydrogen and oxygen production in electrolyzers. The method of an estimation of increase in efficiency geothermal turbine with growth of parameters of steam and results of calculation of expenses of the electric power is resulted. The optimum overheat range of the geothermal steam for providing maximum geothermal station efficiency is defined at the minimum expenses for installation of the additional equipment. Approximate cost of the additional equipment for maintenance of an overheat is estimated and its pay-back terms are calculated.

1 Introduction

The use of geothermal energy makes possible to get electricity and heat usage of fossil fuels. However, the electrical efficiency of modern geothermal plants is still relatively low (12-18%) primarily due to the parameters where the coolant temperature does not exceed 550 K. The basis of conversion of geothermal heat into electricity is the steam-turbine technology, which is the most effective and affordable in this case. Let consider the main components of the electric efficiency of any single-turbine plant:

1. Thermal efficiency of steam-turbine cycle
   a. turbines on the superheated steam (about 60%);
   b. geothermal steam turbine (about 28%);
2. Efficiency of steam turbine;
   a. turbines on the superheated steam (about 90%);
   b. geothermal steam turbine (about 80%);

Thus, the maximum electrical efficiency of modern single-turbine plant is about 53%, and geothermal plant is only 14-18%.

2 The Problem Formulation

To improve the efficiency of geothermal power plant operating in Rankine cycle is necessary to increase enthalpy drop on the turbine. This could be achieved by increasing the steam parameters at the turbine inlet and lowering outlet pressure. Thus to significantly increase the efficiency of the power unit it is needful to replace the geothermal turbine with the high internal efficiency turbine operating at superheated steam with additional superheating of wet steam.

For superheating of steam it is intended to use high temperature steam produced by combustion of hydrogen in oxygen, which are preliminary obtained by electrolysis. Main flow of wet steam is directly mixed with very high temperature (up to 1700 °C) steam from hydrogen-oxygen steam generator working at stoichiometric mixture of components. This technique significantly simplifies the design of superheater and minimizes heat losses [2,3].

3 Thermal Efficiency Analysis of Geothermal Plant with Hydrogen Superheating

An absolute internal efficiency is composed of turbine thermal cycle efficiency and internal efficiency of the turbine. The expression for the single-geothermal power plant with a hydrogen-oxygen steam superheating for the cycle shown in Fig. 1:

$$\eta_i = \frac{G_S \cdot (1+\alpha) \cdot H_{3'-4'} \cdot \eta'_{0i} - \dfrac{N_{H2}}{\eta el}}{Q_{1-2-3} + Q_{3-3'} - Q_{4'-1}} \tag{1}$$

where G_s - steam flow to the turbine without superheating, α - the relative share of high-temperature steam from the added hydrogen steam generator, $H_{3'-4'}$ - enthalpy drop of process 3'-4', η'_{0i} - internal efficiency of the turbine, η_{el} - the efficiency of the electrolyzer, Q_{1-2-3}, $Q_{3-3'}$, $Q_{4'-1}$ – heat supplied and removed.

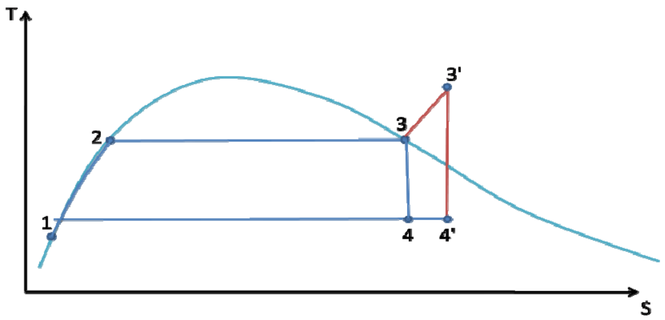

Figure 1: Geothermal power plant cycle with hydrogen-oxygen superheated steam before the turbine.

To determine the internal efficiency of the turbine with the change of steam humidity use well-known relation [4]:

$$\eta'_{0i} = \eta^0{}_{0i} \cdot \chi_{av}{}' \tag{2}$$

where η^0_{0i} - maximum internal efficiency of the steam turbine, χ'_{av} - the average steam dryness in the steam turbine.

From the condition of energy balance, let us write the expression for the determination of additional work, obtained in the implementation of superheat steam, taking into account the power consumption (PC) of electrolysis:

$$\Delta W = \eta'_{0i} \cdot H_{3'-4'} - H_{3-4} \cdot \eta_{0i} - \alpha \cdot q_p^h \frac{1}{\eta_{el}} \quad (3)$$

where H_{3-4} –heat drop without superheating, η_{0i} - internal efficiency of the turbine without superheating.

Typical values η^0_{0i} of wet steam turbines for geothermal power plants are 0.75-0.85, for the calculation we take it equal to 0.8. Substituting the data in (1) and (3) for different values of α we obtain the results presented in Table 1.

Installing the upgraded turbines in superheated steam, one makes η^0_{0i} equal to 0.89-0.9. It should also be taken into account that the efficiency of the turbine at superheating steam at operation on wet steam is smaller than the original, because of none-nominal operation mode. The change of the efficiency of geothermal plants by installing turbines on the superheated steam is shown in Table 1.

Table 1

α	**T, K**	**χ'_4, %**	**η'_{0i}, %**	**η_i, %, at η^0_{0i}=0,8**	**η_i, %, at η^0_{0i}=0,9**	**ΔW/W, at η^0_{0i}=0,9**
0	473	12,2	73	14.5	12.8	0
$1 \cdot 10^{-3}$	477	11.9	73.2	14.0	14,6	0,05
$5 \cdot 10^{-3}$	492	10.8	74.1	12.7	17,7	0,2
$7 \cdot 10^{-3}$	500	10.1	75.3	10.1	15,4	0,12
$1 \cdot 10^{-2}$	513	8,7	74,5	8,3	14.7	0,06
$1.5 \cdot 10^{-2}$	535	7,3	75,8	7,5	11.6	-0,16
$2 \cdot 10^{-2}$	557	6.1	76,3	3,2	10.2	-0,35

Thus, the PC of electricity spent for steam superheat cannot be compensated by increasing the internal efficiency of geothermal turbines and increasing enthalpy drop. However, when replacing wet steam turbine to the superheated steam turbine the efficiency of power plant at the values of α <0,015 can compensate the PC of electrolysis and increase the overall efficiency of power plants by 1-3% (Fig. 2). Taking into account the pressure increase of the turbine by reducing the hydraulic losses in the separator and by reducing the pressure in the condenser to the typical superheated steam turbines (4-5 kPa) the increase can account for 3-5%.

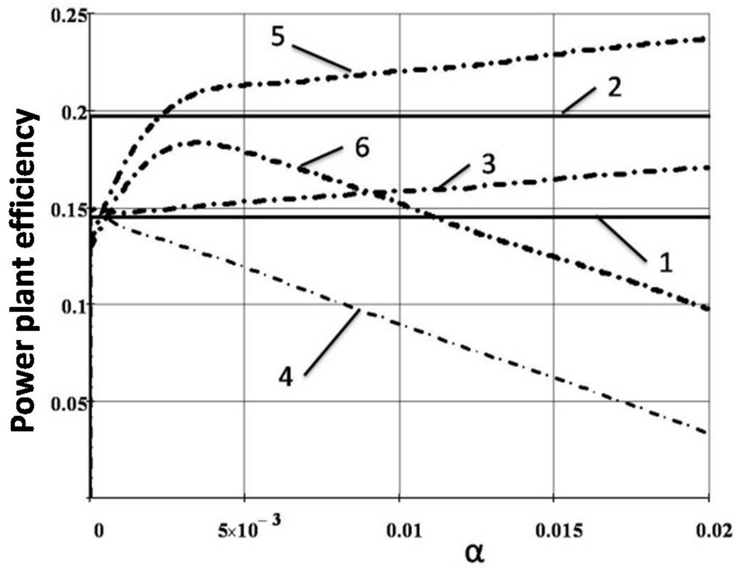

Figure 2: **Changing the absolute efficiency of geothermal power plants, depending on α: 1 - GeoPP efficiency with wet steam turbine without superheating 2 - GeoPP efficiency with superheated steam turbine, 3 - GeoPP efficiency using superheating with wet steam turbine without the PC of electrolysis 4 - GeoPP efficiency using superheating with wet steam turbine including the PC of electrolysis, 5 - GeoPP efficiency using superheating without the PC of electrolysis and installing turbines at the superheated steam, 6 - GeoPP efficiency using superheating including the PC of electrolysis and installing turbines at the superheated steam.**

4 Analysis of Electricity Cost Change with Hydrogen-Oxygen Superheating

At installing the hydrogen-oxygen steam superheating equipment a number of useful properties appear, which may reduce the annual costs of electricity, thereby reducing its price:

3. Reduction of steam humidity at the outlet of the turbine reduces the erosive tearing of the channel, which increases reliability and reduces the number of forced repairs;
4. an opportunity to balance load schedule, which allows power plant operation with a rated capacity of almost constant at optimum values of efficiency.

Annual production costs represent the amount of fuel costs, capital investment costs and operation expenses:

$$C = C_{fuel} + C_{cap} + C_{op} \qquad (4)$$

The fuel component is taken equal to 0, because geothermal plant uses the heat of the Earth. The component of capital investment costs is determined by the following expression:

$$C_{cap} = P_a \cdot \Sigma S_{pp} + C_m = 1.2 \cdot P_a \cdot \Sigma S_{pp} \qquad (5)$$

where P_a - depreciation rate, C_m - annual cost of maintenance, which we take as 20% of the depreciation, ΣS_{pp} - total cost of building a power plant.

Operating costs include the salaries of service personnel and other general station expenses and account for 55-65% of the depreciation. Unit cost of 1 kW of installed capacity (S_{pp}) is 900-1200 $ / kW, and for additional equipment (S_{add}), where 95% of the cost is the cost of electrolyzers, this value is 1700-2200 $ / kW. Let us assume the average value as $S_{add} = 2 \cdot S_{pp}$.

Denoting the relative power of installed additional equipment as θ, and the nominal power of power plant as N_{pp} [kW] we get the full cost of additional equipment:

$$\Sigma S_{add} = 2 \cdot \theta \cdot S_{pp} \cdot N_{pp} \tag{6}$$

The component of operating costs for the installation of additional equipment is practically unchanged, because its maintenance will require a slight increase in state employees. The cost of electricity generated is described by the following expression:

$$E_e = \frac{C}{N_{pp} \cdot 8760 \cdot K_r} \tag{7}$$

Finally, for calculating the cost of electricity, installation of additional equipment we get:

$$\frac{E'_e}{E_e} = \frac{(1.12 + 2 \cdot \theta + 0.6) \cdot 0.8}{(1.2 + 0.6) \cdot K'_r} = \frac{(1.72 + 2 \cdot \theta) \cdot 0.8}{1.8 \cdot K'_r} \tag{8}$$

where E'_e - the cost of electricity generated during the installation of additional equipment, K'_r - utilization coefficient of installed capacity, after the installation of additional equipment.

The results of calculation for different values of K'_r and θ are presented in Table 2.

Table 2

Θ	**K'_r**	**E'_e / E_e**
0.01	0.82	0.94
0.02	0.84	0.93
0.05	0.87	0.93
0.1	0.91	0.94
0.15	0.94	0.96
0.3	0.96	1.07

Thus, the optimal ratio of K'_r=0.85..0.90 and θ=0.03..0.07 lower cost electricity generated will be approximately 6-7%.

5 Conclusions

The use of equipment with hydrogen-oxygen superheat steam on geothermal power plants with wet steam turbines, increases the thermodynamic efficiency of workflow and increases the internal efficiency of the steam turbine, with its modernization, leading to increased efficiency of power plants by 4-6%. In addition, by improving equipment reliability, reduction of the cost of repairing and load management the total cost of electricity can be reduced by 6-7%. The results of the evaluations, optimum proportion of added high-temperature steam, which provides the greatest efficiency and lowest cost of installation of electricity produced, is in the range from 0.002 to 0.01.

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Duration Tests of PEM Fuel Cells in a 50 kW Pilot Power Plant

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1 Introduction

Duration tests are performed in a 50 kW PEM pilot power unit at the Akzo Nobel chlor-alkali plant at Delfzijl, the Netherlands, since April 2007. The rated electrical peak power of the PEM fuel cell unit is 120 kW, but to extend lifetime and to attain high conversion efficiency the unit operates at partial load, feeding 50 kW into the local grid.

Chlor-Alkali plants are a perfect location for PEM fuel cells as they produce high quality hydrogen at low cost and require high power electricity for electrolysis. Chlor-Alkali plants produce the industrial chemicals chlorine and caustic soda (lye) by the electrolysis of brine. For every molecule of chlorine a molecule of hydrogen is produced. It is not always possible to sell the byproduct hydrogen as a chemical or as a fuel. Globally an average of 15 % of the produced hydrogen is vented to the atmosphere (ref 1). The hydrogen production of all chlor-alkali plants is about 1.5 million ton per year (16 billion m^3/y) yielding 2800 MW of electric power with PEM fuel cells, if a conversion efficiency of 50 % is assumed. The 15 % of vented hydrogen could generate 400 MW annually, thus avoiding CO_2-emission of fossil fueled power stations. Another source of byproduct hydrogen is the chlorate industry usually associated with the paper industry. As they tend to be located in remote areas hydrogen is mostly released to the atmosphere. The annual electric power that could be generated from the hydrogen of chlorate production, at 50 % conversion efficiency, is 330 MW.

The 50 kW pilot PEM power plant in Delfzijl Is a joint project of NedStack Fuel Cell Technology B.V. and Akzo Nobel Base Chemicals B.V. The Akzo Nobel chlor-alkali plant in Delfzijl came into operation in June 2006 and produces over 100 kton of chlorine and 3 kton of hydrogen per year. This quantity of hydrogen could generate 6 MW of electricity at 50 % conversion efficiency. Production of electricity from the 50 kW PEM power plant started in April 2007. In March 2010 after more than 14,000 hours of fuel cell operation about 700 MWh of electricity was delivered to the local grid.

2 The 50 kW Pilot PEM Power Plant

The basic building block of the 50 kW unit is a NedStack PEM fuel cell stack of 75 cells, each with an effective area of 200 cm^2.

Figure 1: Module with 12 stacks, with 75 cells each and an effective cell area of 200 cm^2.

At the stationary load of 50 kW a total of 12 stacks (figure 1), comprising 900 cells, is connected in series, generating 630 VDC at 80 A. At this operating point of 0.4 A/cm^2 the nominal stack power is 4.2 kW, while the rated peak power is 10 kW at 250 A. An inverter connected to the local grid converts the direct voltage to 400 VAC, 3 phase. Although an electrolysis plant uses direct power it turns out to be more economical to feed to the grid rather than to the electrolysers. The conversion efficiency of the fuel cells is 55 %. The balance of plant, including the inverter, reduces the overall efficiency to 45 % (LHV of hydrogen). The Pilot PEM Power Plant is located in a 20 foot sea container at the chlor-alkali plant Delfzijl (figure 2). More information is in ref 2-4.

3 Results

Since April 2007 several types of Membrane Electrode Assemblies were tested in the pilot plant in Delfzijl. Non-availability of the unit due to maintenance of the chlor-alkali plant, to diagnostic failure or to cell failure was relatively large as the maintenance team was located 200 km away in Arnhem. The PEM system however is very reliable and the few technical problems encountered so far could be solved satisfactorily. A drawback of the design with series connection of voltages is that the whole unit stops when the voltage of a single cell falls below a threshold. After such a trip the hydrogen is automatically replaced by nitrogen, reducing the relative humidity of the anode gas in this set-up. Subsequent desiccation is likely to cause shrinkage in the plane of the membrane (ref 5, 6). After start-up the humidity is restored and swelling will occur. It is found that the lifetime of reinforced membranes is a factor of two longer than that of normal membranes. An example of the voltage decay in a stack with 25 µm thick reinforced membranes, measured during 8155 hours on the grid, is given in figure 3.

Figure 2: **Container with the 50 kW PEM Power unit at the Akzo Nobel chlor-alkali plant in Delfzijl.**

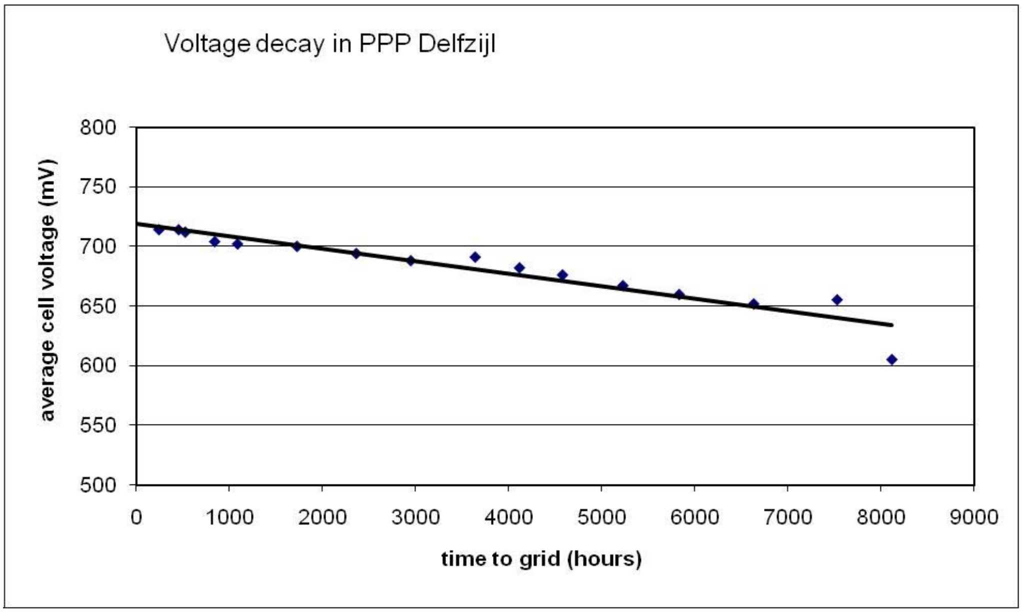

Figure 3: **Decay of the voltage of a stack with MEA's (current 80 A, cell area 200 cm^2) with reinforced membranes at PEM pilot plant Delfzijl. Failure occurred after 8155 hours on the grid.**

4 Design of 1 MW Unit

Semi-mobile chlor-alkali-plants with a chlorine production of 15 kton/year, are foreseen in the near future. They are a perfect match for a 1 MW PEM fuel cell unit. All by-product hydrogen is then converted to electric power reducing the power consumption from the grid by 20 %.

For the present large chlor-alkali plants 1 MW is the minimum size to have a certain impact. At 1 MW the balance-of-plant can be reduced as to raise the overall conversion efficiency to 50 % (LHV of hydrogen). The problem of non-availability of a PEM power plant due to cell failure is solved by switching the power modules in parallel. For the 1 MW Solvay project 12 modules of 85 kW will be connected in parallel. Failure of a cell in a module will trip one module but the other 11 will compensate for the loss by automatically raising the current. Stack replacement is designed to be rapid and restoration of the original situation will occur within 1 hour.

An impression of the Solvay 1 MW PEM power plant is given in figure 4. It will fit a 40 ft container. Delivery to the Solvay chlor-alkali plant in Antwerp is planned by the spring of 2011.

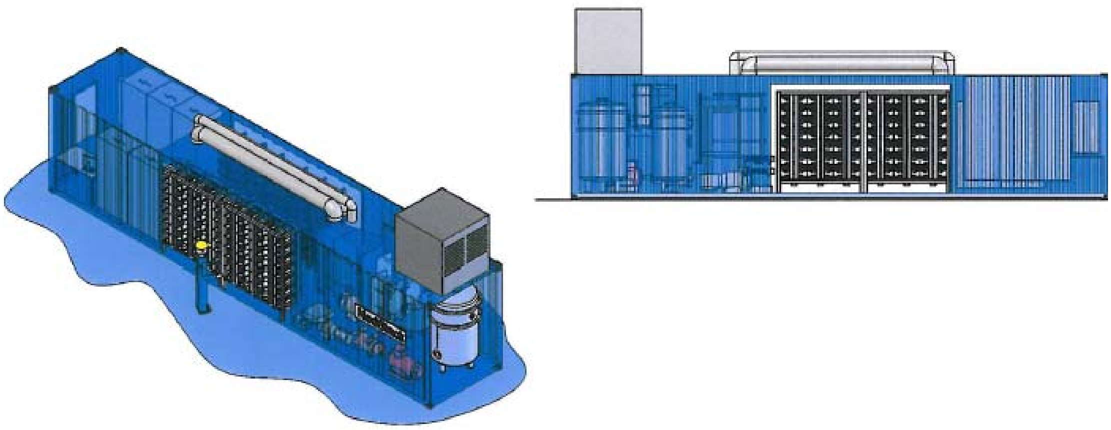

Figure 4: Design of the Solvay 1 MW PEM power plant.

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TA Transportation Applications

Fuel Cell Power Trains

Peter Froeschle and Jörg Wind

Abstract

The world is facing severe challenges due to the limitation of fossil energy resources and rising green-house-gas concentration in the atmosphere. Hence the automotive industry is searching for new concepts to fulfil the requirements of the transport sector for the future. One of the most promising approaches for future road transport is the electric vehicle featuring the fuel cell system technology in combination with an electric engine. With this technology most disadvantages of vehicles with an internal combustion engine can be solved without bigger disadvantages concerning driving performance, range and price. Therefore this technology has medium- and long-term the potential to achieve a significant market share. After several decades of developing prototypes and test vehicles of fuel cell vehicles, the automotive manufacturers are now on the verge of commercialize this seminal technology. In the last years a couple of OEMs introduced new generations of fuel cell vehicles, produced in small series, with the aim to validate the technology and to improve the customer acceptance. The aim of the article "Fuel Cell Power Trains" is to describe the layout and functionality of the fuel cell hybrid power train as well as to overview the involved OEMs with their current fuel cell vehicles. Thereby is shown the application of the fuel cell technology not only in passenger cars but also in buses and delivery vehicles.

Development of Experimental Equipment for Regenerative Braking Energy with PEMFC Application

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1 Introduction

Electric and fuel cell vehicles are operated by electric control among the components such as battery, supercapacitor, motor or generator and fuel cell. Fuel cell system by using hydrogen can produce electricity to drive the fuel cell vehicle which can be controlled by the power from battery and supercapacitor together. The kinetic energy of moving vehicle is dissipated to environment as thermal energy when brake system is operated. Regenerative braking energy can be used to save total energy consumption of vehicle driving. Especially it is effective for the city driving because the vehicle repeats stop and start frequently.

An experimental equipment for educational purpose, which consists of battery, BLDC motor, supercapacitor and flywheel with a PEMFC (Polymer Electrolyte Membrane Fuel Cell) stack, shows the way to use the regenerative braking energy. The flywheel is originated from the idea of a fast moving vehicle. A generator linked with the flywheel converts mechanical kinetic energy of the flywheel to electric energy during braking period and works as a motor which consumes the electric energy to produce kinetic energy during driving period. The electric energy is stored into the supercapacitor and the battery, and is used for accelerating the flywheel speed later. The electric energy from the fuel cell stack is used for normal driving of the flywheel and sometimes for charging the battery.

Increasing regeneration energy from braking system affects regeneration current and SoC(State of Charge) of supercapacitor. The equipment represents a good simulator to understand how the energy consumption of a hybrid vehicle can be saved by calculating theoretical kinetic energy of the flywheel and conversion efficiencies from kinetic energy to electric energy, and measuring electric current and SoC of supercapacitor.

2 Theoretical Background and Experiment

Mechanical kinetic energy of a rotating flywheel system is used as the kinetic energy of moving vehicle. The flywheel is made to calculate and to check various kinetic energy by attaching additional disks to a basic disk. The theory is given with the following equations.

$$\Delta E = E_2 - E_1 = (1/2)J(\omega_2^2 - \omega_1^2)$$

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$$J = \int r^2 \, dm = \pi t \rho (1/2) R^4$$

J is the polar moment of inertia and ω is the angular velocity. By using the information data of the flywheel disks the kinetic energy can be calculated by the equations. The basic flywheel disk has the radius (R) of 185 mm, the thickness (t) of 30 mm and the density(ρ) of 7,870 kg/m^3.

When there is no load, the flywheel continues rotating until the kinetic energy of the rotating flywheel is absorbed by mechanical friction and air friction. When regenerative energy is produced in the generator, the flywheel continues rotating until the kinetic energy of it is absorbed by generator and brake.

Experimental regenerative braking system is shown as follows. Motor and generator are used to check the conversion efficiencies of motor and generator between kinetic energy of flywheel and electric energy.

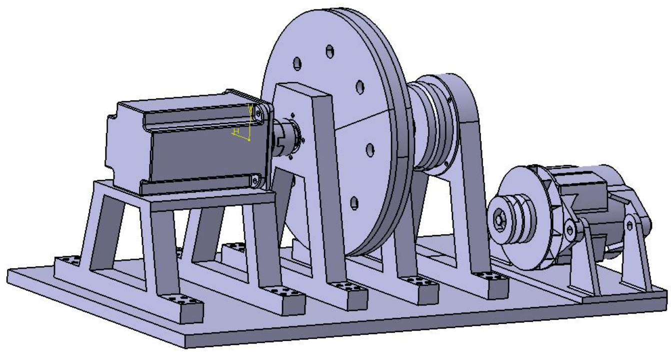
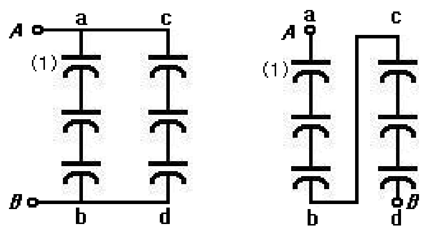


Figure 1: Regenerative braking system.

A BLDC motor with the power of 1.5 kW at 4.78 Nm, 24V, 66.3A and 3000 min^{-1} is used to turn the flywheel. Usually motor needs motor controller because motor has 3-phase current input and output but supercapacitor and battery have direct current input and output. Fuel cell stack produces direct current output electricity. Motor controller can support various experimental conditions by control of revolution speed (min^{-1}) and current.

Supercapacitor is a physical electric energy storage with large power density which charges and discharges quickly. It is used in UPS (uninterrupted power supply), hybrid electric vehicles and fuel cell vehicles.



(a) Parallel circuit (b) Serial circuit

Figure 2: Parallel-serial connecting of capacitor.

Supercapacitor is used by serial or parallel circuit connection as illustrated by the following figure to get electric energy or to release the electric energy from or to the total system.

An electrical character of supercapacitor is like a general character of capacitor. Each of following numerical equations shows serial connection, parallel connection and stored energy of capacitor respectively.

(Serial): $1/C = 1/C_1 + 1/C_2 + \ldots + 1/C_n$ [F]

(Parallel): $C = C_1 + C_2 + \ldots + C_n$ [F]

(Energy): $E = (1/2)CV^2$ [J]

The supercapacitor has the characteristic of a condenser and a battery. The state of stored energy is expressed by SoC as following numerical formula.

$SoC(\%) = (V_o)^2/(V_{max})^2 \times 100$

The hybrid system with supercapacitor extends the life time of battery and is used to support peak power as auxiliary power source. The benefits of the system are to reduce the voltage drop of main power and to support for the starting power as auxiliary power.

Ni-MH battery is used to save electric energy from fuel cell or generator and to release it to the motor. The characteristics of the battery are 1.2 V, capacity of 100 Ah at 20°C, nominal energy of 120 Wh, energy density of 155.9 Wh/L, specific energy of 66.7 Wh/kg and air cooling. The temperature range of battery-use is between -40°C to 55°C. It is very much safe because there is no electrolyte liquid which might be spilled out by vibration and impact.

Automobile companies are developing compact fuel cell system to apply for the power system of automobile with hydrogen fuel which can replace the internal combustion engine and oil based fuel. Because the price of fuel cell stack is too much expensive the hybrid system with battery and supercapacitor is useful for the fuel cell vehicles. A fuel cell stack made by Ballard is used to supply electric energy to experimental equipment.

3 Conclusions

An educational and experimental device for regenerative braking energy with motor, generator, supercapacitor, battery and fuel cell is developed to explain how to get, save and use the regenerative energy. It is possible how to calculate the conversion efficiency from the mechanical kinetic energy of flywheel to electric energy which is saved in battery and supercapacitor. The device can be used to demonstrate for the regenerative energy of various vehicles and trains. Students can know how to save the discarding energy of vehicles by brakes.

Acknowledgements

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Design of an Energy Storage System for a Hybrid Electric Fuel Cell Bus

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1 Introduction – Presentation of the H_2-Bus Project

A cooperation of the German companies Vossloh Kiepe and Hoppecke, the Dutch company Advanced Public Transport System BV (APTS), the Institute for Automation Engineering (IA) of the University of Applied Sciences Cologne and the Institute for Power Electronics and Electrical Drives (ISEA) of the RWTH Aachen University develops and constructs a total of four 18 m fuel cell driven articulated city buses with energy storage system. Starting in 2010, two of them are going to be exploited at regular line service in Cologne, the other two in Amsterdam. The project “H2-Bus” is promoted by the Netherlands and the German state of North-Rhine Westphalia (part of the “NRW Hydrogen HyWay” lead project).

The authors are responsible for the sizing of the fuel cell system and the energy storage system as well as the energy management systems as described in the following sections.

2 Characteristics and Requirements of the Fuel Cell Bus

The drive train is energized by a hydrogen fuel cell (FC) system. An energy storage system supports the FC and recovers braking energy. The following conditions and features are mandatory for sizing both systems:

- The traction power of at least 200 kW has to be ensured.
- In case of a fuel cell malfunction, the energy storage system has to provide a reserve of driving range of not less than 1 km.
- Due to the high costs and low life expectancy of fuel cells, the energy storage system has to cover dynamic power demand changes (accelerating, regenerative braking) and allow for stationary fuel cell exploitation.
- To achieve sufficient storage system lifetimes at affordable costs also hybrid storage systems with two different storage technologies are taken into account.
- Limitations to current and voltage due to the power electronics (DC/DC converter, traction inverter, DC-link)
- The average passenger load is assumed to approx. 3,5 tons
- Auxiliary consumers (air conditioning, steering assistance) have been analyzed and are assumed to (“average” scenario) continuously 19.5 kW plus fuel cell system consumers (pumps, heat dissipation,…). The “worst case” scenario is assumed to continuously 43 kW (in total).
- Weight and available installation space

3 Approach: Sizing of Fuel Cell System and Energy Storage System

A vehicle model in MATLAB/SIMULINK has been developed to calculate the energy and power demand. Figure 1 shows a schematic of the drive train. Each component is linked to the DC link via a DC/DC-converter to enable maximum flexibility in terms of energy and power flow. The latter is controlled by an energy management system (EMS). Hybrid storage systems, composed of two different storage devices, are considered, too ("Energy storage device 1" and "Energy storage device 2").

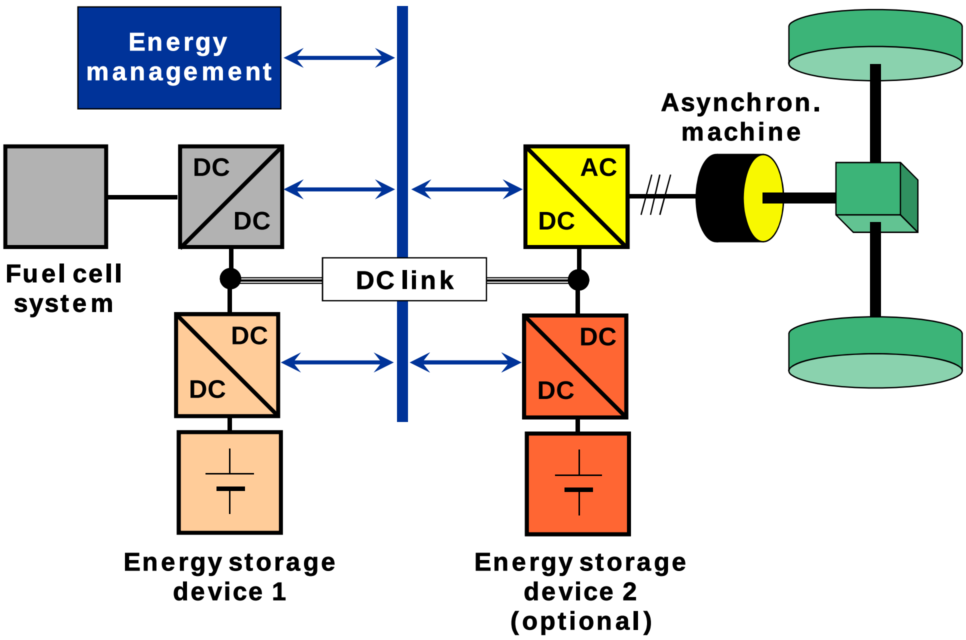

Figure 1: Schematic of the drive train.

Figure 2 shows the speed profile used as simulation input and the resulting power demand of the traction drive. It can be seen that the fuel cell system, the most costly component, would have to be oversized (demand only for traction > 200 kW) and would have to cope with dynamic load changes in case no energy storage system is used. In addition, the energy highlighted as red areas would be wasted as braking energy cannot be recovered.

For this purpose, different battery technologies were compared. Unlike private cars, buses of the local public transport serve up to 6000 hours a year, resulting in high stress for the battery system. Lithium ion batteries show excellent performance data. Reasons for discarding them from consideration were safety issues, the demand for high mechanical robustness and the lack of experience in heavy duty automotive applications. There are safe, reliable or mechanically robust lithium ion batteries, but it is difficult to achieve all features at a time and, in consideration of the tight project schedule, availability is a key factor. Further, nickel metal hydride (NiMH) batteries and electrochemical double layer capacitors (DLC) were investigated. Both of them are frequently used in hybrid electric transportation applications (buses, trams, trains) already today.

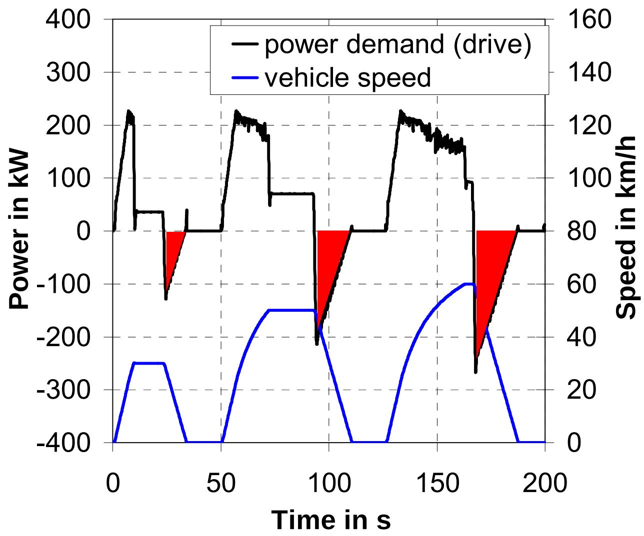

Figure 2: Speed profile and resulting traction power demand, 0 % acclivity.

Impedance-based models for the storage devices have been developed to be used in the vehicle model. Considering the requirements listed above, different storage system configurations among other were investigated by simulation in detail:

I. 450 NiMH cells (75 Ah, 1.2 V/cell)
II. 12 DLC modules (each module: 125 V rated voltage, 63 F nominal capacity)
III. 252 NiMH cells (75 Ah) and 6 DLC modules

For configuration III, 3 operating strategies were derived and compared, each having different advantages and disadvantages:

A) The NiMH battery is primarily used. Once it cannot provide any more requested power, the DLC covers the rest.
B) The DLC are used primarily. Once they are empty or cannot accept any more energy, the NiMH battery takes over the difference.
C) The state of charge (i.e. voltage) of the DLC system is controlled in function of the vehicle's speed to always being able to accept energy provided by regenerative braking. The NiMH battery covers the remaining dynamic power demand.

As benchmark, the following criteria were used:

- Load leveling to keep the fuel cell system in a stationary operation point
- Stress of respective energy storage device:
  Heat generation (NiMH & DLC) and depth of cycling (NiMH only)
- Overall system efficiency and H_2 consumption
- Uphill performance

4 Results

Table 1 shows an overview of the simulation results of the three configurations.

Table 1: Overview of energy storage configurations, 0 % acclivity, aux. scenario: “average”, “stress” is given in terms of cycle depth and heat generation in the storage system.

	FC operation	NiMH stress	DLC stress	Weight	Fuel consumption
NiMH config. I	σ_P: 7 kW	ΔSOC: 4.6 % $P_{loss,cell}$: 19.9 W	-	1.51 t	192 gH_2/km
DLC config. II	σ_P: 35 kW	-	$P_{loss,module}$: 150.5 W	0.86 t	183 gH_2/km
Hybrid system config. III					
Strat. A)	σ_P: 15 kW	ΔSOC: 9.4 % $P_{loss,cell}$: 58.6 W	$P_{loss,module}$: 85.9 W	1.36 t	216 gH_2/km
Strat. B)	σ_P: 10 kW	ΔSOC: 3.5 % $P_{loss,cell}$: 12.4 W	$P_{loss,module}$: 669.7 W	1.36 t	194 gH_2/km
Strat. C)	σ_P: 4 kW	ΔSOC: 3.8 % $P_{loss,cell}$: 14.3 W	$P_{loss,module}$: 334.7 W	1.36 t	186 gH_2/km

Using configurations I and III C), the fuel cell system can be operated with a standard deviation (σ_P) of roughly 7 kW and 4 kW respectively. Both values are considered to be acceptable. In contrast, configuration II shows 35 kW standard deviation, which is due to the low energy capacity of the DLC system, limiting the available fuel cell power support relatively soon. Figure 3 shows the used drive profile (“actual speed”) and the resulting power behavior of the different components for configuration II. As soon as the DLC modules’ power has to decrease, the fuel cell system operation point has to match the resulting dynamic difference to the power demand.

The stress of the energy storage components is deviating significantly depending on configuration and operating strategy. As depth of cycling (ΔSOC) has a major impact on aging of NiMH batteries, it was desired to stay below 5 % of the nominal capacity. The temperature is another major influencing factor of aging of both NiMH batteries and DLC. It is represented by the heat generation ($P_{loss,cell}$ and $P_{loss,module}$) caused by losses due to the inner resistances[1]. Configurations I, III B) and C) are considered to be acceptable for the NiMH battery. For the DLC modules, this is valid for configuration III C), only. According to manufacturer instructions of the DLC, roughly 400 W of losses per module will lead to a temperature increase of 15 K above ambient.

[1] Heat generation due to gassing effects – as they occur in NiMH batteries – are not included in this calculation.

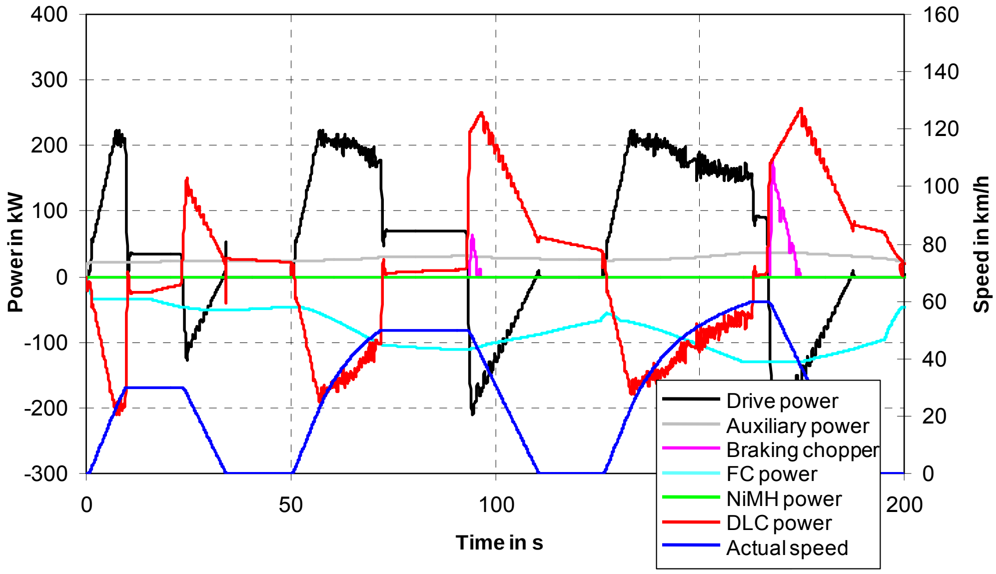

Figure 3: Simulation results, configuration II, aux. scenario: "average".

The fuel consumption depends on many parameters. Except for weight, efficiencies of the components have an important influence. With the NiMH battery generally having a lower efficiency, NiMH-orientated configurations and strategies (configuration I and III A)) show a higher H_2 consumption. Furthermore, the components' efficiencies (energy storage devices and FC system) themselves depend on current rate and temperature. This correlation results in the fact that operating strategy C) consumes less hydrogen than B).

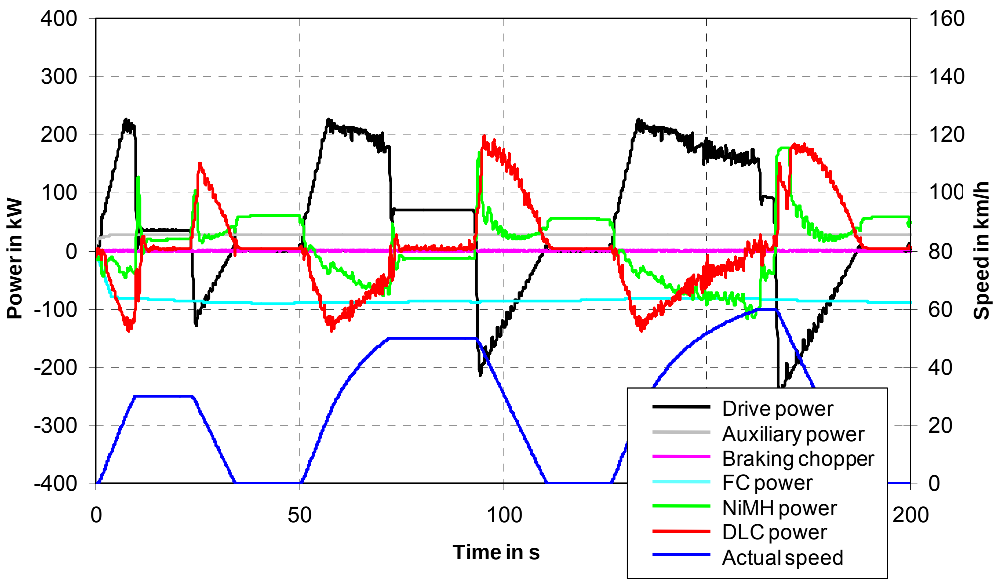

Figure 4: Simulation results, configuration III C), aux. scenario: "average".

Figure 4 shows the simulation results for configuration III C). The fuel cell system is operated at approximately 83 kW net power output. At the beginning of acceleration phases, the DLC modules provide the higher share of drive power. In the further course it is (partially) replaced by the NiMH battery's share. This behavior allows a good power distribution and keeps down stress of both components. At the very beginning of the braking phases the NiMH battery has to accept the main part of the recovered power. This is due to the fact that, according to the operating strategy, the DLC voltage is low at higher speed and thus limits the power capability.

5 Conclusions

The following conclusions can be drawn:

- Configuration II is not suited to sufficiently support the fuel cell system to achieve stationary operation. Furthermore, the low energy capacity is even more disadvantageous at uphill routes and, in case of a fuel cell system malfunction, allows for less than 0.8 km driving distance only.
- In general, configuration I seems to be suited for the given purpose.
- Using a hybrid storage system, the stress for the components and the fuel consumption can be reduced if the load is reasonably shared (strategy C)).

An H_2 consumption of 200 g/km (Table 1) results in an average power demand of roughly 85 kW. Further simulation results show that the necessary fuel cell net power varies from 80 kW to 120 kW on average. The latter is considered to be sufficient for the bus system.

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für regionale Entwicklung

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HYSYS – System Components for Hybridized Fuel Cell Vehicles

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1 Project Overview

Fuel Cell Electric Vehicles (FCEV) are considered to contribute largely to a future sustainable mobility. FCEVs as well as other electrified vehicles use electrical drive train components which have still to be improved to be ready for the mass market at low cost. Principal functionality of FC vehicles under all day conditions has already been demonstrated with a relevant number of prototype cars from a large number of car manufacturers, also in projects funded by the EU (like CUTE/ECTOS). Nevertheless, FC-vehicles, FC-stacks and -systems do not yet meet all requirements for mass market introduction. Several components for FC-hybrid vehicles have to be improved to meet all necessary requirements for mass production. The overall goal of the project HySYS is the improvement of fuel cell system and electric drive train systems for fuel cell hybrid vehicles and ICE hybrid vehicles with a clear focus on fuel cell hybrid vehicles. To achieve this goal several key components for FC vehicles have been developed and being tested on the test bench. Work in HySYS is focused on electrical turbochargers for air supply, low cost humidifiers, hydrogen sensors for automotive use, effective low cost hydrogen supply line, high efficient, high power density drive train and high power Li-Ion batteries. All final tests will be done in two validator vehicles which are built up in the project by Daimler or modified by CRF. The project has been started in December 2005 and will end in November 2010. All system components have been specified, developed, produced and tested on the test bench. Most of them are currently being integrated in the two validator vehicles.

2 Project Objectives

Electrified vehicles, such as Fuel Cell Electric Vehicles (FCEV), Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV) are considered to be the most promising candidates for a future sustainable mobility. The ICE-hybrid vehicle offers an opportunity to have another viable technical solution for sustainable transport available with a high number of vehicles on the market much earlier. All those technologies use electrical drive train components which have still to be improved to be ready for the mass market at low cost. Due to their superior efficiency when compared to hybridized ICE vehicles and the significant larger driving range as well as short refueling times when compared to BEVs, FCEVs are expected to be the preferred technology if the technological and economic barriers are overcome. Therefore, the HySYS project focuses on FC systems. However, components that can be used in other electrified vehicles are also considered and synergies with those have a high priority. Nevertheless, FC-vehicles, FC-stacks and -systems do not yet meet all requirements for mass market introduction. Several components for FC-hybrid vehicles have to be improved to meet all necessary requirements for mass production. Due to the large operation experience with FC-vehicles, the car industry is able to develop all necessary requirements and specifications together with suppliers and research institutes.

The overall goal of the project HySYS is the improvement of fuel cell system and electric drive train systems for fuel cell hybrid vehicles and ICE hybrid vehicles with a clear focus on fuel cell vehicles. Therefore, the system component work has the highest priority. Nevertheless, the evaluation of the results in real vehicles is essential. While the primary market for FC vehicles is the passenger car market, in this project the fuel cell system components, system architecture, operating strategies and package designs developed are implemented using a commercial delivery van platform in the minibus version. It is assured that all learnings and improvements can be used also for passenger cars.

In summary the objectives are as follows:

- Specifications for hybridized Fuel Cell Vehicles and Hybrid Electric Vehicles
- Identification of synergies between components of different vehicle architectures
- Low cost automotive electrical turbochargers for air supply with high efficiency and high dynamics
- Low cost humidifiers with high packaging density
- Low cost hydrogen sensors for automotive use
- Effective low cost hydrogen supply line
- High efficient, high power density drive train
- Low cost high power Li-Ion batteries
- Enhanced FC-drive train efficiency
- Two FC-vehicles to validate the achieved results and visualize the progress

3 Project Results

3.1 Fuel cell system components

For the air supply the concept of an electrical turbo charger (ETC) has been chosen. After the assembly of the 3rd generation ETC “HYSYS 02” the prototype was tested on a test bench. A maximum aerodynamic efficiency of 73% and the maximum total efficiency of 63% of the ETC were realised. This optimized ETC built up in a single housing fulfils the ETC functionalities and interfaces requirements for the air supply module of the HySYS FC-System at the test bench (see Figure 1). Furthermore significant reduction of noise has been achieved.

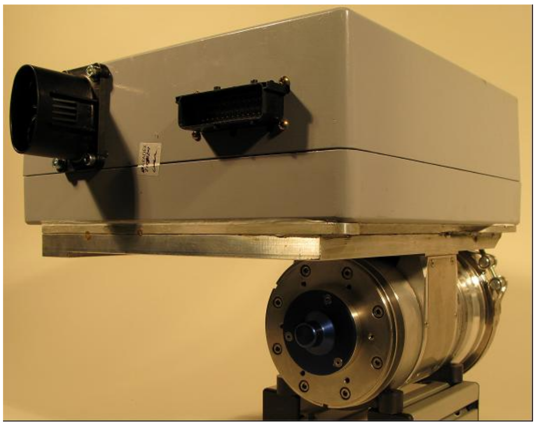

Figure 1: Final prototype ETC 3rd generation HYSYS02.

Figure 2: Detail of the air humidifier.

On the air humidifaction, the consortium developed a gas-to-gas humidifier. The chosen membrane materials combined with the best investigated solution for hollow fibre coatings have been realised and tested on an accelerated test procedure with promising results in small scale component level. For the first full scale humidifier module a new construction of the cartridge was realised to support the FC-system packaging and interface requirements. Two prototypes have already passed the assembling phase using the casting box and thereafter the testing procedure at the component test bench. A section of the humidifier module containing the full size hollow fibre cartridge is shown in Figure 2.

For hydrogen humidification the 3rd generation fuel recirculation pump prototype (HRP) is finalised as a compact single housing component including all its power electronics and cooling. The HRP and the hydrogen water separator prototype based on gravimetric separation principle have been tested by the developed hydrogen humidification line controls strategy at the hydrogen line test bench under simulated FC-System environment conditions.

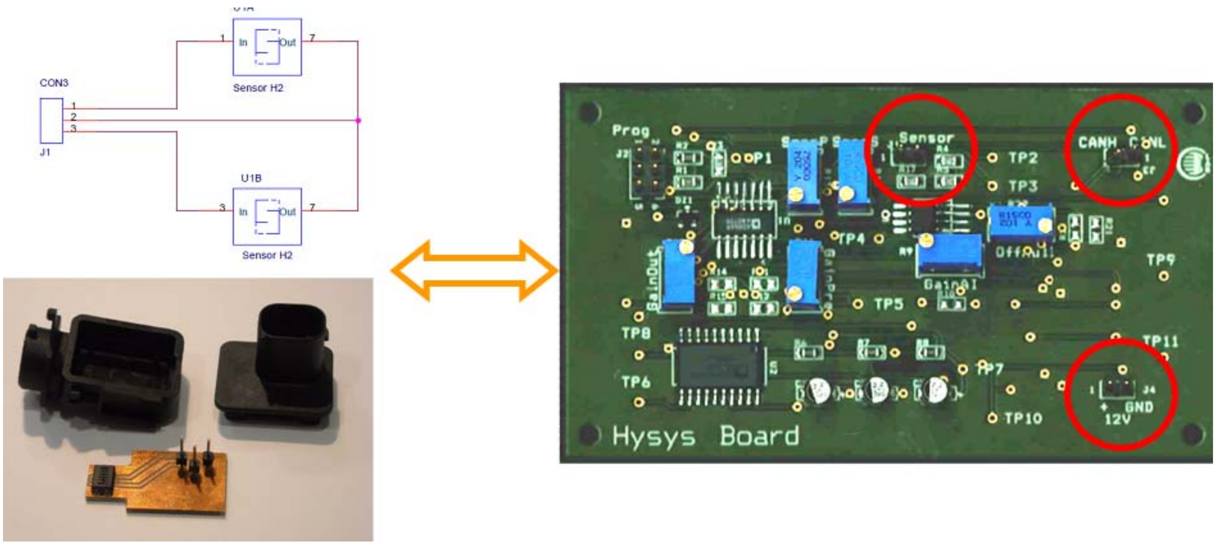

Figure 3: Integrated sensor prototype. The left part is the H_2-sensing element, which includes two silicon chips.

A hydrogen sensor development is investigated by a new manufacturing approach for automotive application. The first sensors are built and the first samples of the electronic system design for the hydrogen sensor are finished. It has been realised in parallel to the development of the H2-sensitive elements. The signal treatment and interface electronics of the hydrogen sensor system are finalised with an integrated sensor and circuit design shown in Figure 3.

Within the work on the Hydrogen supply architecture the line was enhanced by the hydrogen metering device prototype (HMD) that have been designed, built and validated even by live time tests. A photograph of the new hydrogen metering device prototype is shown in Figure 4.

At the time a 3rd final generation prototype is built up, delivered, already implemented and successfully tested at two different system environments for the two validator vehicles (Merecedes Sprinter and Fiat Panda). The 3rd generation prototype is already integrated at the hydrogen module and successfully tested at the Daimler FC system and achieved the full specified performance for the real FC-system testing (80 kW Daimler validator) as well as the performance at the simulated system environment with lower power (Fiat validator).

Figure 4: The prototype of 3rd generation hydrogen metering device integrated in the FC-System.

3.2 Electric drive system components

For the electric motor and power electronics, two different approaches have been followed, one for the Daimler validator and the other for the Fiat vehicle. Figure 5 shows torque and power for the e-motor developed for the Fiat vehicle.

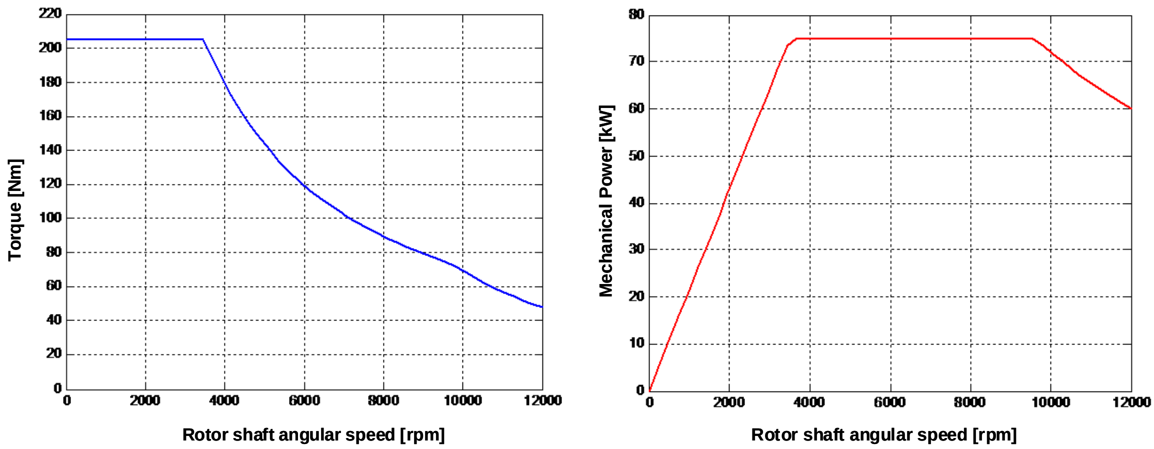

Figure 5: Traction e-drive: measured max transient torque and mechanical power vs. speed.

The developed traction e-drive has been compared with the Fiat state of the art solution (the direct inverter induction e-machine based traction e-drive applied in the HyTran IP Fiat Panda Hydrogen full performance FC vehicle validator): in terms of performance, an increase of torque close to 30% and of mechanical power of around 25% have been reached. In terms of efficiency, an advantage of absolute losses reduction of a factor close to 2 on the overall max values has been obtained. The e-motor and power electronics for the Daimler vehicle has also been finalized and tested on the test bench. Figure 6 shows the e-machine on the test bench.

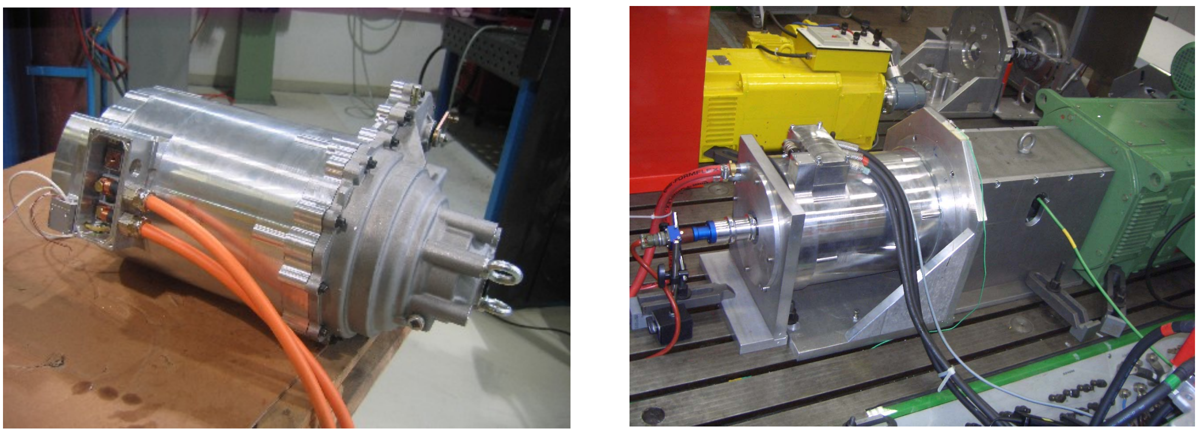

Figure 6: E-machine for Daimler validator with gear box and on test bench.

On the battery side the 80 cells Li-Ion Battery Systems (BS) on bench set up has been completed and the tests are going to be performed according to the defined charge-discharge profile (see figure 7)

Figure 7: 80 cells BS and BS test cooling network.

3.3 Fuel cell system performance and vehicle integration

The tests carried out with the fuel cell system were mainly focused on the achievement of maturity of the fuel cell system for vehicle integration. Figure 8 shows a comparison of the efficiency of the measured HySYS fuel cell system and the efficiency curve for a fuel cell system from "WELL-TO-WHEELS ANALYSIS OF FUTURE AUTOMOTIVE FUELS AND POWERTRAINS IN THE EUROPEAN CONTEXT" (Version 2c, March 2007). This curve reflects the high expectations from 2003 (the FC-System efficiency curve from 2007 is identical to the version from 2003) on FC-System efficiency. The calculation of efficiency of the HySYS fuel cell system is based on the Faraday fuel consumption due the high accuracy of stack current measurement. The comparison shows that the HySYS FC-systems meets the expectations of improvement foreseen in 2003. The shown efficiency curves are quite similar in the range to 50% net power and almost identical in the range above 50% net power.

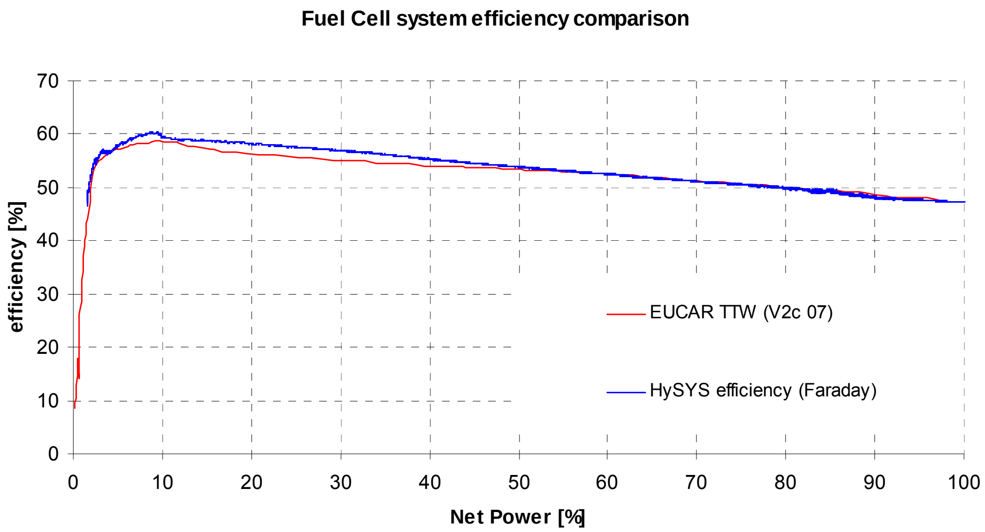

Figure 8: Fuel cell system efficiency comparison (HySYS and fuel cell system efficiency curve from EUCAR WTW study).

The integration of the fuel cell system and all other components is currently ongoing. The vehicles will be available for tests in summer 2010.

Project partners

Acknowledgement

HySYS is an integrated project, co-funded by the participating companies, research institutes and universities and by the European Commission (EC) under the 6th Framework Programme (contract N° 019981).

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HydroGen4 – The First Year of Operation in Europe

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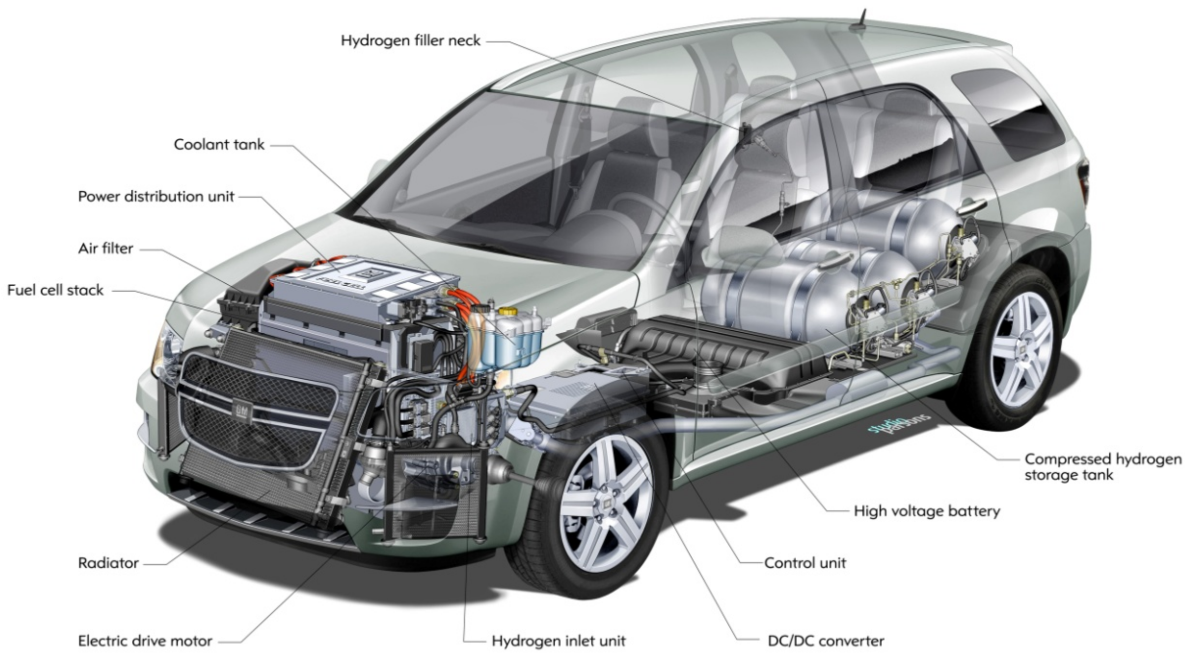

Figure 1: Opel HydroGen4 fuel cell electric vehicle.

1 The Opel HydroGen4

HydroGen4 is Opel's fourth generation fuel cell electric vehicle (FCEV) (Figure 1). It features improvements in everyday usability, performance and durability compared to its predecessor. The fuel cell stack comprises 440 single cells and provides the power for the 73 kW synchronous electric motor, delivering zero to 100 km/h acceleration in around 12 seconds (Table 1). Opel has opted for fueling with compressed hydrogen, thus avoiding the boil-off phenomenon occurring when hydrogen in cryogenic liquid form is used. HydroGen4's three carbon-fiber composite tanks hold 4.2 kg of hydrogen at a pressure of 700 bar, sufficient for an operating range of 320 kilometers. The vehicle is fitted with a 1.8 kWh high-power buffer battery to cover peak electrical loads during acceleration and to store energy from its regenerative braking system in order to enhance overall efficiency. The fuel cell system can start and run at sub-zero temperatures down to -25°C, a considerable advance over its predecessor and an important benefit for everyday usability. The HydroGen4 was designed to be as safe as conventional vehicles resulting in unique hydrogen safety features in each of its major systems.

Table 1: Opel HydroGen4, technical data.

General:	
Vehicle type:	5-door, front-wheel-drive vehicle
Seating capacity:	4
Dimensions:	
Length/Width/Height:	4796/1814/1760 mm
Wheelbase:	2858 mm
Cargo volume:	906 liters
Curb weight:	2010 kg
Payload:	340 kg
Fuel storage system:	Carbon fiber composite (3 vessels)
Service pressure:	700 bar
Storage capacity:	4.2 kg
Fuel cell system:	Polymer Electrolyte Membrane (PEM)
Number of cells:	440
Power:	93 kW
Battery system:	NiMH high-power battery; regenerative braking
Power:	35 kW
Energy content:	1.8 kWh
Electric traction system:	3-phase synchronous electric motor, with integrated power electronics and planetary gear
Power:	73 kW continuous, 94 kW maximum
Torque:	320 Nm
Performance:	
Top speed:	160 km/h
Acceleration 0-100 km/h	12 sec
Operating range:	320 km
Operating temperature:	-25°C to +45°C
Safety:	Driver and passenger frontal air bags and roof rail side-impact air bags; ABS, traction control, StabiliTrak (ESP)

2 The HydroGen4 Fleet in Berlin

In November 2008, ten HydroGen4 were deployed in Berlin as part of the Clean Energy Partnership (CEP) demonstration project. The CEP is *the* European lighthouse project aiming to prove the everyday suitability of FCEV technology and hydrogen as a fuel for transportation [1] [2]. It is funded by the German Ministry for Transport, Building and Urban Development (BMVBS). Two vehicles out of the fleet are used by Opel, while the others are operated by business partners (B2B) since early 2009 (Figure 2). In the following, the first year of this customer operation is being reviewed, including vehicle operation data, customers' feedback as well as learnings for the next generation of FCEVs.

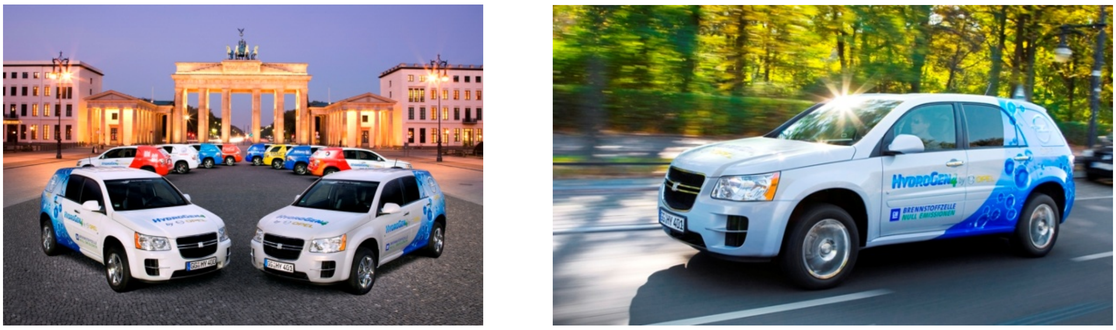

Figure 2: European HydroGen4 fleet (left), HydroGen4 running on Berlin roads (right).

ADAC, Allianz, Axel Springer AG, Coca-Cola, Hilton, Linde, Schindler, Total, and Veolia were the first business partners to test drive a HydroGen4 over a period of several months. The usage and driving patterns of these companies are as different as their businesses. While some of the partners operate the HydroGen4 in the same way as all the other cars of their fleet, other companies use the vehicle in a unique way, e.g. providing shuttle services for VIP guests. The toughest requirements, however, can be associated with the usage pattern of the HydroGen4 operated by the ADAC providing regular road assistance services. In order to achieve this, the HydroGen4 has been modified in the same way as ordinary ADAC cars, including the installation of yellow flash lights as well as the ADAC driver information display and tool box system. In addition, the fuel cell system of the car has been adjusted to enable recharging of the on-board starter batteries used by the ADAC driver to offer jump start assistance for stranded cars.

3 Vehicle Operation Data and Customer Feedback

Although ADAC operates the vehicle under toughest conditions, it did show an outstanding reliability during the first year of operation with just two days out of service due to unplanned maintenance of the propulsion system. But also the other nine HydroGen4 cars performed well with altogether only 17 days of unplanned service. Since HydroGen4 was the first FCEV within the CEP to offer full cold start capability, the vehicles were operable throughout two hard winters. From first customer deployment in early 2009 until the end of February 2010, the entire fleet achieved an operation time of over 3,500 hours, corresponding to a driven distance of more than 83,000 kilometers. The distribution of operating hours and associated distances driven per vehicle are shown in Figure 3 (left) and Figure 4 (right). The velocity distribution of the whole fleet (Figure 3, right) clearly indicates that the vehicles were mostly operated in urban traffic with about 37% share of idle mode alone. The average speed ranges from 14 km/h (ADAC) to 33 km/h (Axel Springer AG) and is an indicator for the very different driving profiles of the B2B partners. These differences are important to gain as much learnings as possible from the demonstration project.

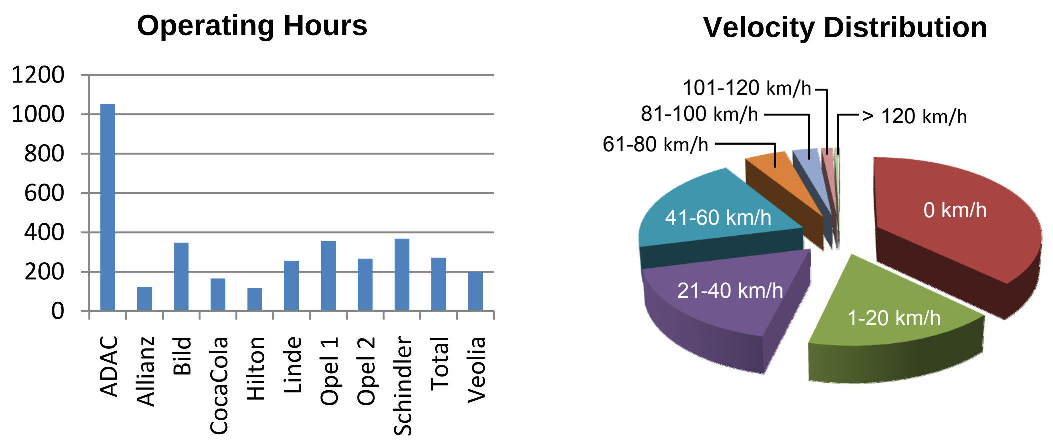

Figure 3: Operating hours since deployment per vehicle (left) and fleet average of velocity distribution (right).

So far, all the B2B customers provided a very positive feedback on their daily experience of driving and refueling the HydroGen4. In particular, they liked very much the acceleration behavior, as well as the low noise level inside and outside the car. Criticism only concerned conventional technology (e.g. missing parking distance control), not the fuel cell system.

4 Hydrogen Refueling Data and Customer Feedback

During the first year of operating the HydroGen4 vehicles in Berlin, three hydrogen fueling stations were principally available to our B2B customers [3]. The refueling process was considered as being rather easy and convenient. However, the drivers were not satisfied with the actual availability of the fueling stations. Since early 2009, our drivers have reported a total of 173 days when it was not possible for them to refuel at one of the hydrogen stations. In combination with the large distance between the stations, this caused severe inconveniences for the drivers in case there was not sufficient hydrogen left in the tank to reach another station. Hence, an effective information system is planned to be installed by the infrastructure providers of the CEP to inform the drivers when a station is out of service and when it is in operation again. In spite of the mentioned problems, a total of 778 refuelings was achieved since deployment. Figure 4 (left) shows the distribution of the number of refuelings per vehicle. Currently (April 2010), only one of the hydrogen stations in Berlin allows for fast refueling within 3 minutes at 700 bar, with hydrogen pre-cooled at -40°C. However, in order to provide an optimized refueling process with respect to refueling time and filling level at all stations, those to be built in the future should be designed according to SAE J2601.

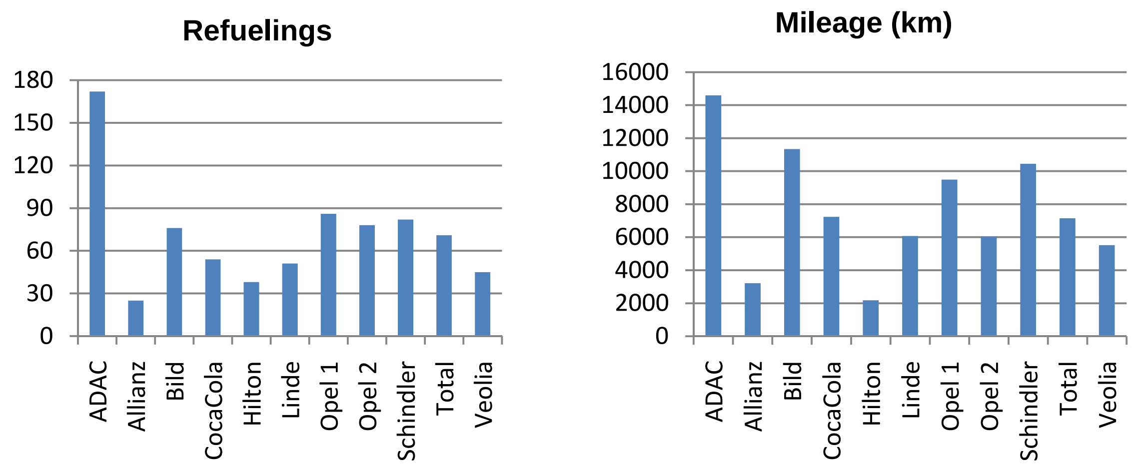

Figure 4: Number of refuelings since deployment (left) and driven kilometers since deployment (right) per vehicle.

5 Learnings and Next Steps

During the first year of operation, we had a number of learnings from the daily customer operation under “real world” conditions. In Winter 2008/09, the cars performed without any problems even though ambient temperatures in Berlin stayed very low for a long time, reaching levels down to -20°C. This winter (2009/10), however, we were facing a freezing issue with a valve on the cathode side of the fuel cell system at these very low sub-freezing temperatures. The identified reason was that after implementation of a software update (in summer 2009), intruding moisture had caused the valve to freeze and impeded a system start. After several tries, however, the valve usually could be actuated; hence this issue was characterized as “customer inconvenience” only. The problem was successfully solved by the subsequent software update. Also, we were challenged with electrical contact difficulties concerning the high-voltage battery. These, however, could be sorted out by rewiring.

All technical issues as well as the customer feedback and the vehicle data were directly fed into the ongoing fuel cell propulsion system development, leading to reduced hydrogen consumption, as well as increased performance, reliability and durability. Thus, all the findings from the CEP project which is part of our global demonstration activities were of significant importance for further development and reinforced our confidence for fuel cell technology to be ready for volume production in the foreseeable future. The next step on this pathway towards commercialization of FCEVs will be our next generation fuel cell system providing standard automotive durability at reduced cost (Figure 5). Due to further improved system integration it will be half the weight and half the volume compared to the current generation. At the same time, technical advancements will reduce fuel cell degradation and thus enhance durability to reach levels that customers expect from a car. Due to a new electrode design with considerably lower platinum content and the use of knowledge from volume production of conventional propulsion technology, system cost will decrease significantly as well.

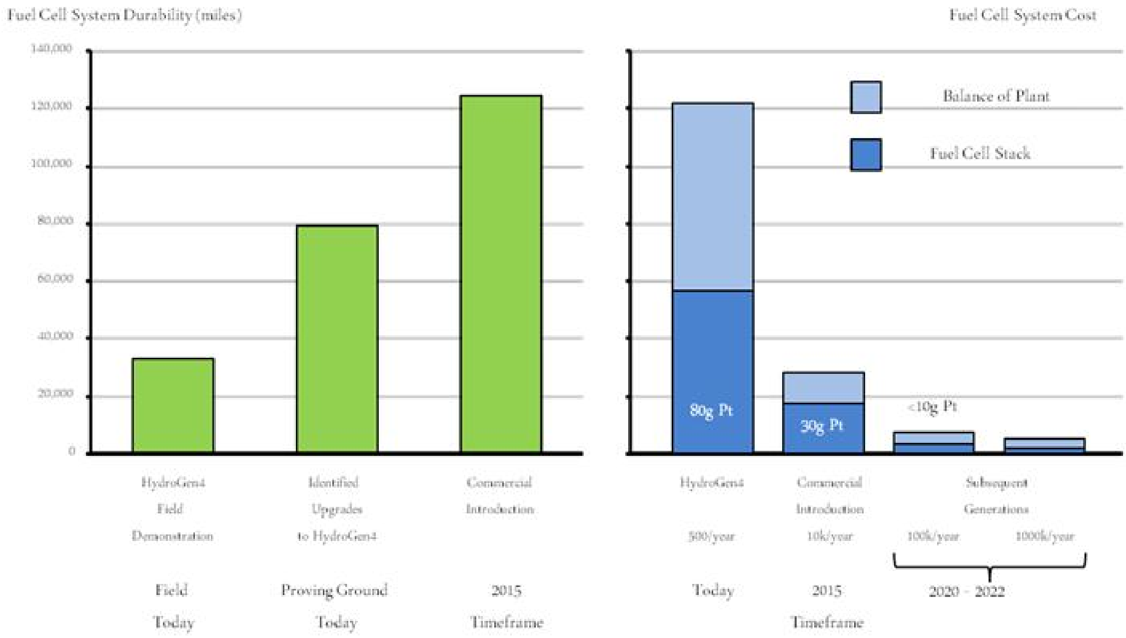

Figure 5: Fuel cell system durability progression and cost reduction.

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The Honda FCX Clarity – A viable Fuel Cell Electric Vehicle for today and beyond 2015?

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1 Introduction

Honda has developed a new fuel cell electric vehicle (FCEV) in order to respond to global warming and energy issues. The new vehicle, the FCX Clarity, incorporates enhancement in driving performance and fuel efficiency against previous Honda Fuel Cell Electric Vehicles (Honda FCX) and embodies a new appeal not available in the reciprocating engine powered vehicle.

Figure 1: Honda FCX Clarity.

The key to the FCX Clarity's development was the achievement of size and weight reductions and increased efficiency in the fuel cell power train.

In 2002, Honda introduced the 2003 model year FCX, the first fuel cell electric vehicle certified by the US Environmental Protection Agency (EPA), and thereby demonstrated the strong basic performance of the vehicle. Since then, research and development was conducted targeting for enhancing the performance of this new technology and thus promoting it.

Without the necessity to arrange the fuel cell stack close to the electric motor and its transmission powering the fuel cell car, components can be distributed within the vehicle allowing for a radically changed package layout and design. However, the Honda FCX introduced 2005 had a number of limitations that were due to a larger powerplant (fuel cell and related system components) as well as the chassis borrowed from Honda's first electric vehicle brought to the market in California beginning of 1998. Because of these chassis limitations, nothing about the exterior identified the FCX as an automobile created with leading edge technology.

For Honda's new fuel cell electric vehicle (FCEV), the FCX Clarity, a new powerplant that includes a new, smaller and higher output fuel cell stack and most importantly a new vehicle platform specifically for a fuel cell car with a new package layout and design taking full advantage of the freedom related to innovative packaging was developed. The target is conveying the message of the potential of the new technology to a much broader audience, immediately recognizing the vehicle as Honda's advanced fuel cell car.

2 Style and Design of the FCX Clarity

The design concept was to create a futuristic automobile easy to be recognized as being something new thus meaning an eye-catching design and providing a glimpse into the future when opening the door and inspire a new generation of drivers having visions about the automobile society and the global environment.

Additionally the designers felt that the uniqueness of the technology and available features, namely strong environmental performance, interior spaciousness enabled by the new package, and the high torque yet quiet ride due to electric propulsion were appropriate for a premium car of the future. Design features are the exterior design with its new proportions, a short nose and long cabin emphasized through its dynamic surface design. The new form is completely unlike that of any conventional sedan.

Up to now, large fuel cell stacks have been located under floor of a relatively high standing vehicle such as MPVs or SUVs. The new Honda FC Stack was given an innovative new structure that made it efficient and compact enough to be placed in the centre tunnel. As a result, the sedan package has the required low floor, low centre of gravity and the low overall height having been impossible in a conventional FCEV. Additionally the more compact front-wheel drive motor made the short nose design possible with achieving at the same time a long cabin that increases interior space for all occupants without making the vehicle any longer.

The result is generous cabin space of a large-class body in a medium-class body.

Furthermore by reducing the hydrogen tank system size and the auxiliary power source and adding a high-deck trunk, sufficient trunk space has been made available.

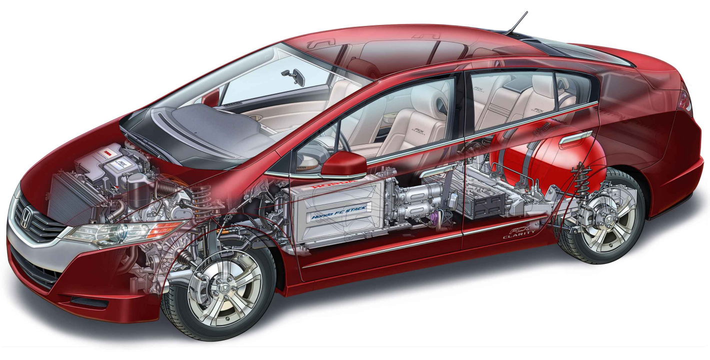

Figure 2: Honda FCX Clarity ghost drawing.

The interior was explicitly designed ahead of time, optimizing its wide open cabin space to create spacious and comfortable occupant space and a cockpit which gives a new sense of fun with futuristic features.

3 FCX Clarity Power Train

The FCX Clarity's fuel cell power train system has Honda's proprietary V Flow FC Stack at its core with a weight power density 2 times higher and a volume power density 2.2 times higher than the fuel cell power train of the previous Honda FCX. In addition to increasing the maximum power to 100kW, the V Flow stack achieves a 50% increase in volume power density and 67% increase in weight power density compared to the previous Honda FC Stack.

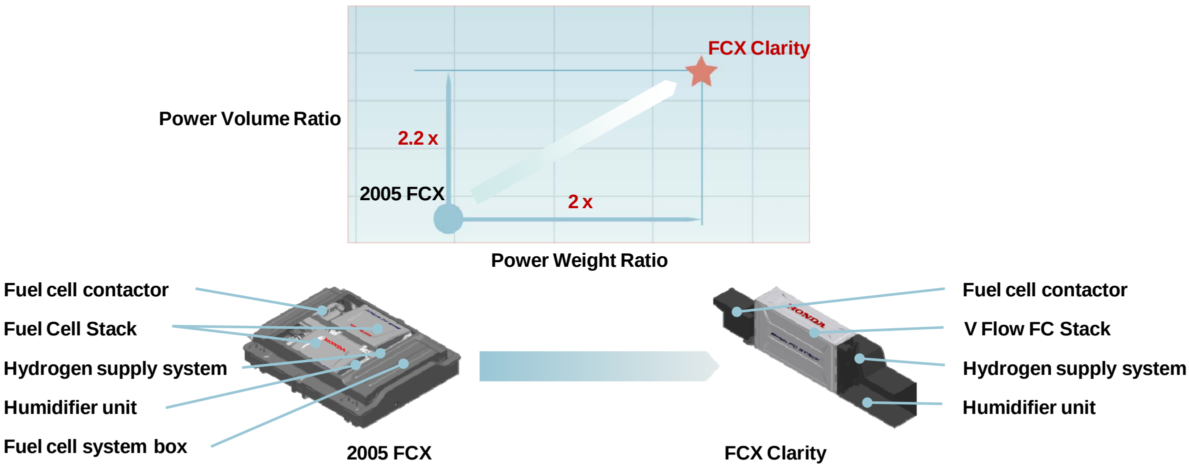

Figure 3: Honda fuel cell stack and system comparison.

4 V Flow FC Stack

In order to generate electricity by the fuel cells it is commonly known that hydrogen and air need to be continuously provided over the electricity generating surfaces of the membrane electrode assembly (MEA). However, if the water produced when hydrogen and oxygen react accumulates in the gas channels, it can impede the gas flow, preventing hydrogen and air from being supplied uniformly to the generating surfaces and making generation unstable. But in order to make a fuel cell stack more compact, it is necessary to reduce the thickness of the cells by reducing the depth of the gas flow channels hydrogen and air. However, reducing the depth of the channels would increase the adhesion force, thereby even promoting water accumulation.

In order to reconcile a stable generation performance with reduced depth of the gas channels, it is necessary to increase the water drainage capacity to the same degree that the water adhesion forces increase. This led to the development of a V Flow cell structure, in which hydrogen and air flow vertically, rather than horizontally, as in the previous Honda FC Stack and conventional fuel cell stacks.

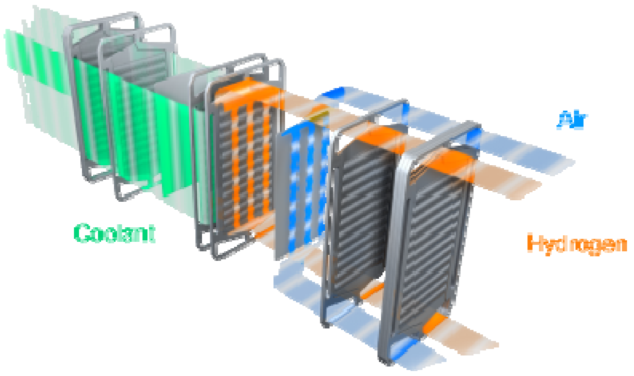

Figure 4: Honda V Flow FC Stack.

In the horizontal-flow cell structure, the pressure difference between inlet and outlet functioned as the only force promoting drainage of the process water in the flow channels. The new vertical-flow cell structure adds gravity to this pressure difference, thus increasing the drainage capacity. This made a much more stable electricity generation possible despite the reduction in depth of the flow channels. As a result, the flow channels depth was reduced by 17% over the previous generation fuel cell stack.

5 Aromatic Polymer Electrolyte Membrane

The Honda V Flow fuel cell stack is based on an aromatic polymer electrolyte membrane with high conductivity and durability.

The membrane material is prepared from the aromatic block copolymer, consisting of alternating stiff sulfonic acid-bearing segments and hydrophobic flexible polymeric sub-units.

A bi-continuous microphase-separated morphology of the membrane has been attested, contributing to its excellent water resistance while keeping high proton conductivity. The membrane delivers the same chemical stability as a conventional poly(perfluorosulfonic acid) one, while outperforming the latter in power output of the fuel cell, life time and temperature range. In particular the cold start capability of the V Flow fuel cell stack of the FCX Clarity had been improved from initially -20°C to now -30°C.

6 Wave Flow Channel Separators

Generation performance can be maximized by a high uniform flow of hydrogen and air over the reaction surface as described above but also when allowing for a uniform coolant flow through the cells as well.

If particularly the coolant does not flow uniformly, localized areas of higher temperature (hot spots) will occur in the membrane electrode assembly.

The use of stamped metal separators and straight flow channels creates a configuration in which hydrogen, air and coolant, all flow in the same direction. This required three manifolds positioned in a row in each cell introducing all three media, reducing the width of their supply path to the generating surfaces and limiting supply.

Positioning the gas manifolds vertically and widening the gas supply paths in addition to bi-furcating the short sides of the generating surfaces, would be an effective means for a more uniform supply.

Wave flow channel separators were therefore used for a horizontal flow of the coolant. The wave flow channel separators that turn the flow into the horizontal direction, across the flow of hydrogen and air, enabled the width of the supply paths for both gases and the coolant to be increased.

In addition, because each wave flow channel is longer than a corresponding linear flow channel, and varies the flow, the dispersion of hydrogen and air increased.

As a result, hydrogen and air pass over the entire surface of the electrode layer.

More effective use is made of the generating surfaces, resulting in a 10% increase in generating performance compared to the linear flow channels.

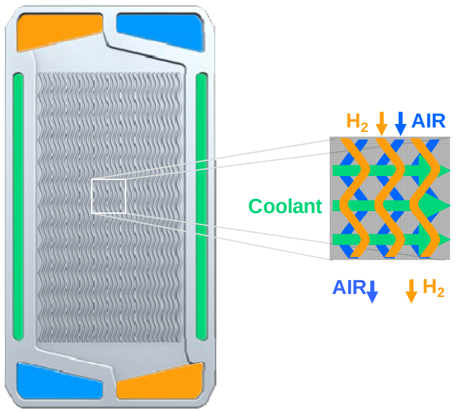

Figure 5: Wave flow channel separator.

In addition, the horizontal coolant flow helps to achieve a better cooling of these generation surfaces allowing coolant layers that were previously needed for each cell to be halved in number, and the number of separators required for every two membrane electrode assemblies to be reduced from four to three.

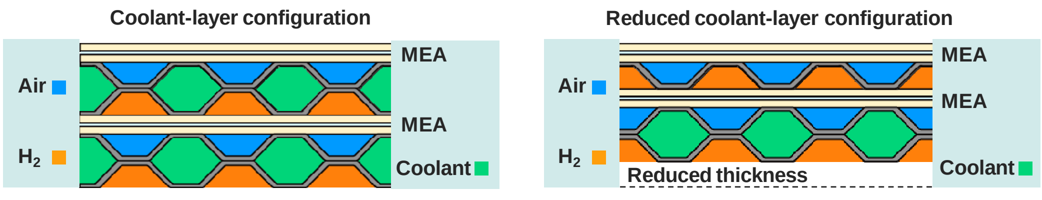

Figure 6: Honda V Flow FC Stack coolant-layer configuration.

Therefore the stack thickness has been reduced by in length by 20% and its related mass by 30%.

7 Increased Productivity

Since fuel cell stacks are made up of hundreds of layered cells, achieving an increased productivity for the cell components is a major issue and subject to optimization. Production technologies that increase productivity including specifications appropriate for these production technologies needed therefore to be developed.

In case of the previous MEA, in order to produce a Catalyst Coated Membrane (CCM) prior to sandwiching between the diffusion layers, the electrode was hot-pressed onto the membrane after the electrode had been coated on a support film. For the new cells, a technique of shape-controlled electrode coating on the membrane has been invented to enable direct formation of the electrodes in a predetermined shape onto the roll-shaped electrolytic membrane. Additionally, progressive stamping using metal coils has been employed to produce the stamped metal separators, in place of the previous method of stamping individual plates in successive batches for continuous production.

Previously MEA easily broke, making their handling during layering a considerable challenge. In the new configuration, two cells formed from two MEA and three separators are treated as one unit, enabling automatic layering by robots.

8 Conclusion

Major achievements have been made in developing the advanced Fuel Cell Electric Vehicle FCX Clarity.

Considering when the actual development of fuel cell related technology has started at Honda and looking to the challenges ahead for its application in transportation, productivity in all areas has to be further improved and made explicitly faster for a typical mass production of such vehicle. Limiting factor is not the body in white and its production but all new fuel cell related components that need to be manufactured at a very high quality level to ensure the required lifetime. Measures have been introduced but need to be further explored and new specifications need to be defined.

In order to tackle all relevant issues after production such as servicing and maintenance, Honda developed already for the FCX Clarity the entirely necessary logistic chain from development to sales and service. All information, such as workshop manuals, spare parts lists and its related ordering system and so on are in place.

Ramping up production to the widely discussed necessary levels, component costs have to be reduced further and this not only based on higher volume but also initial material cost, especially for the fuel cell stack. Defined cost targets are very well established and might possibly be reached. The timing though remains a challenge.

The FCX Clarity as such is showcasing the ultimate solution in clean transport for Honda and therefore remains very high on our agenda.

Comparing the achievements made in the fuel cell power train development with conventional technology, the future is already here today. Looking at the currently discussed alternatives it is very obvious that the fuel cell car has a while ago leap frogged the battery electric vehicle and this for good reasons. The FCX Clarity is a viable solution for today and the near term future while the fuel cell electric power train installed will be the viable and ultimate solution for vehicle propulsion for today and beyond 2015.

Comparative Life-Cycle Cost Analysis of Hydrogen Fuel Cell Vehicles

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1 Introduction

Anthropogenic energy consumption has been rising steadily for centuries, ever since fossil fuels became available on a larger scale. It has become an accepted fact that in future renewable energy sources will again need to provide a growing share. This applies to all energy sectors but much of the responsibility is allocated to the transport sector. There, increasing efforts towards low- and zero-emission transportation indicate that a broader mix of primary energy sources will gain in significance, e.g. for the production of synthetic fuels. Furthermore, electric drivetrains will become available. Overall, these trends underline the necessity to observe the entire energy pathway with regard to the relevant parameters such as efficiency, emissions, costs or availability of energy conversion pathways. This paper describes technical and economical analyses of fuel cell electric vehicles and comprises corresponding comparisons with conventional vehicles. Starting point is a thorough analysis of hydrogen fuel production, transport and refuelling, followed by description of vehicles. Comparative life-cycle analyses of fuel cell and conventional vehicles are covered in the final section of this paper. They allow identifying vehicle concepts that are most promising in view of market introduction and long-term competitiveness.

A comprehensive publication with all details of this study will be available in late 2010, after the completion of the author's dissertation at RWTH Aachen University, titled "Vergleichende Gesamtkostenanalyse von Brennstoffzellenfahrzeugen".

2 Hydrogen Fuel

The analysis of hydrogen as a fuel should ideally include the entire energy pathway: production, distribution, storage, refuelling and conversion, comprising technical, environmental and economic issues. In view of existing studies in this field (e.g. EUCAR-CONCAWE), emissions have not been analyzed here. The main focus is set on technical aspects and costs of current systems. Detailed cost models have been used to calculate the cost for the provision of hydrogen [STE08] to end customers at fuelling stations. They take into account all relevant components, raw materials, labour and amortisation. Hydrogen can be produced from different sources, with hydrocarbons (steam reforming) and water (electrolysis) belonging to the most prominent pathways. Natural gas reformers are mature technologies and well adapted in most diverse technical processes. As a result, hydrogen produced from natural gas is comparably cheap at about 3.40 €/kg in a facility scaled to about 100 t/H_2 per day (Figure 1). Reformers for biomass use the same technology as the ones for natural gas but tend to be much smaller due to dispersed availability of biomass. Hydrogen production costs are therefore signifycantly higher, at about 6.30 €/kg. In both cases, primary energy accounts to most of the costs. Locations for electrolysers do not depend mainly on electricity production sites. Furthermore, hydrogen production via electrolysis can make use of intermittent primary sources such as wind and solar energy. With electricity priced at 0.10 €/kWh, hydrogen can today be produced at costs of roughly 9 €/kg. However, solar electricity is much more expensive, taking into account the poor full load ratio of 20% in central and southern Europe. Solar hydrogen costs are at least 17 €/kg. Wind power plants yield more full load hours (up to 45%) and therefore allow for cheaper electrolysis for hydrogen priced at about 4.50 €/kg. Coal-fired power plants tend to be cheap with regard to electricity production if CCS is not included in the process. However, if CO_2 is to be separated and sequestrated, they become as expensive as their solar-powered counterparts.

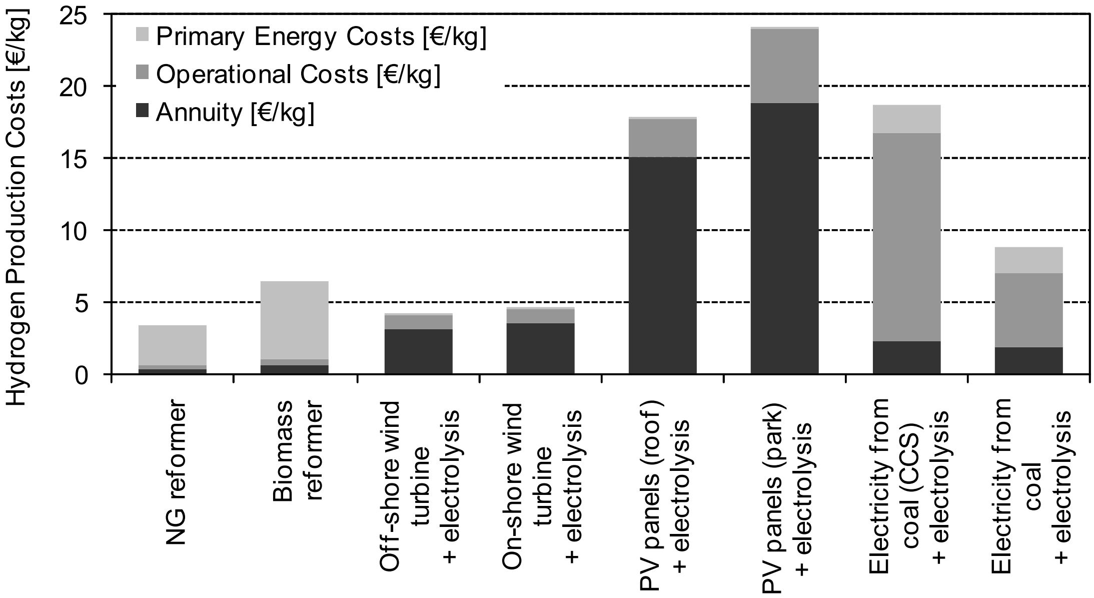

Figure 1: Hydrogen production costs for different primary energy pathways.

Hydrogen distribution can be realised continuously via pipelines or intermittently by different surface transport modes (truck, rail, ship). In pipelines, it is usually compressed to about 100 - 150 bar and adds about 0.80 €/kg for a transport distance of 500 km, provided that the pipeline yields a throughput of more than 70 t/d. Technically, they are similar to natural gas pipelines. Compressed hydrogen transport by truck trailers is preferred if the required transport capacity is low, and costs are about 0.50 €/kg for transport distances of up to 50 km. At higher transport volumes, liquefied transport is cheapest and costs about 1.20 €/kg for a transport distance of 200 km (Table 1).

Table 1: Cost for the provision of hydrogen, including transport and dispenser.

		Transport		
		Tube trailer (50 km)	LH2 (truck) (200 km)	Pipeline (500 km)
Sales price, incl. profit margin (20%) and VAT (19%) [€/kg H_2]	NG reformer	5.89	6.89	6.32
	Biogas reformer	10.24	11.24	10.66
	On-shore wind turbine, electrolysis	7.50	8.50	7.93
	Off-shore wind turbine, electrolysis	6.93	7.93	7.36
	PV panels (roof), electrolysis	26.40	27.40	26.82
	PV panels (park), electrolysis	35.37	36.37	35.80
	Electricity from coal, electrolysis	13.74	14.74	14.17
	Electricity from coal (CCS), electrolysis	27.54	28.54	27.97
Incl.: transport cost and fuelling station [€/kg H_2]		1.14	2.14	1.71

2.1 Hydrogen-powered vehicles

Hydrogen fuel cell vehicles are electric vehicles that have a fuel cell acting as an on-board electricity generator. As a consequence, the drivetrain investment cost of such vehicles consists not only of hydrogen storage and fuel cell system, but also contains the electric machine and potentially batteries or supercapacitors. All types of hybridization have been showcased in the past. Today, almost all fuel cell passenger vehicles are powered by PEM fuel cells operating at relatively low temperature (<100°C). The FC system can be manufactured for about 70 €/kW (80 kW system, [CAR05]). In this example, the total drivetrain cost is approximately 12,500 € (156 €/kW) and includes the electric machine (50 €/kW) and 700 bar CGH storage (capacity 5.5 kg, 20 €/kWh). The drivetrain can easily be configured in a hybrid layout with batteries or supercaps. The fuel cell can then be scaled down, potentially leading to reduced investment costs while retaining the vehicle performance. The operating costs represent another part of the vehicle's total cost of ownership. Those include primarily the cost of hydrogen as described before and servicing costs on a €/km basis.

If a vehicle uses 1 kg / 100 km, then the running cost ranges from about 8 € / 100 km for hydrogen from natural gas to 38 € / 100 km for hydrogen from PV parks. Servicing costs are estimated to be 0.02 €/km (Figure 2).

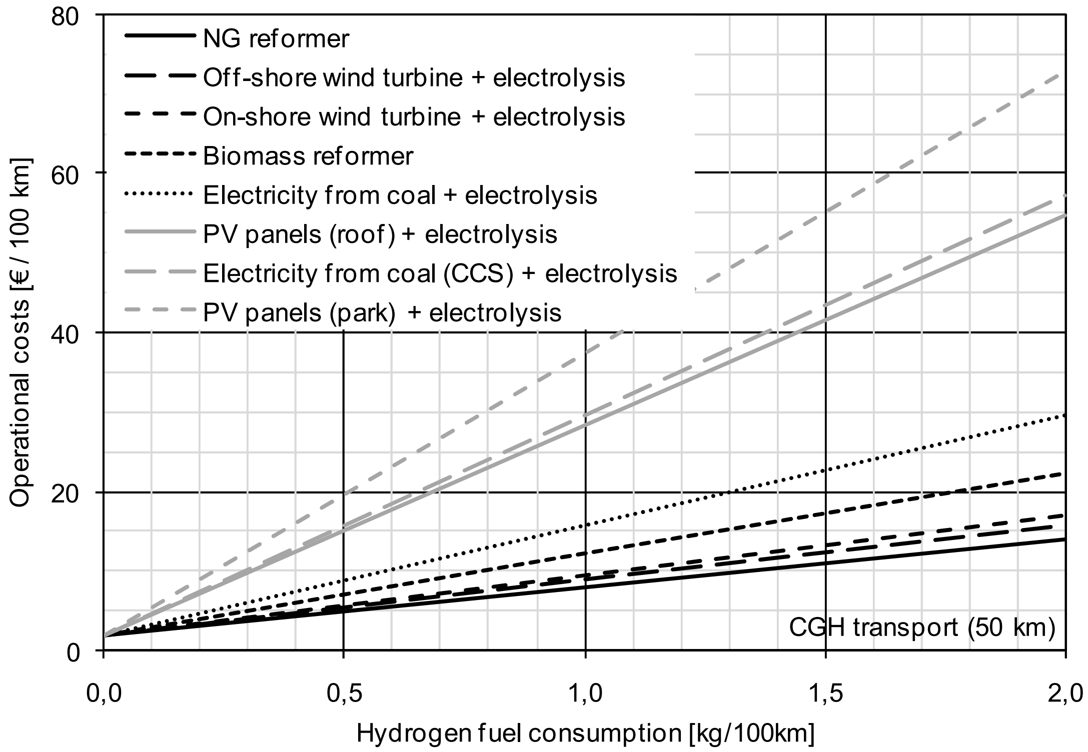

Figure 2: Operating costs of hydrogen fuel cell vehicles as a function of hydrogen consumption and provision pathway.

3 Sensitivity Analysis of Fuel Cell Hybrid Electric Vehicles

It is obvious that vehicle costs strongly depend on the hydrogen fuel consumption. As a result, the optimization of drivetrain efficiency adds to any investment cost benefit achieved through technological breakthroughs. Therefore, the analysis of diverse drivetrain concepts is a major part of this study. Non-hybrid and hybrid vehicle concepts in different vehicle classes have been analyzed with regard to their performance and their efficiency in the NEDC (New European Driving Cycle). A detailed simulation model was developed to calculate the relevant data. Basic fuel cell vehicles without hybridization achieve a drivetrain efficiency of 30 to 38% (Table 2). If combined with an advanced energy management system, the drivetrain efficiency can reach 60%, an increase of up to 50% compared to non-hybrid versions. The electric machines are individually scaled according to the power output of fuel cell, battery and supercapacitor. The vehicle mass is also determined based on the used components.

Table 2: Efficiency (in %) of hydrogen FC vehicles in different vehicle classes (NEDC).

		Compact class				Medium-sized				Luxury class		
Hybridisation [kWh]		**Stack power [kW]**										
Battery	**Supercap**	**30**	**50**	**70**	**90**	**50**	**70**	**90**	**150**	**70**	**90**	**150**
-	-		30.3	32.1	33.3		32.7	33.9	35.8		35.8	38.2
0.5	-	41.3	44.5	45.2	46.9	44.7	47.0	48.7	54.6	53.2	55.2	59.8
2.0	-	46.2	48.6	51.0	52.8	52.0	52.3	54.1	58.5	56.6	58.4	62.6
-	0.15	42.1	45.2	47.2	48.9	46.0	48.1	49.8	54.0	52.7	52.6	56.6
-	0.45	41.9	44.8	46.7	48.3	45.3	47.3	48.9	52.8	51.5	53.0	55.7
-	0.71	39.8	43.9	46.2	46.3	45.2	47.2	49.3	53.1	51.5	53.1	56.2

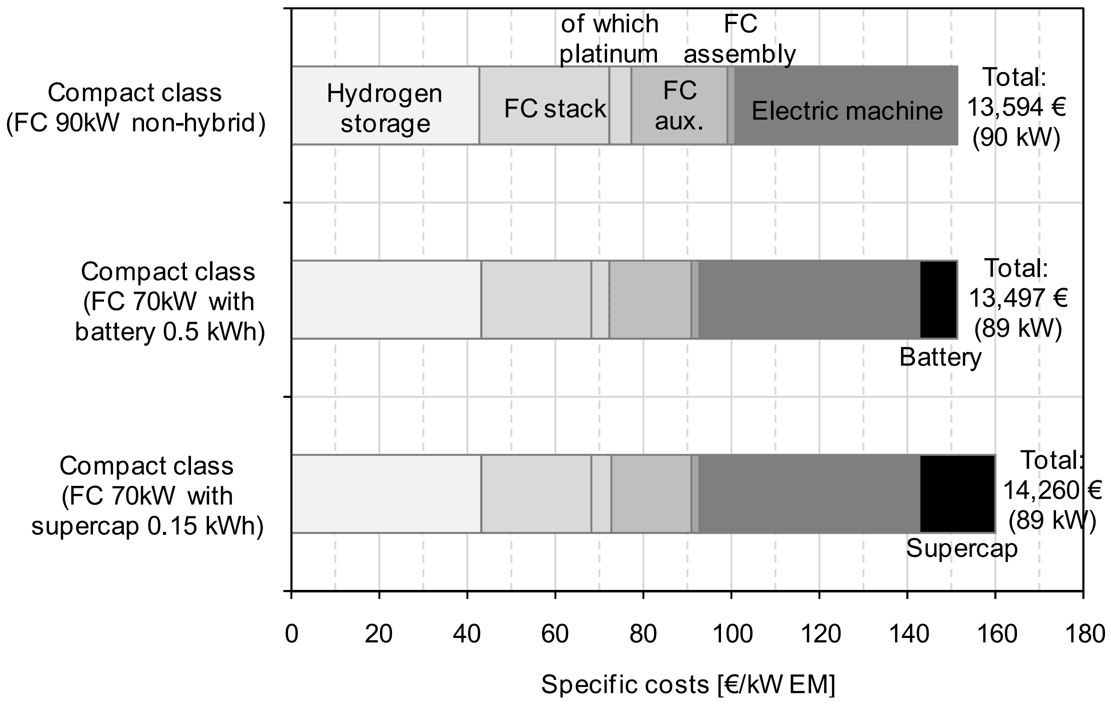

Figure 3: Drivetrain costs for different FC vehicles (Compact class).

Drivetrain costs have been calculated for every vehicle. Costs for non-hybrid vehicles consist almost equally of the costs for storage, fuel cell system and motor (Figure 3). The hybridisation leads to a reduced share of the fuel cell system. In some cases, total drivetrain costs do not rise despite the hybridisation. Since the hybridisation increases the efficiency, the total cost of ownership is lower than for non-hybrid vehicles, regardless of the cost for hydrogen. In case of higher drivetrain costs (e.g. in case of some hybrids with supercapacitors or “triple hybrids”), the cost benefit depends on the mileage / amortisation target.

4 Comparative Life-Cycle Analysis

Comparisons to conventional vehicles are vital for the success of fuel cell vehicles. As a final part of this study, a number of conventional vehicles were compared to the simulated fuel cell vehicles. This comprised the comparison of performance and costs. As a starting point for these final analyses, a performance indicator was developed to quantify the technical comparability of vehicles. It takes into account the acceleration, top speed and driving range, but not the costs. The TCO of the conventional vehicles is calculated using their respective drivetrain costs and running costs over a given amortisation distance (e.g. 200,000 km). The resulting value is then converted into hypothetical FC drivetrain costs and hydrogen fuel costs necessary for equal costs of the compared vehicles. It can be represented as a straight line in a hydrogen fuel cost vs. drivetrain cost diagram (Figure 4).

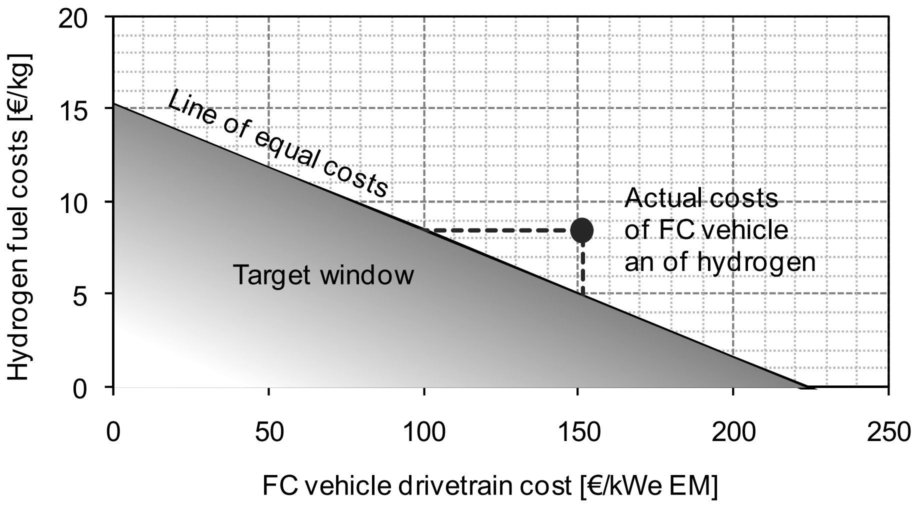

Figure 4: Line of equal costs for a given conventional vehicle and actual hydrogen costs / FC vehicle costs marked as a dot.

The actual FC vehicle can be marked as a dot in this diagram, as both its drivetrain costs and the cost for hydrogen have been determined earlier. If the dot is below the line of equal costs, the FC vehicle is cheaper than the conventional vehicle. It is more expensive if the dot is above the line. This representation of costs makes it easy to identify the required cost reduction for either hydrogen or the drivetrain in order to reach the same total costs as for the conventional vehicle. The slope of the line depends on the hydrogen fuel consumption and the amortisation distance. Rising costs for conventional fuels lead to a constant increase of the line of equal costs. On the other hand, the reduction of FC vehicle costs result in the dot moving leftwards closer to the line, and in case of changing hydrogen costs it moves vertically. As an example, the cost influence of the FC system is shown in Figure 5. In this case, even if the FC system did not cost anything, the vehicle would still not be competitive due to high costs for the hydrogen storage and the electric machine. The diagram on the right-hand side illustrates the effect of improved hydrogen fuel economy.

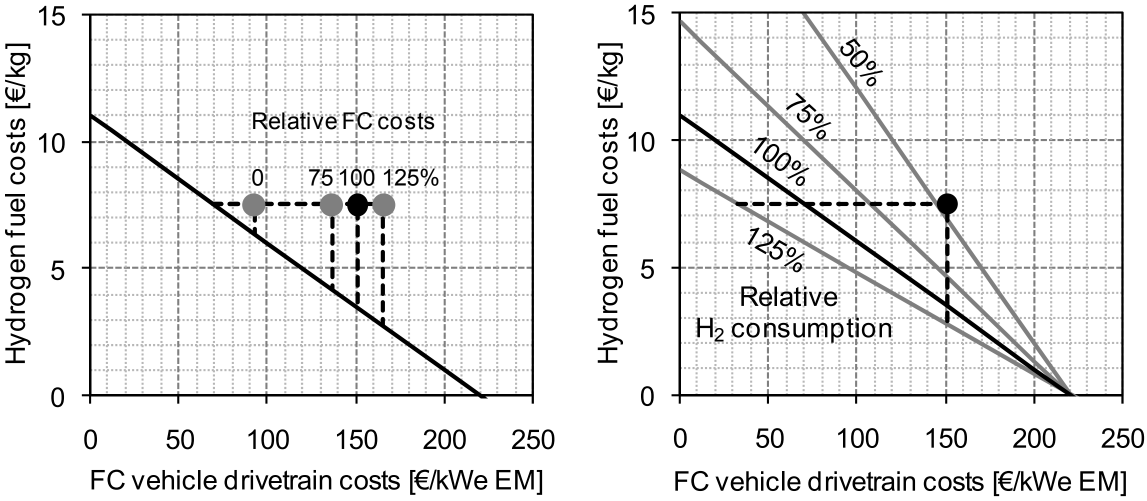

Figure 5: Cost comparison for different FC system costs (left) and different hydrogen fuel consumptions (right).

It becomes obvious that in this case it makes more sense to look at ways to improve efficiency than to reduce FC system costs.

5 Conclusion

The rising number of FC vehicles presented in recent years underlines the assumption that this technology is well under control in mobile application. However, market readiness is a completely different story due to high costs of hydrogen tanks, electric machines and FC systems. Infrastructure problems also persist and need to be addressed. Nonetheless, major OEMs and hydrogen producers recently agreed to aim for a noteworthy FC vehicle population by 2015. Current activities concerning battery-powered electric vehicles charged from the grid are not competing with FC vehicles, but yet another backbone towards the ultimate goal: sustainable and eco-friendly mobility.

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PHILEAS – The Operation of a 18m Hybrid Fuel Cell Bus in the Cologne Area

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Carsten Bußjaeger, RVK – Regional Transport Agency Cologne, Germany

1 Introduction

Hydrogen buses can become a dominant technology for future sustainable public transport systems. However, this will only occur if hydrogen buses and associated refuelling can meet key commercial requirements for cost reduction and well to wheel sustainability. Therefore the Hydrogen Bus Alliance (HBA) has initiated an industry dialogue in 2008 which served as a basis for the strategy paper published in 20091 (www.hydrogenbusalliance.org). In this strategy document the target prices for hydrogen busses can reach a commercial level (diesel-hybrid-bus equivalent) by 2015.

Moving closer to the aim of zero emission public transport in European cities, four new hybrid fuel cell busses are being built with Dutch and German partners during late 2009 and 2010. The first bus is presented during WHEC 2010 and put into demonstration in August 2010 in the greater Cologne area in Germany and – after a test-period - operated in daily public transport service both in inner city transport and interurban traffic. Today, the cost of the hydrogen fuel cell transit bus is significantly higher than the cost of a conventional diesel bus. However, the consortium around the Dutch manufacturer APTS established a comprehensive technical plan to reduce costs significantly. Specifically, the consortium expects to reduce capital costs to the general range of a diesel hybrid bus. By anticipating operating cost savings due to fuel efficiency and low maintenance needs, this concept should make the fuel cell system cost-competitive with conventional diesel-systems while using a zero-emission technology. The consortium aims to offer commercial fuel cell busses by 2015 depending on a procurement volume greater than a few hundred units per year.

The bus has a total length of 18 metres and is currently the only articulated hybrid fuel cell bus in the world. The lightweight chassis and the bus-system is manufactured by the Dutch Company APTS and the PEM fuel cells are supplied by Ballard Power. The electrical integration has been organized by the Düsseldorf-based Company Vossloh Kiepe while the Batteries are supplied by Hoppecke.2 The bus will be operated by the regional public transport service in Cologne and Hürth (RVK) and is connecting cities in the south of Cologne (Hürth and Brühl) with Cologne central station. The hydrogen necessary for the operation of the bus (approx. 15KG / day and bus) originates from waste hydrogen streams from chemical industry which has a total capacity to power more than 1000 busses in the area of Cologne. The quality of the hydrogen meets the commercial grade defined in SAE J2719.

2 Technical Concept

The 18 meter fuel cell bus is 100% low floor and offers all wheel steering and fully independent suspension. The top speed is at 80 Km/h and the acceleration 0 to 60 Km/h is measured with 20 seconds. German climate conditions are met (-15°C to + 45°C) and the busses are designed for most German cities. The bus can handle grades until 10% with completed seated load and brings a significant noise reduction of <75 dB external and internal. The range is about 300 kilometers which is equivalent of today's standard diesel bus technology. The bus will be in operation for 16 hours per day and will travel approximately 55.000 KM per year in urban transit and inner city drive cycles. The Hydrogen Fuel Package supplied by Dynetek can store 35 kg of gaseous hydrogen at 5000psi (350bar) and includes carbon wrapped tanks, regulators, valves, piping and custom mounting points. The systems and components are certified and compliant with Germany industry standards.

The Vossloh Drive System is designed as a serial hybrid system and includes the motor, the energy storage system (Batteries supplied by Hoppecke) and a propulsion control system. Vossloh Kiepe is the world's leading producer of efficient, low-emission hybrid electric propulsion systems for heavy-duty vehicles. Vossloh has equipped more than 1200 trolleybuses with AC-technology. Those busses are in service world wide and have travelled more than 400.000.000 kilometres.

The supplier of the Fuel Cell module Ballard Power has equiped over 50 busses (CUTE, Vancouver, London).3 Based on the state of the art automotive fuel cell stack, Ballard's FCvelocity-HD6 fuel cell module offers 150kW of electrical power at 550-800V. The dimensions are 1270 x 870 x 505mm and the operation temperature level is at 63 degree C. Experience from previous versions of this concept allows the FCvelocity-HD6 advantages in cost, through design for volume manufacturing, and compatibility with APTS system requirements. The heavy duty power module features a control unit that can interface with a CANBus system controller, making integration easier for the Phileas hybrid fuel cell bus platform. Besides the technology Ballard warranties a reliable operation for 12.000 hours or five years. This has been a necessary requirement to convince to allow the operator RVK to demonstrate this technology.

For service and maintenance support APTS will set up a support center in the Cologne area. Vossloh located 25km away from Cologne can provide service from the existing service infrastructure and Ballard will set up service and spare parts centre in NRW region to support the fuel cell buses. In addition Ballard will provide training to transit operators to carry out preventive maintenance work on the fuel cell modules.

In the Rhine-Area around Cologne and other parts of NRW, big resources of hydrogen as a by-product from the chemical industry are available.4 HyCologne focuses on using these resources and is building up a local network of innovation for hydrogen related technologies. Currently there are twenty members organised in a cluster. Starting early 2010 HyCologne establishes a hydrogen bus fleet and aims to replace a significant part of the existing diesel-fleet until 2020. Therefore a project has been set up to use the availably by-product hydrogen. The project called "Chemergy" will demonstrate clean energy solutions that make use of an existing but currently untapped source of hydrogen fuel – hydrogen emitted as the by-product of a sodium chlorate manufacturing plants. The purified hydrogen could be used to continually fuel a fleet of up to 500,000 hydrogen-powered passenger cars or 1000 busses (fuel cell hybrid) in the Greater Cologne area, significantly reducing greenhouse gas emissions, local air pollutants, and the use of fossil fuels. By making use of an existing by-product stream, the plant significantly reduces the financial cost and energy required to provide 99.99% pure hydrogen.

„Chemergy“ is a milestone for electric traffic & transport concepts which are both economically viable and environmentally friendly, and it offers competitive fuel costs and profits made possible by the favourable local situation. The development of the infrastructure is clearly beneficial for the location’s and the region’s competitiveness. In parallel to the local activities the project partners examine how the findings of the Chemergy project can be transferred to other regions and how the potential resources of the industrial by-product hydrogen can be put to use in the area, in Northern-Rhine-Westphalia (NRW)5 and in Germany as a whole to ensure optimal results in efficiency.

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Modular Test Equipment – Flexible Application Test Bench for Fuel Cell Power Systems

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Manfred Strohmaier, Engineering und Anlagenbau GmbH, Germany

1 Introduction – Modular Test Equipment

A complete fuel cell power system consists of various components like fuel cell stack, heat exchanger, humidifier, compressor, expander or control valves. Acceptable test results can only be achieved by using an efficient test design taking into account the complexity of interaction between different components. The detailed investigation of these components requires tests with real system components as well as tests with test bench components.

For such tests a flexible and fast exchange of components is required. The supply of all components in a modular and optimised design allows such testing concepts. The modules must be well maintainable and safely exchangeable. Furthermore, only precise control and accurate data acquisition allows precise investigation of complex processes in the system.

2 Flexible Test Bench System – Concept

Test equipment for technical systems requires the same development standard as the prevailing system. Due to the changing demands in testing fuel cell systems - more system and component testing rather than 'stack'-testing - a flexible solution is required to perform a larger variety of tests. MOEHWALD GmbH has developed a suitable concept for an innovative test bench meeting such requirements.

2.1 Standard test equipment for stack-test

Actually, state of the art test benches for 'stack'-testing consist of the following components described in the block diagram below.

All components like the medium supply, humidifier, cooling system, pressure control, loading and controlling, data recording and software are 'hard wired' and cannot be replaced with other components. Figures 1 and 2 show a MOEHWALD GmbH standard stack test bench with fast steam humidification. The test bench provides a basic standard of gas circuits for anode and cathode gases, an exhaust unit, a cooling circuit and an electronic load. Optionally, additional gas circuits for mixing noxious gases are available.

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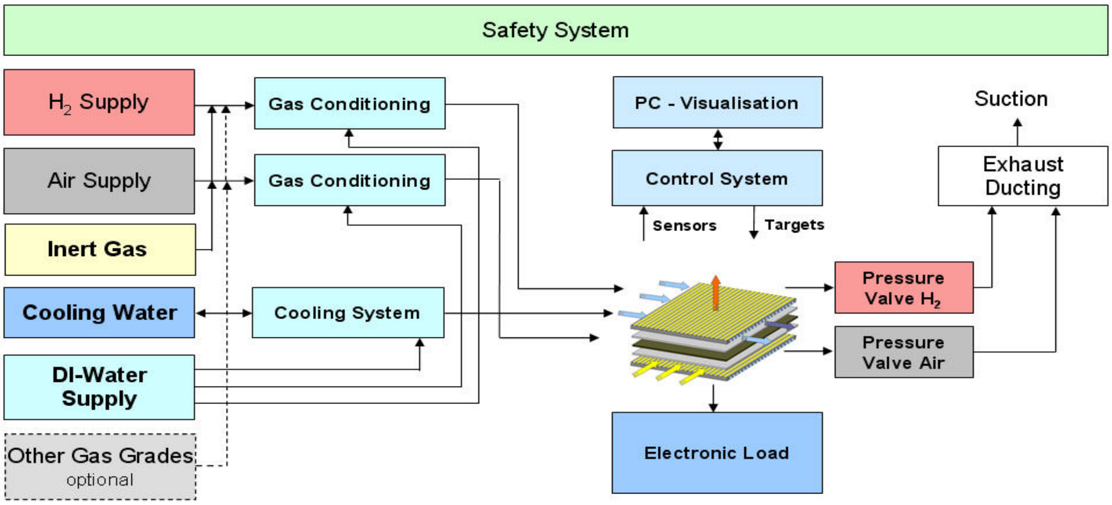

Figure 1: block diagram of standard stack test equipment – hard wired.

The continuous operation of a fuel cell stack can be realised through an automation system with a time based load control. The sensors, actors and the control software allow a load conditioned setting of mass flow, temperature, humidity, fuel gas pressure and cooling medium temperature. In addition, the test bench is equipped with an independent and comprehensive safety and alarm-processing system, which allows a comfortable integration into the customer's laboratory safety functions, e.g. a building management system.

Figure 2: MOEHWALD GmbH PEM stack test bench FCP5000-15 (15kW).

2.2 Flexible test bench for stack, components and system testing

The underlying idea of the new test bench concept is to allow a flexible exchange of provided standard test bench elements with components of the fuel cell system. The result is a test system that combines the capability of stack, components and system testing in only one bench. For stack testing idealised bench components are used to assemble an optimised test environment, for component testing, the stack is part of the test bench system. Like a - construction kit - the concept is realised by several independent test bench components. They can be put together to a complete, functional test system according to the requirements defined by the test engineer. Ideally every single test bench component has got its own integrated controller in order to allow an adaptation to the required process behaviour via software. The system is able to simulate different real components or can be used to develop components that perfectly fit into the overall system. This, in turn, leads to high demands on dynamic behaviour of the applied actors and sensors. An overlaid host computer with appropriate real-time software responding to the varying requirements of such variable machinery provides control over all elements of the 'construction kit'.

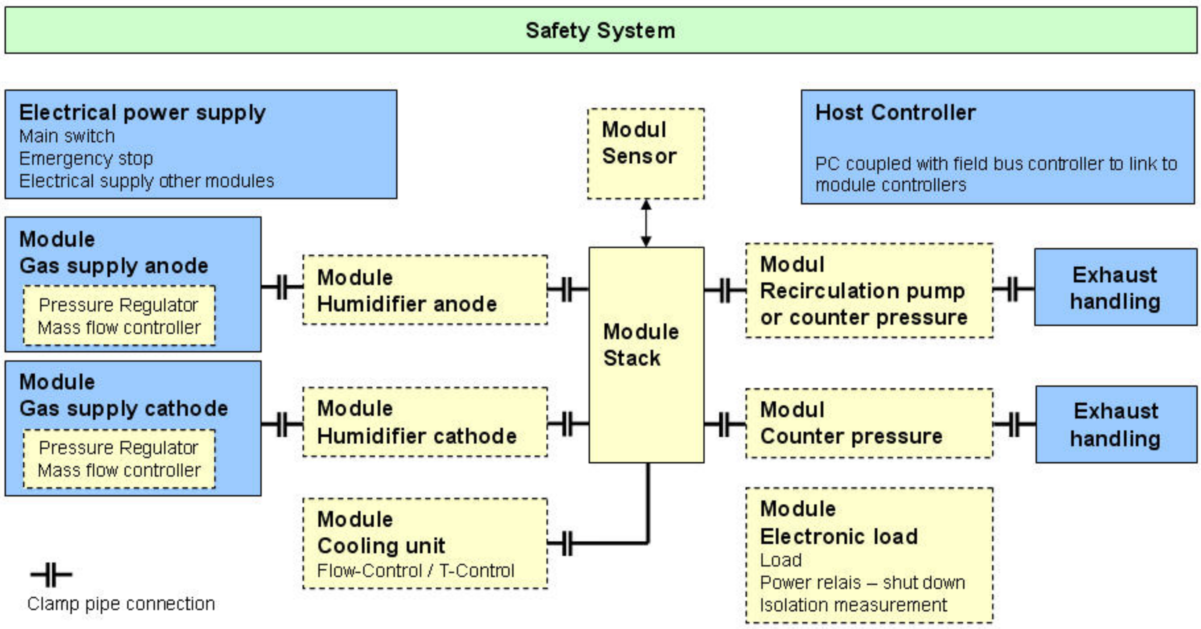

Figure 3: Block diagram - concept modular flexible test bench.

Figure 3 shows a block diagram which exemplifies the new concept on the basis of a test bench for a PEM fuel cell system. Modules in dashed line can be omitted or added, others in solid line are integral part of the system. Essential system parts that must not be omitted are the safety system, the electrical power supply as well as the host controller, gas supply and exhaust handling. Other modules like humidifier, cooling unit, sensor module, stack module, counter pressure, recirculation etc. can be arranged or substituted by system-oriented components achieving the test engineers conception.

3 Flexible Test Bench System – Main Components

3.1 Test bench – Power feed-in and emergency stop

Electrical power components are placed in a separate cabinet, assuring test bench modules feeding and emergency stop control. Each test bench module is equipped with a terminal box, containing the required electrical hardware plus an EtherCAT© slave for process I/O. The hardware includes components - connected to the central emergency control unit – to assure, that every single unit is set to a safe basic condition in case of an emergency stop.

3.2 Control system with data acquisition

Control and data acquisition of the system, made up of alterable modules, is performed by a host PC including a field bus controller e.g. EtherCAT© master. Each test bench module contains its own EtherCAT© slave linked to the master.

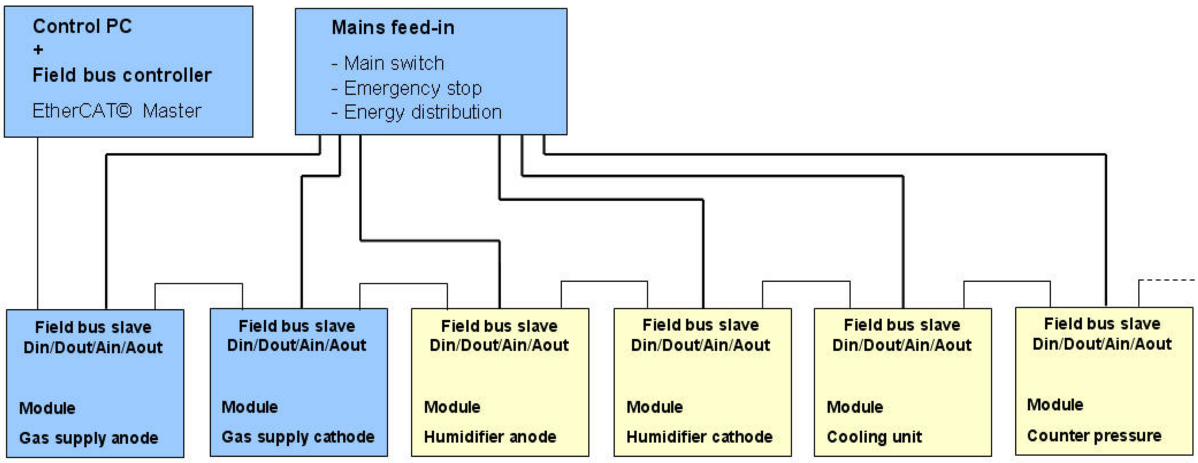

Figure 4: Block diagram – control concept.

The slave unit is in charge of peripherals control and measurement data acquisition. This master/slave system achieves highest flexibility required for the possibility of an incremental increase of process I/Os in each module and the increase of the total amount of slave modules.

3.3 Test bench control software RT-Labor

Applications requiring high performance, fast data acquisition and high flexibility are best suited with Moehwald real-time software system RT-Labor. RT-Labor supplies the test engineer with a comfortable software tool to configure individual test- and measure-cycles by drag and drop without programming knowledge. Together, a standard PC with modern hardware components plus RT-Labor Software, establishes the base for high performance applications in data acquisition and controlling:

- Priority controlled, pre-emptive and multitasking operating system
- Cycle time up to 100µs
- Data acquisition control - time and event triggered
- Integration of Multi I/O PC cards for faster data acquisition (up to 1 MHz)
- Ring buffer for post mortem recording
- EtherCAT© connection to peripherals
- CAN bus support

3.4 Mechanical construction

To fulfil practical requirements concerning safety functions, the modularised equipment must be encased. This includes hard wired components as process media and electrical energy feed-in as well as safety functions for explosion-proof design e.g. suction, gas-warning and prevention of electrostatic discharge.

The stack module is mounted in central position of the cabinet, other modules are arranged around to provide short connection paths for high dynamic response. To realise the modular concept – construction kit – the modules are interconnected with appropriate alterable clamp pipe connections shown in figure 5.

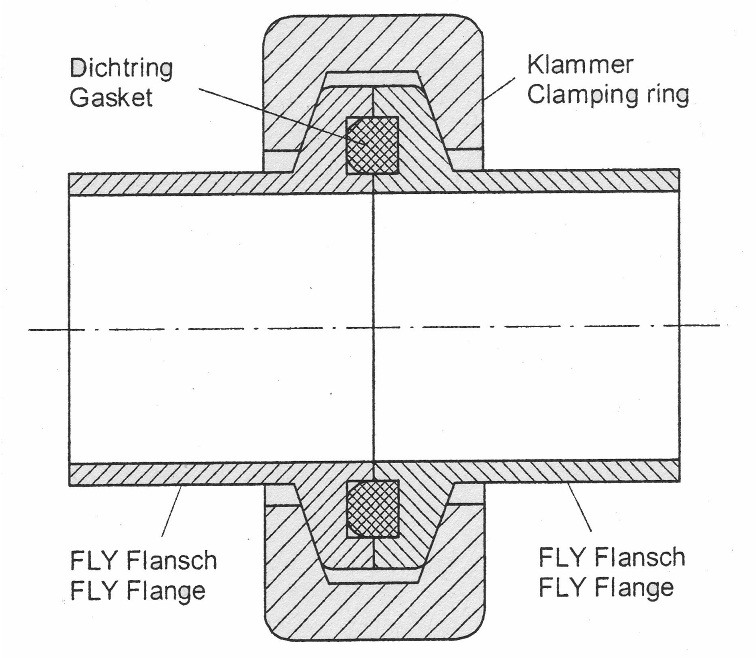

Figure 5: Draft: clamp pipe connection – from Linnemann GmbH.

Using those connectors - flexible and adequate for use with the module-concept, but not pre-defined to assure 'technical tightness' - requires stringent effort to assure leak-tightness, especially regarding the handling of hydrogen. Procedures to assure leak-tightness are air pressure leakage tests followed by a hydrogen sniffing procedure at all interfaces. Tightness checks have to be performed after each retrofitting of the assembly as well as cyclic checks in predefined fixed time intervals.

4 Conclusion

The concept of a modular test bench provides the test engineer with powerful test equipment for fuel cell development. It offers the whole testing range from the stack to a complete system in just one bench. This guarantees high technical flexibility and is a cost-effective solution for the development of future fuel cell components.

5 Moehwald GmbH – Optimal Results for More Than Three Decades

Moehwald GmbH develops and manufactures measurement and testing technology for fuel cells, fuel cell systems, Li-Ion batteries and systems, hybrid drives as well as diesel/gasoline injection systems and hydraulic components. Worldwide, successful customers rely on our testing technology for development and production. We are trusted partner of all global automotive manufacturers.

More than 30 years of experience in the development of test benches and manufacturing systems, as well as the know-how of our interdisciplinary project teams stand behind our customised solutions. As a subsidiary of Robert Bosch GmbH we have access to the latest technology of one of the most innovative industrial companies.

Figure 6: MOEHWALD GmbH customers worldwide.

On the development of fuel cell test benches, MOEHWALD closely cooperates with MS2, a company experienced in design and operation of fuel cell and fuel cell test systems. Jointly, both companies have successfully realized several test systems.

Moehwald has been ISO 9001 certified since 1997.

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H_2 Bus NRW – The Hybrid Electric Fuel-Cell Bus

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1 Introduction

Clean and quiet, ample passenger capacity and low energy consumption, this sounds like a description of the bus of tomorrow. The “hydrogen bus” is an innovative approach to tomorrow’s local public transport. It’s special feature: fuel cells powered by hydrogen (H_2). Emitted from the exhaust pipe is simply steam and nothing more. The first prototype of the Phileas H_2 bus is on show up to May 20, 2010, at the World Hydrogen Energy Conference being staged in Essen. Developed under the overall control of Vossloh Kiepe and APTS, the bus is part of a series of test vehicles destined for local public transport services in Amsterdam and Cologne.

Figure 1: Phileas – 18-m vehicle.

2 City Bus with Hybrid Drive Including Fuel Cell

So that the vision may come true, a Dutch-German consortium led by Vossloh Kiepe is working on the development of this idea up to the stage of standard production: a city bus with series hybrid drive including fuel cell. The vision is a clean future for local public transport with no pollutant or noise emissions and this vision is becoming reality with the progressive implementation of the corresponding hybrid electric fuel-cell bus concept. Three companies are involved: Advanced Public Transport Systems, HOPPECKE Batterie Systeme, and Vossloh Kiepe. Other scientific project partners taking part in the design of the energy storage and energy management modules are: the Electrochemical Energy Conversion and Storage Systems Research Group, Institute for Power Electronics and Electrical Drives at RWTH Aachen University and the Institute for Automation Engineering at Cologne University of Applied Sciences.

Supporting the consortium are government departments in both Germany and the Netherlands. The Dutch government and the EU together with the European Regional Development Fund are sharing in the funding of the project as are the North Rhine-Westphalian Ministry of Economic Affairs and Energy plus the Ministry for Building and Transport. The state's Minister of Economic Affairs, Christa Thoben, presented the confirmation of financial aid in February 2009 to Vossloh Kiepe at its Düsseldorf headquarters, thus announcing the go-ahead for the research project.

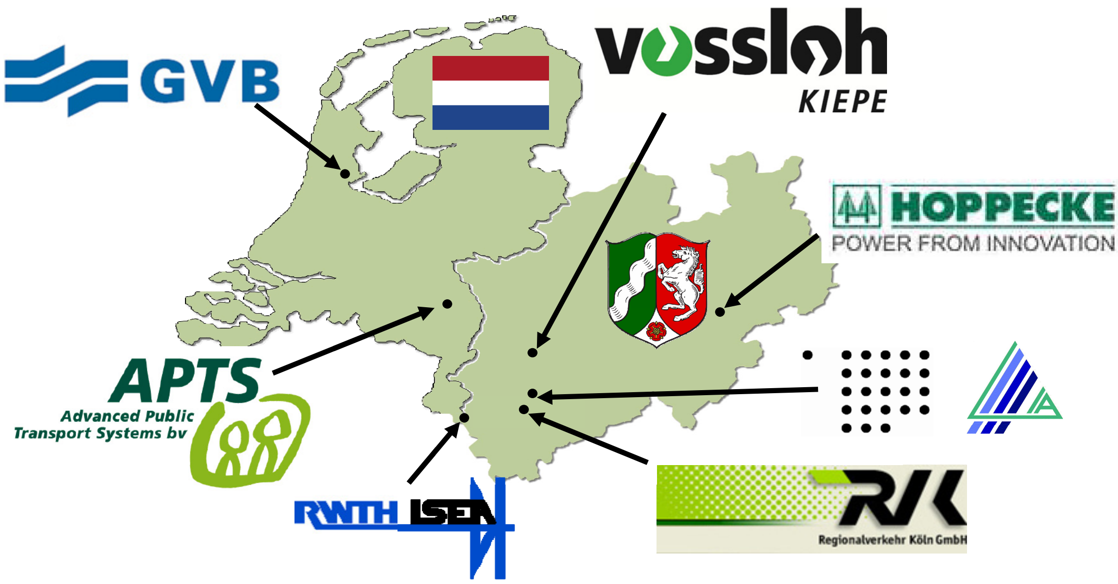

Figure 2: Project partners.

3 Innovative Lightweight Construction and State-of-the-art Drive Technology

The hybrid fuel-cell bus is based on the Phileas series (Figure 1: Phileas 18-m vehicle) built by Advanced Public Transport Systems BV (APTS). It was selected by the project partners for its lightweight modular design. In this way, innovative lightweight engineering is merged with advanced drive technology. Headquartered in Helmond, APTS is a member of the Dutch

VDL Group that builds annually some 2,000 buses. The company's ultramodern articulated buses have been in operation for some years now in the Netherlands, France, and Turkey. The Phileas bus is specifically engineered for comfortable passenger transport on very busy bus services. The triple-axle vehicles have a comparatively high capacity (35 seated and 140 standing passengers) and are nonetheless agile. Despite their length, the Phileas buses, just as standard 12-m buses, have a relatively tight turning circle made possible thanks to self-steer wheels mounted on all three axles.

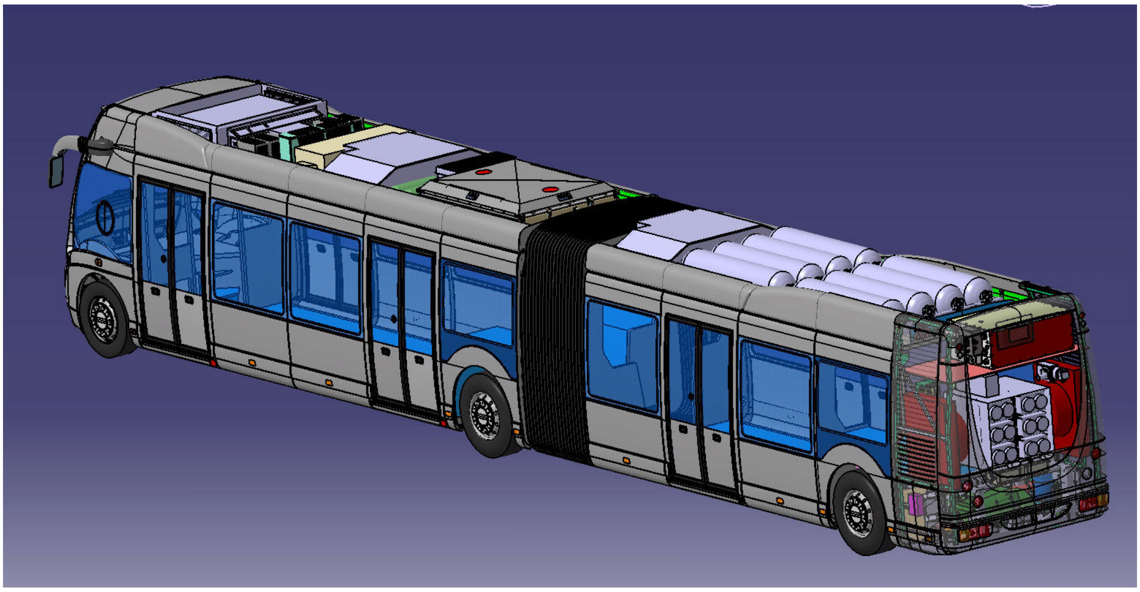

Figure 3: Phileas – H_2 bus system.

4 Drive System

The new version of the Phileas bus (Figure 3: Phileas – H_2 bus system) has a fuel-cell system located in the rear of the vehicle. Energy is also supplied by batteries and supercapacitors. A brake-energy recuperation device allows these energy storage modules to be recharged by converting kinetic energy into electrical when the brakes are applied. The electricity thus generated can then be used for the next start-up phase. The supercaps are chiefly used for covering peak load demands (starting-up/accelerating) while the batteries handle normal/cruising load requirements. The fuel cell works much like a base-load power plant and continuously feeds electrical energy into the onboard energy storage module.

The complex series hybrid system (Figure 4: System overview) is provided by Vossloh Kiepe GmbH. Hence, this Düsseldorf-based enterprise is responsible for the entire energy management system and supplies both batteries and supercaps. The nickel-metal hydride battery and the battery management system have been engineered in cooperation with Brilon-based Hoppecke Batterien GmbH & Co. KG. The traction unit is an asynchronous motor rated at 240 kW.

The first generation of this series hybrid drive systems has already been used on the 24-m double-articulated hybrid bus known as the LighTram. In the shape of this second-generation vehicle, Vossloh Kiepe is now extending its capabilities and the output range of the series hybrid bus. On the basis of the series hybrid drive platform, it is now possible to build, alongside diesel-electric, also all-electric vehicles. The fuel cell is sourced by APTS from the Canadian manufacturer Ballard Power Systems. For base-load requirements this has an output of up to 150 kW.

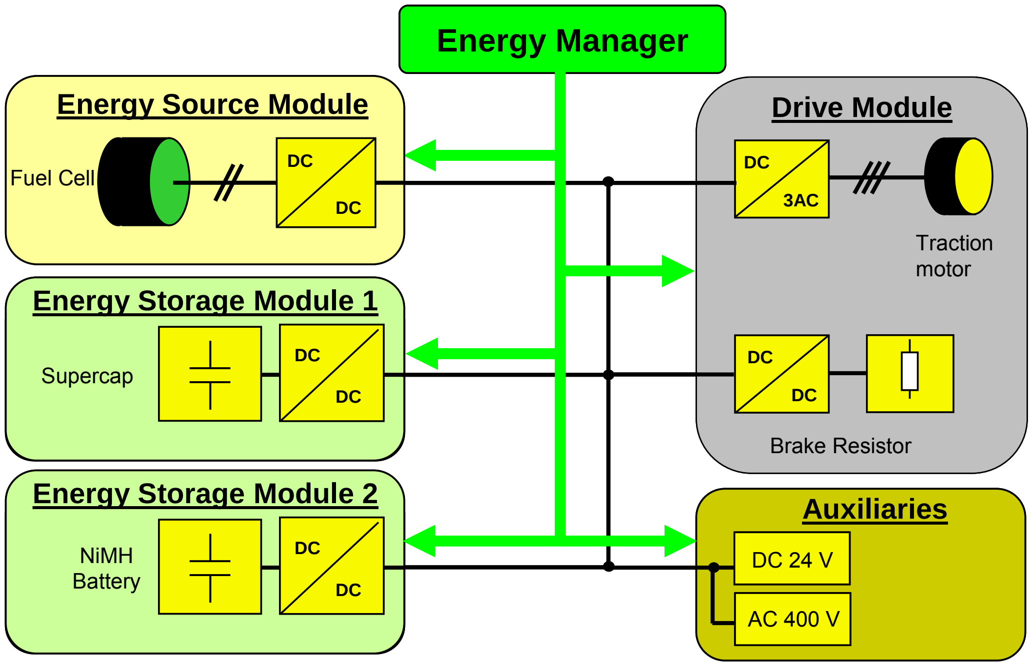

Figure 4: System overview.

5 Toward the "Hydrogen HyWay"

The hydrogen required for the fuel-cell system is stored in gaseous form in pressure tanks which can be filled up to 350 bar and are seated on the vehicle's roof. With 40 kg of hydrogen, the bus can operate up to 300 km. Dependable and even cost-efficient supplies of this fuel will be available in North Rhine-Westphalia through sufficient quantities of hydrogen sourced as a byproduct from the chemical industry located in the region around Cologne (such as from Bayer and InfraServ). For some years now, HyCologne, the regional innovation network for hydrogen and fuel cells, has been advocating the sensible use of these valuable resources. Meanwhile, altogether 16 organizations are represented in this interest pool and all of them are pushing ahead with the market rollout of fuel-cell systems.

6 All the Advantages at a Glance

The thinking behind all these efforts is that hydrogen-driven buses have numerous advantages over diesel vehicles. Fuel-cell buses have zero emissions since the exhaust pipe emits nothing but steam. The exhaust gas can simply be termed "waste air." Normal diesel engines, in contrast, operate at low efficiency especially when starting up and, in addition, emit pollutants (such as soot) plus noise. Fuel cells, in contrast, are very quiet. So such state-of-the-art energy converters may be seen as a major step toward "green" local public transport since both noise and pollutant emissions have been significantly reduced and, in the case of the latter, completely eliminated.

Irrespective of such considerations, energy consumption by these innovative vehicles is well below that of their diesel cousins since the entire system works extremely efficiently together with the fuel cells. Simply through the use of the series hybrid drive system combined with Vossloh Kiepe's newly developed energy management system, the vehicle's specific consumption can be lowered by up to 25 percent and the life-time of the fuel cell significantly prolonged. Thanks to the lightweight design, the dead weight is much the same as that of conventional city buses. The zero-emission hybrid will therefore have virtually the same passenger capacity as a conventional city bus. So it embodies the combined goals of creating a zero-emission local public transport vehicle and ensuring this innovative bus's operability on regular services. The top speed will be over 80 km/h.

7 Political Framework

In procuring these innovative zero-emission vehicles, the Cologne and Amsterdam public transport services (RVK and GVB) are giving their support to this technological development. In the actual acquisition of the buses, they are being assisted by the NRW Ministry of Economic Affairs, the NRW Transport Ministry, and the Dutch Transport Ministry. Politically, the project is also designed to help the regions merge closer together and act as a step toward the goal of a joint hydrogen pipeline extending up to Amsterdam.

8 Project Phases

The entire project for developing a hybrid fuel-cell bus ready for series production and platformed on the Phileas has three phases:

The first: development of a drive system culminating in a recommendation for the energy storage module and the design details of the fuel-cell system.

The second: four vehicles to be assembled, two to go to Cologne (Regionalverkehr Köln GmbH, RVK) and another two to Amsterdam (GVB), both in 2010.

The third: the buses will be tested on regular services for a period of several years.

The first official presentation of the concept took place during #rail2009 in Dortmund. The first prototype is presently being shown at the 18th World Hydrogen Energy Conference in Essen. More details are available at the Vossloh Kiepe booth 830 in hall 3.

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Hydrogen Driven Municipal Vehicle (hy.muve) – Vehicle Concept Demonstration and Field Testing in Switzerland

Peter Schlienger, **Christian Bach**, Swiss Federal Laboratory for Materials Science and Technology (Empa), Switzerland
Felix Büchi, PSI, Switzerland

1 Motivation

Among others, hydrogen is discussed as future fuel for road vehicles [1]. After a more basic research oriented phase, several pilot and demonstration oriented projects are ongoing in Europe [2]. The overall targets of fuel consumption and CO_2 reduction as well as fuel diversification hasn't change.

Early practical experience with fuel cell systems is essential for research institutions, vehicle manufacturers and the vehicle supply industry. This experience is particularly important for issues relating to the development of market implementation strategies, sampling of experience in real world operation and the study of socio-economic aspects in a sensible market phase.

At present, fuel cell powertrains are primarily being tested in passenger cars and buses. In these sectors, successful market introduction faces tough challenges in view of high driving dynamics, packaging requirements in limited space and cost expectations. Therefore, market introduction is to be expected after 2015. The present project is aimed at the introduction of a fuel cell drivetrain into a municipal vehicle (road sweeper). Considering their driving profile (operation by trained personnel, fleet operation from a fixed refuelling point, modest driving dynamics, predominantly low part-load operation, smaller relative share of powertrain in total cost, possibility to operate such vehicles in pedestrian areas and even indoors), these vehicles appear to be particularly well suited for an early introduction and possible commercialisation of fuel cells in a niche market.

2 General Goals of the Project

The Swiss company Bucher Schörling, the worldwide market leader in the manufacturing of municipal vehicles, is the key industrial partner in this project. In collaboration with other industrial partners, a prototype fuel cell municipal vehicle has been developed and is now close to a pre-production series which will be delivered to four Swiss cities for testing. Municipal service vehicles with their hydrostatic powertrain and auxiliary drives are a new field in which fuel cell converters have rarely been tested in the past. As the relevant components differ in specifications from those of passenger cars, a chain of innovative Swiss component suppliers would be given an opportunity to participate in the market introduction of this product.

In parallel to the technical development and demonstration phases in several cities, non-technical challenges for the implementation of innovations will be identified and promising strategies will be expanded further.

On the technical side, the questions of the powertrain layout with respect to efficiency, consumption, cost and spatial, thermal and electrical integration into a commercial vehicle represent a first challenge. These questions require fundamental knowledge with respect to modelling, development and testing of hydrogen based fuel cell powertrains.

A second challenge is the performance in aging and durability studies of the fuel cell system as well as analysis of handling and operation. This part is actually one of the most important research fields in respect to the market entry of fuel cell vehicles. It includes the identification and quantification of factors which limit PEM fuel cell durability due to contamination in the market fuel, aspiration-air pollution and technology disaffection using property change analysis during long-term testing.

A third challenge is the development of an innovation implementation strategy for hydrogen powered vehicles, which is based on socio-technological analysis with the evaluation of all included parties and the identification of barriers and risks. There are few studies based on public long-term real world testing of fuel cell vehicles so the assumptions on these issues are presently rather based on expert's estimations or are carried out by industrial partners without publication of the results. Therefore, the strategy would highly be of interest in other fields with hydrogen implementation plans.

We are planning, in addition to these findings and based on the technical development, to monitor inter- and intra organisational routines, collaboration and communication concepts. Mastering this potential for organisational innovation will prepare the participating partners for future technological opportunities.

3 Project Phases

a) Model phase: Development of a longitudinal dynamics model

The powertrain of the existing diesel-powered municipal vehicle (Bucher Schörling CityCat 2020) had to be modelled and the torque demand of the engine had to be investigated for different types of operation (road sweeping including auxiliary drives, vehicle transfer without auxiliary drives, uphill and downhill operations, etc.). Additionally, other important matters as range, starting time, operating temperature, maximum vehicle inclination, etc. had to be defined. Based on the results, a representative municipal driving cycle could be defined.

Based on the analysis of operation conditions, the specifications of the complete fuel cell powertrain were determined using a technical model of the complete drivetrain (fuel storage, fuel cell, electric motor, cooler, electric system, etc.) and basic requirements for the components were defined. The longitudinal dynamic model provided the scientific foundation for powertrain specifications, including efficiency, consumption, energy management, vehicle range, etc., enabling variation of the operating conditions and evaluation the effect of all individual specifications on practical use by means of a computer [4].

b) Concept phase: Powertrain integration, concepts and packaging

For integrating the fuel cell powertrain in the municipal vehicle to the stage of everyday use in customer hands, a 3-step development was required:

1st step: Integration concept:

To exploit the advantages of the combination of a fuel cell system with a hydraulic power train in the municipal vehicle, an adapted concept with respect to integration of the electric, thermal and control properties was required. Based on the results of the model phase, components in the electric and thermal loops could be defined based on the available technology.

This step included the design of the control architecture and functionality of the overall power management system and interface to the vehicle. Subsequently, the hardware as control unit, power management, sensors, actors, MMI were defined.

2nd step: Packaging study:

On the basis of the drivetrain specifications from the longitudinal dynamics model, a packaging study has been done, including 350 bar hydrogen storage and the complete drivetrain. The packaging study also had to include the possibility of capturing the unwanted reaction water of the fuel cell system. All possible modifications of the vehicle had to be done with a view to later serial production (Figure 1).

Besides the packaging study, the interfaces between vehicle and powertrain had to be evaluated and an overall control concept, including integration into the vehicle control system, had to be defined.

After approval of the whole vehicle concept by Bucher Schörling, a prototype vehicle was built (Figure 2).

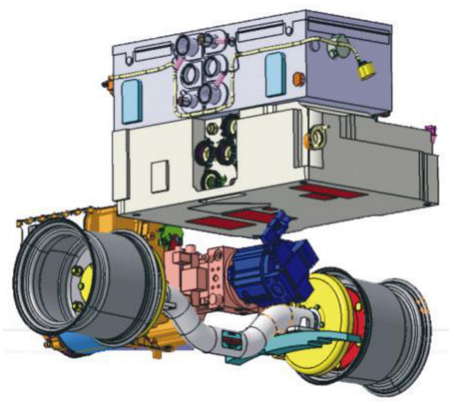

Figure 1: First packaging study of fuel cell system assembly.

Figure 2: Bucher Schörling CityCat H_2Project vehicle.

3rd step: Component testing:

Based on the results of concept and packaging study the main components as well as the control unit had to be tested prior to integration with respect to specifications.

c) Realisation phase: Prototyping, vehicle adaptation and control design

Implementation of the detailed control concept and strategy as well as the embedding in the overall vehicle control system needs extensive testing for adaptation of the thermal and dynamic behaviour of the complete powertrain. This includes the optimisation of the start/stop, the power, the thermal control strategies as well as certification and safety aspects for the operation in public.

d) Testing Phase: Vehicle laboratory and field tests

After the realisation phase, the vehicle was first tested in the laboratory with regard to system performance (max. power, torque, dynamics, powertrain efficiency) and ambient conditions before it could be used in the field.

This laboratory testing also included a comparison of the hydrogen-powered municipal vehicle with a diesel-powered vehicle regarding energy efficiency and consumption [5].

After laboratory testing, 18 months field testing under real world conditions are being performed in four Swiss cities equipped with a mobile hydrogen fuelling system. The field testing includes investigations regarding drivability, handling, technical reliability, fuel consumption and durability and aging studies (degradation, poisoning, etc.), using property change analysis.

After the field test phase a second laboratory test phase will give results with respect to aging and offers exploitation of parameters which have become apparent in the field test phase.

e) Evaluating learning effects, operating behaviour

Practical experience in an early implementation phase provides a unique opportunity for additional Swiss industrial partners to enter the developing fuel cell network with innovative solutions. Taking this research and implementation-project as an empirical case study, the socio-technological investigation will systematically identify relevant challenges and solutions. The recording and systematic evaluation of cooperation, communication and network contacts is of special interest for the development of the prototype vehicle and field testing. Also innovation and implementation costs and benefits of the involved partners will be evaluated both from a short- and long term perspective.

An adequate research design with well suited research instruments for monitoring and evaluating technology-induced organisational adaptation processes will be developed and applied. The interaction of humans with the new technology and its operation will be investigated (e.g. How do technicians with diesel experience respond to a hydrogen-powered vehicle with an electric powertrain? Do they feel safe working with it?). Also under investigation are strategies in use that have to be adjusted to the new technology within a company. These questions will be addressed within the whole supply chain affected by the technological innovation.

In parallel to these more organisational issues, the functionality of the technology in practice will be evaluated as well as a pragmatic and preliminary cost assessment will be conducted. Also, operators' acceptance, reactions of stakeholders as well as public awareness will be evaluated.

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ZEMShip

Jesse Schneider, **Sebastian Dirk**, Proton Motor, Germany

Abstract

On August 29th, 2008, the first commercially used fuel cell passenger ship has been put into service on the Alster lake in Hamburg. From now on up to 100 passengers will be able to enjoy their ride on the inner city lake and its connected canals-without generating any local emissions.

1 Introduction

Zemships (Zero Emission Ships) is a joint project carried out by nine partners and headed by the Ministry of Urban Affairs and Environment of the Free and Hanseatic City of Hamburg. The budget of Project Zemships, which has been started in 2006, amounts to 5.5 million Euros. 2.4 million Euros of the overall budget have been co-financed by the European Union. The other part of the Zemships budget is contributed by its partners. This poster session will describe the technology behind the ZEMShips project.

The hybrid fuel cell propulsion system of Zemships comes from Proton Motor. Its key components are:

- 48 kW (peak) fuel cell system *PM Basic A50* using the proprietary fuel cell stacks by Proton Motor
- Hydrogen tanks at 350 bar for three days of operation (typical)
- Batteries as energy storage for buffering and peak load „shaving“
- Energy management system and fuel cell controls for optimally efficient operation

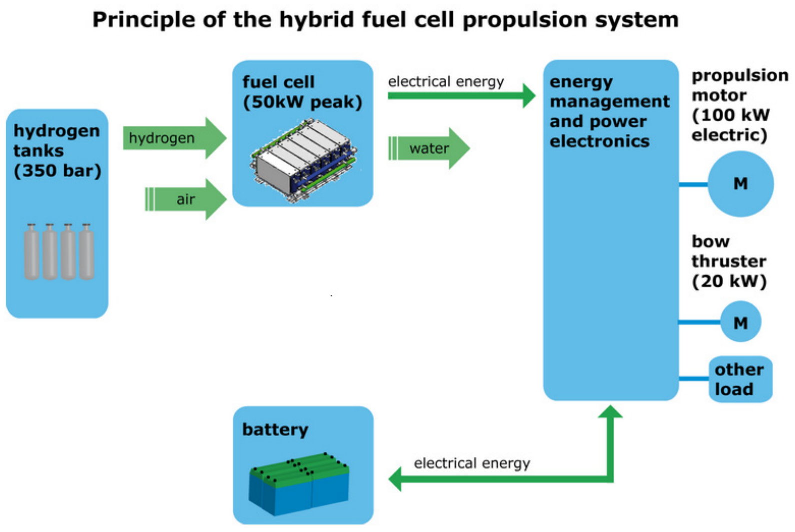


Figure 1: Principle of the hybrid fuel cell propulsion system.

2 Clean and Energy Saving

From the innovative drive system, because the vessel produces no exhaust gases and is very quiet in operation.

The drive system is projected to run almost twice as efficient as a conventional diesel powered ship on the typical routes in Hamburg.

3 Fuel Cells

Fuel cell systems combine efficient fuel utilization and, due to the use of hydrogen as the energy source, environmentally friendly operation. Additional characteristics of the systems are a high level of efficiency coupled with advantageous partial-load and load-change behavior. These electro-chemical energy converters generate absolutely no emissions - the product of the electrochemical conversion process in the fuel cells is simply pure water. Zemships is powered by a PM Basic A 50 fuel cell system by Proton Motor with 48 kW peak.

Proton Motor has developed the fuel cell system *PM Basic A 50* and its fuel cell stacks dedicated for the use in commercial vehicles. The liquid-cooled PEM fuel cell systems (PEM = Proton Exchange Membrane) feature a particularly simple, sturdy and modular construction. This enables them to cover a wide range of applications. Another core component is an integrated, low-energy water management system. Thus, external humidification is not required.

4 Hybrid System

The integrated battery package takes surplus energy from the fuel cells, for example when the ship is stopped at an interim port and requires less power. When the ship needs maximum power for example during casting-off and coming aside maneuvers the batteries supply the energy back to the engine. An intelligent energy management system controls the division of work between fuel cells and battery. Thus the hybrid system ensures maximum efficiency of operation and lifetime with minimized cost.

5 Hydrogen Storage System

The hydrogen is stored on board in 350 bar pressure tanks. The 50 kg of hydrogen stored provide enough energy so that the ship only needs to be refueled about once every three days

6 Experience

With over 10,000 passengers carried over the past few years, the ZEMship has collected over a thousand hours of experience in real world, daily operation. The ZEM ship is planned to be run another 2 years, while collecting valuable information for the next generation systems.

Figure 2

Hydrogen Internal Combustion Engines

H. Eichlseder, P. Grabner, and R. Heindl

Abstract

Over 100 years of development maturity, dual fuel capability and insensitivity to fuel purity distinguish the internal combustion engine as an interesting concept for direct conversion of hydrogen into useful mechanical work – particularly as a bridging technology while an H_2 infrastructure could be constructed. Within this chapter the state of the art in hydrogen engines is presented by example of vehicles from different manufacturers. The physical properties of hydrogen make it an excellently suitable fuel for use in internal combustion engines and lead to a broad range of possible mixture preparation concepts. A brief introduction of these concepts is given together with a theoretical comparison of their respective potentials, advantages and challenges. Consequently, aside from existing vehicle solutions extensive theoretical work is going on at universities and research facilities, yielding to increase power output and engine efficiency. A few results and examples intend to give a brief overview of the recent hydrogen combustion system development for the ICE.

Visualization of Knocking Combustion in a Hydrogen Spark-Ignition Engine

Mithun Kanti Roy, **Nobuyuki Kawahara**, **Eiji Tomita**, Okayama University, Japan

1 Introduction

Internal combustion engines which use hydrogen as a fuel will play a major role in the future automotive propulsion systems. Hydrogen has a wide flammability range and high burning velocity for combustion in a Spark-ignition (SI) engine. Its wide flammability range provides smooth engine operation at a very lean mixture with a low NO_x level. In addition, its high burning velocity may contribute to a relatively high thermal efficiency with a shorter combustion period at the ignition timing close to top dead centre (TDC). However, the extremely rapid combustion of hydrogen causes abnormal burning such as knocking, pre-ignition and backfiring at higher loads reducing the engine reliability and limiting the engine power [1]. Numerous investigations have shown that the onset of knock, which is caused mainly by the autoignition of the unburned end-gas before being consumed by the propagating flame. The autoignition of the end-gas also creates a rapid increase in pressure, which sets up a pressure wave that impulsively acts against the cylinder walls and then oscillates at the resonant frequency about 5-7 kHz [2]. The aim of this work is the investigation of the phenomena occurring during the knock initiation and development period through the visualization and spectrum analysis in a hydrogen spark-ignition engine. A specially designed hydrogen fuels rapid compression and expansion machine (RCEM) that could only be fired once was used for the experiment. The experiments clearly show that the location where autoignition occurred was identified from the high speed direct images by their brightness in the end-gas region. The chemical luminescence emissions such as OH* radical were detected due to hydrogen oxidation during knocking combustion.

2 Experimental Apparatus and Method

In this study, RCEM that can only be fired once was used to investigate end-gas autoignition and combustion characteristics of hydrogen. The bore and stroke of RCEM are 78 mm and 85 mm respectively with a pancake combustion chamber and a compression ratio of 9.0:1. The engine was operated at 600 rpm by a controllable electric motor. Figure 1 shows a schematic diagram of the experimental set-up used in this study. Initially, a homogeneous H_2-O_2-Ar mixture was introduced into the mixture tank and engine cylinder, which were connected by a pipe, at an initial pressure P_0 through an open valve with the piston set at TDC. The specific heat ratio of Ar gas is much higher than that of N_2 so that in-cylinder mixture temperature at the TDC is much higher than that of air. The initial pressure P_0, of the mixture was varied from 40 to 60 kPa and the initial temperature was maintained at 323 K. The pre-mixed gas was ignited by an electric spark at crank angle θ_{IT}. In-cylinder pressure was measured with a Kistler 6052C piezo-electric transducer. The RCEM has a cylindrical quartz window 32 mm in diameter positioned on the top of the cylinder head. The window is on the opposite side from the spark electrode as shown in Fig. 1. In-cylinder combustion images were captured by two types of high-speed video cameras: a high-speed colour video camera (Memrecam GX-1, NAC Image Technology) with a resolution dependent on the camera speed, and a monochrome camera (HPV-1, Shimadzu Hyper Vision) with a resolution of 316 × 260 pixels. Chemiluminescence signal was obtained using two spectrometers (Oriel MS257™ and Andor Technology SR 163i) equipped with an Intensified CCD (Andor Technology, DK720-18F-04, 1024 X 156 pixels).

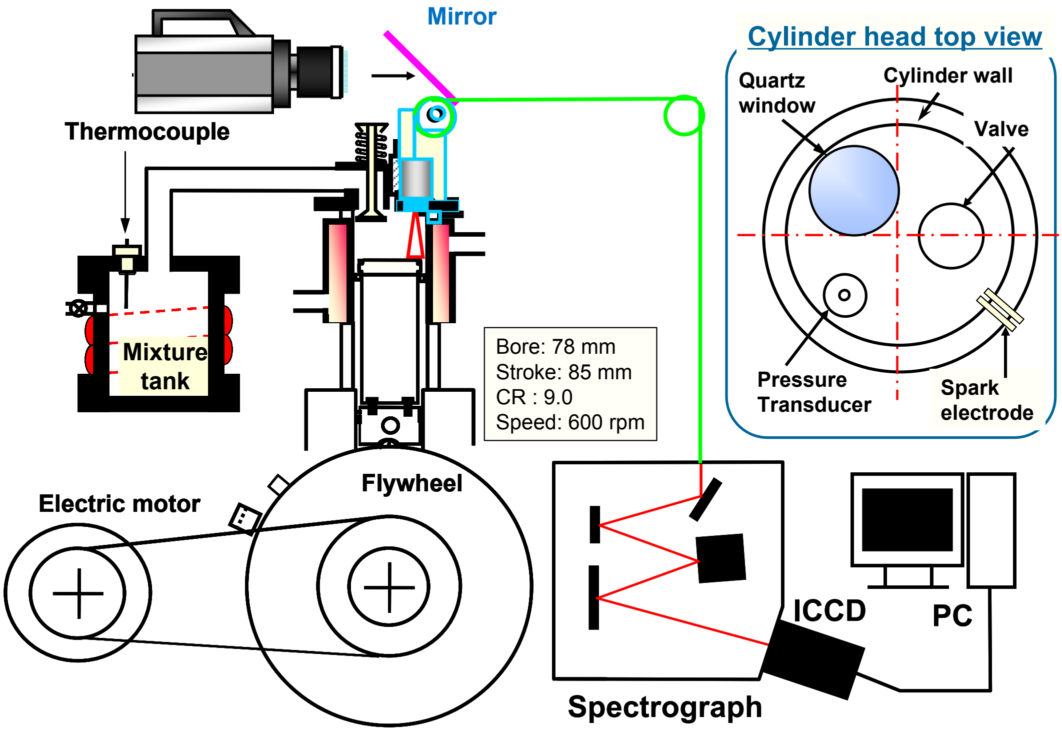
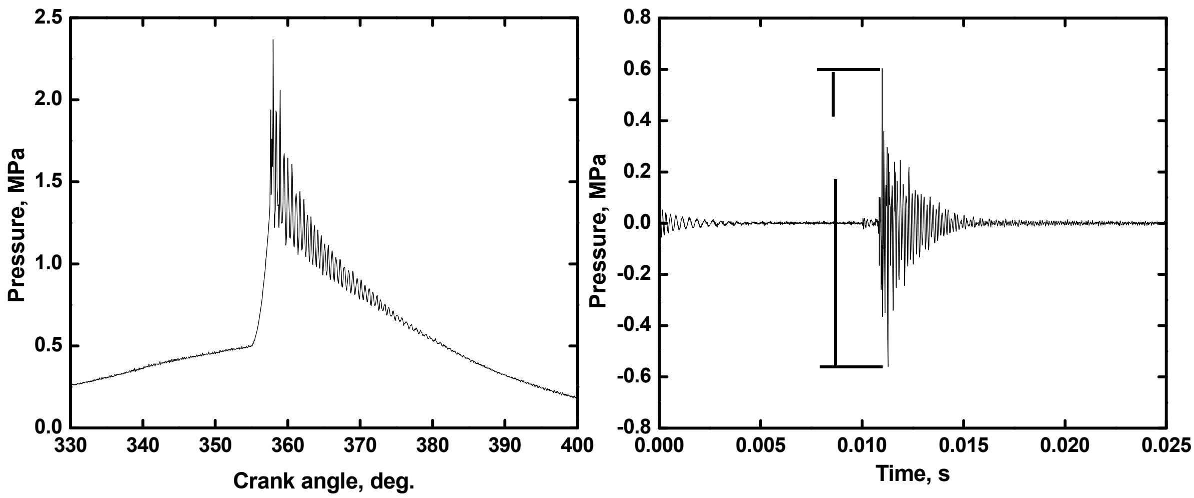


Figure 1: Schematic diagram of the specially designed rapid compression-expansion machine with a high-speed photography and spectroscopy system.

3 Result and Discussion

Combustion in an SI engine can occur as a normal or abnormal phenomenon, depending on the engine operating condition. In this experiment, H_2-O_2-Ar mixtures developed different pressure histories during knock combustion due to differences in the energy release rate, which was affected by the amount of unburned fuel and the mixture composition in the end-gas. Figure 2(a) shows a pressure versus crank-angle diagram plotted using in-cylinder pressure data. Here knock is distinguished by strong pressure oscillations that occur near the maximum pressure and continue for part of the expansion stroke. Pressure pulsation in engine cylinders - during normal combustion in a SI engine cylinder pressure progressively increase during combustion process. In knocking combustion, a sharp increase in pressure occurs when the end-gas is autoignited before the flame front reaches the cylinder wall. The knock intensity (KI) in this research work was calculated using the pressure data by using digital butterworth band-pass filter with 2.5 kHz cutoff frequency. KI has to be defined, peak of the oscillation component of in-cylinder pressure. Figure 2(b) shows the filtered pressure traces with marking describing the point used for calculating KI. The rate of pressure rise had a discontinuity at the knock occurring crank angle and the bandpass-filtered signal started to increase just after the onset of knock.



(a) In-cylinder pressure oscillation. **(b) Time-series of knock intensity, KI**

Figure 2: In-cylinder pressure history and the knock intensity. (H_2-O_2-Ar, Φ =1.0, θ_{IT}=355°, P_o=40kPa)

In general, pressure measurements provide global information and do not indicate the species involved in knocking. Figure 3 shows the time-series images at a specific crank angle for both normal and knocking combustion cycles with typical in-cylinder pressure histories. The upper images of this figure correspond to the normal combustion cycle (H_2+air mixture) whilst the lower images correspond to the knocking combustion cycle (H_2+O_2+Ar mixture). During the normal cycle after the spark ignition, a premixed low luminous flame was observed. Figure 3 shows that the flame gradually propagated from the lower right side to the upper left side of the combustion image (frames A to D). Flame front propagation for the normal cycle was very smooth and no signs of autoignition were visible in the end-gas region.

In the knock cycle after the spark ignition, a spark-initiated blue-colour flame propagates into the end gas, in which preknock oxidation develops. During this process it is noticed that flame hesitates to propagate into the end-gas and a propagating flame does not spread as a semicircular flame front in a uniform way across the combustion chamber. A wedge-shape end-gas is always produced ahead of the flame front retardation in knocking cycle. It is assumed that the “stressed” end-gas will give a chemical inhibitory effect and cause the slowing down of the incoming propagating flame, this provide sufficient time for the end-gas autoignition. The autoignited kernel of the end-gas appeared in front of the propagating flame in the upper left corner of the frame G in Fig. 3. At the instance of knock, corresponding to frame H, the unburned end-gas region suddenly flashed white and expanded towards the burned gas region with high density pressure waves. The propagation of abnormal combustion is caused by autoignitive pressure wave [3].

The effect of cycle-to-cycle variation of engine combustion was evaluated by comparing knocking images for the same ignition timings, as shown in Fig. 4. The autoignition location near the cylinder wall fluctuated cycle-to-cycle, but remained inside the end-gas region, which was compressed by the propagating flame front. The exact location where autoignition occurred was identified from the high-speed color images by their brightness. In this experiment cylinder wall temperature was very low but most of the time the knock was generated in the end-gas region near the cylinder wall. We found that in hydrogen SI engine combustion at condition applied in this experiment, the knock occurrence region is near the cylinder wall in the end-gas region.

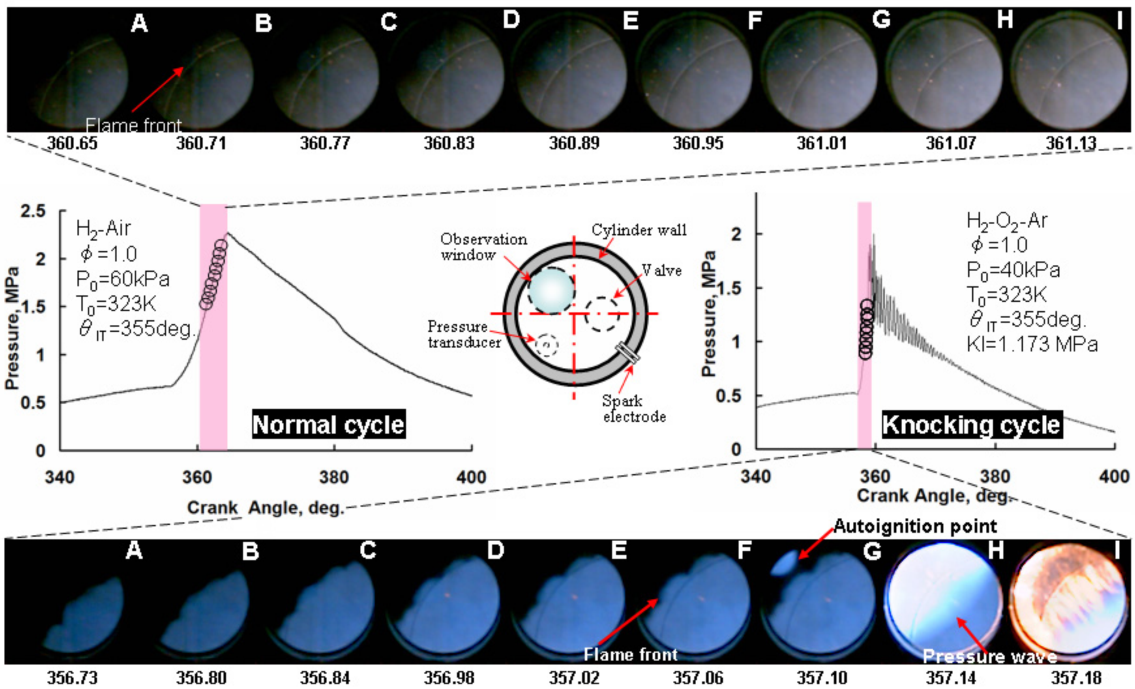


Figure 3: Time-series direct combustion images, including in-cylinder pressure histories for normal and knocking cycle taken at 80,000 frames per second.

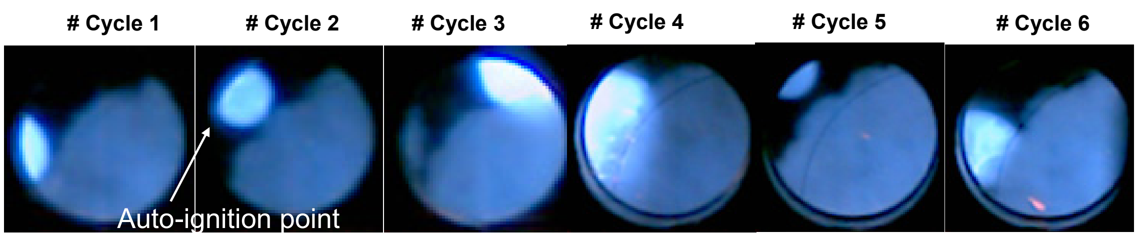
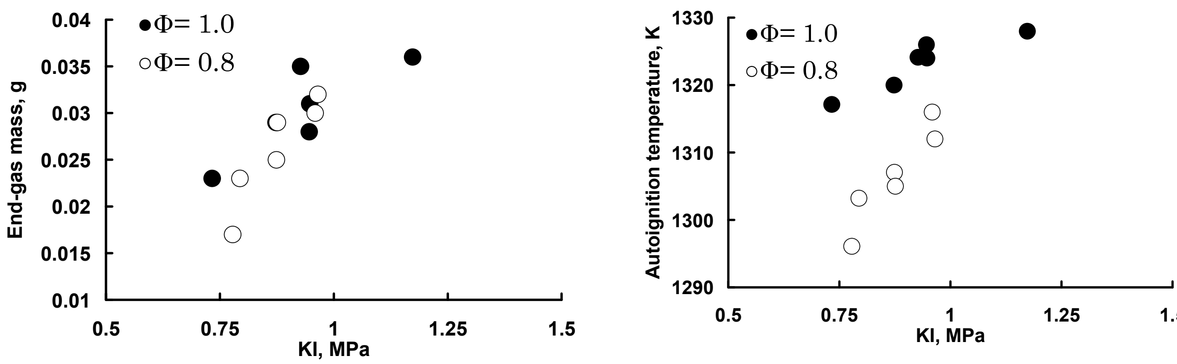


Figure 4: Cycle-to-cycle combustion images with the autoignited kernel in the end-gas region. (H_2-O_2-Ar, Φ =1.0, θ_{IT}=355°, P_o=40kPa)

Figure 5 shows the KI for different combustion cycles has a close relationship with the mass fraction of the unburned end-gas mixture and the autoignition temperature evaluated from the in-cylinder pressure. The volume of the unburned region could be estimated from the high-speed color images. The volume of the unburned region was determined from the image obtained before the appearance of autoignition inside the end-gas region. The volume of the unburned region was defined as (S0–S)x H, where S is the burned region obtained from the visualized images, S0 is the total area of the image, and H is the height of the combustion chamber. The mass of the unburned mixture was obtained using the mixture density estimated from the unburned gas temperature and volume. Figure 5(a) shows that large amount of the unburned end-gas mass leads the higher KI. Spark-initiated flame propagates into the end-gas in which preknock oxidation develops. The unburned gas temperature was estimated using the in-cylinder pressure with a two-zone model [4]. Autoignition occurred at the point with the maximum temperature, and then propagated throughout the entire volume. Figure 5(b) shows the relationship between the autoignition temperature and KI. Higher end-gas temperatures increased the autoignition reaction process and increased the chance of knocks occurring. Based on the captured images, it can be confirmed that the KI was strongly related to the mass fraction of the unburned end-gas and autoignition temperature.



(a) End-gas mass

(b) Autoignition temperature

Figure 5: KI relationship between the unburned end-gas mass and the autoignition temperature. (H_2-O_2-Ar, θ_{IT}=355°, P_o=40kPa)

The chemiluminescence emissions of the normal propagating flame and burned gas before and after the autoignition of the end-gas were obtained using spectrometer equipped with an ICCD. The measurement location was set based on the higher frequency occurrence of auto-ignition inside the end-gas region. Chemiluminescence is the natural light emission as the energy released from chemical reaction. The reaction mechanism for hydrogen combustion is rather easy compared with hydrocarbon combustion, leaving only OH* radical emission as the only practical measurement path. These excited species emit photon at discrete wavelength as they moved from higher excited energy states to lower energy state. Figure 6 shows the overall spectrum for knocking cycle obtained between wavelength of 200 and 800 at the end-gas and burned gas measurement location. This figure shows that OH radical emission was detected in the UV spectra near 309.4 nm as the energy released during chemical reaction before the end-gas autoignited and in the burned gas region there are two other peaks such as sodium (Na) and potassium (K) near 589 and 767 nm respectively.

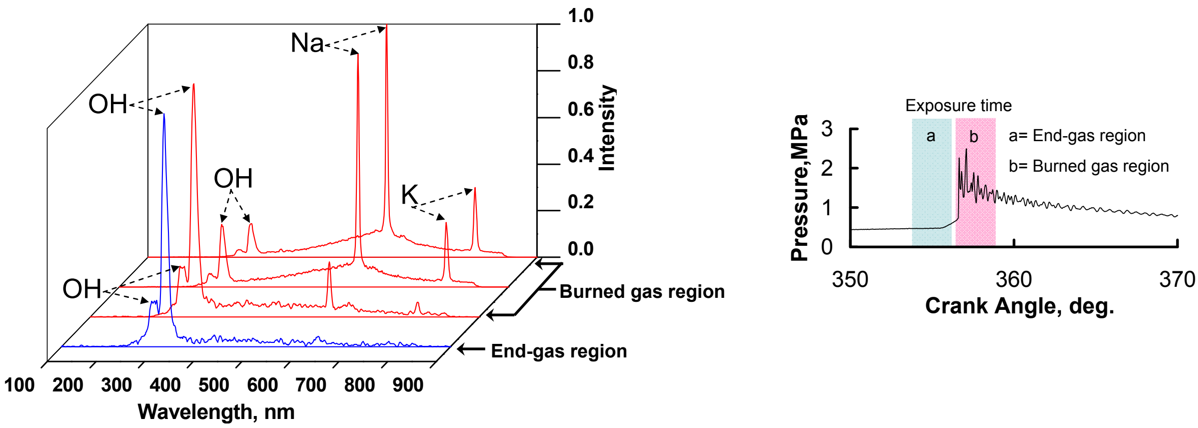


Figure 6: Overall spectral profile for the end-gas and burned gas region during knocking cycle. (H_2-O_2-Ar, Φ =1.0, θ_{IT}=355°, P_o=40kPa; Grating= 150 line/mm, Center wavelength= 500nm, Exposure time= 2ms)

The emission peaks of Na and K may be attributing to the combustion of lubricating oil that was noticed from the high-speed combustion images. The water molecule (H_2O) is very stable and may assume to be formed at about over 600 nm as the end product of the reaction possessing excessive energy. Figure 7 shows the overall spectrum for non-knocking cycle combustion obtained between wavelength of 200 and 800 nm at the burned gas region. As shown, there are two significant peaks of OH radical in UV spectra and also other emission peaks of Na (near 589 nm) and water vapor (over 600 nm). At the end stage of the burned gas region during non-knocking combustion, the other peak of K at 770 nm was detected as shown in Fig. 7. Figure 8 shows the UV spectra band of OH* radical emissions at knocking combustion during different periods, before and after autoignition. There are four strong main band heads R1, R2, Q1 and Q2 at 306.36 nm, 307.77 nm, 307.88 nm and 309.04 nm respectively, corresponding to the diatomic molecular transition ($A\ ^2\Sigma \rightarrow X\ ^2\Pi$) [5]. As shown in Fig. 8 two bands of OH* radical emission were detected just before the autoignition at wavelengths of 282 and 307.84 nm, is the indication of the knock onset. It is thought that the flame doesn't reach the measurement point because there is a possibility of flame reflection. When the end-gas pressure and temperature increased sufficiently high by the compression of propagating flame front, then the OH* radical may be produced by thermal excited radical. Figure 8 also shows that after the autoignition OH* radical emission intensity becomes stronger with increasing pressure and temperature in the knocking combustion.

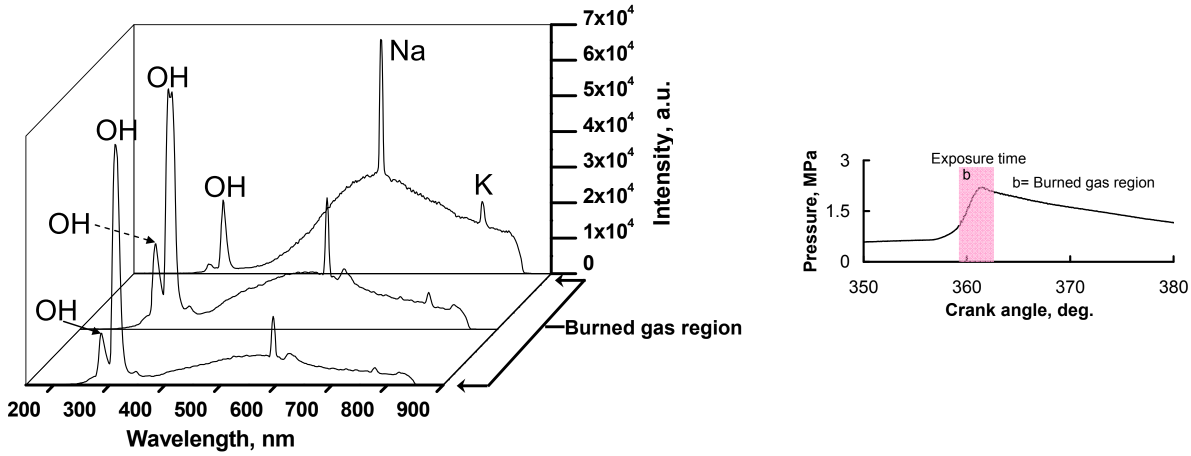


Figure 7: Overall spectral profile for the burned gas region during non-knocking cycle. (H_2-Air, Φ =1.0, θ_{IT}=355°, P_o= 60kPa; Grating= 150 line/mm, Center wavelength= 500nm, Exposure time= 2ms)

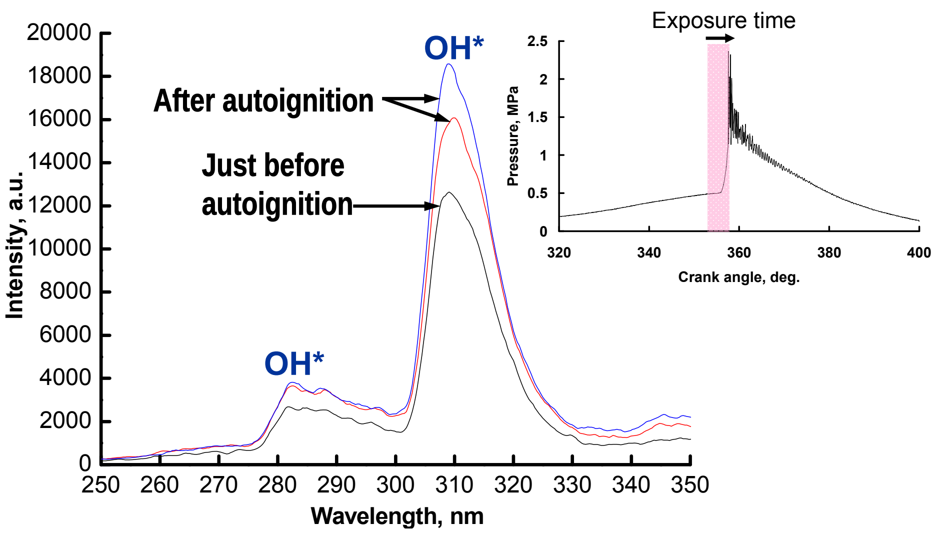


Figure 8: Experimental typical OH* spectra at just before and after knock combustion. (H_2-O_2-Ar, Φ =1.0, θ_{IT}=355°, P_o=40kPa; Grating= 300 line/mm, Center wavelength= 350nm, Exposure time= 2ms)

4 Conclusions

In this study, the experiments with RCEM were conducted to investigate autoignition and combustion behavior of hydrogen fuel based on in-cylinder pressure measurements, high-speed imaging and spectroscopy analysis. The following conclusions should be drawn from this experiment:

1. During knocking combustion, the autoignited kernel of the end-gas region that was compressed by the propagating flame front could be visualized. The direct photography can detect the precise position and brightness of the combustion flames that can not be observed by shadowgraph.
2. A large amount of unburned end-gas and a higher autoignition temperature has a good relationship with an increased KI.
3. We try to understand the hydrogen oxidation before the end-gas autoignition with the help of emission spectroscopy analysis. In the end-gas region OH* radical is the indication of the onset of hydrogen oxidation.

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Heat Transfer Comparison between Methane and Hydrogen in a Spark Ignited Engine.

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Abstract

Hydrogen is one of the alternative fuels which are being investigated at Ghent University. NO_x emissions will occur at high engine loads and they are a constraint for power and efficiency optimization. The formation of NO_x emissions is temperature dependent. Consequently, the heat transfer from the burning gases to the cylinder walls has to be accurately modelled if precise computer calculations of the emissions are wanted. Several engine heat transfer models exist but they have been cited to be inaccurate for hydrogen. We have measured the heat flux in a spark ignited engine with a commercially available heat flux sensor. This paper investigates the difference between the heat transfer of hydrogen and a fossil fuel, in this case methane. Measurements with the same indicated power output are compared and the effect of the heat loss on the indicated efficiency is investigated. The power output of hydrogen combustion is lowered by burning lean in contrast to using a throttle in the case of methane. Although the peak in the heat flux of hydrogen is 3 times higher compared to methane for a high engine power output, the indicated efficiency is only 3% lower. The heat loss for hydrogen at a low engine load is smaller than that of methane which results in a higher indicated efficiency. The richness of the hydrogen-air mixture has a great influence on the heat transfer process in contrast to the in-cylinder mass in the case of methane.

1 Introduction

Researchers worldwide try to find an alternative for fossil fuels to reduce the CO_2 emissions and to secure the energy supply. There is no silver bullet, so several possibilities are being investigated at Ghent University. One of them is the hydrogen-fuelled combustion engine. Research has proven that the combustion properties of hydrogen enable to achieve a high efficiency for all engine loads by using several operational strategies [1]. Moreover, hydrogen engines have near-zero noxious and zero greenhouse gas emissions. All this makes them an attractive alternative for the current drive trains.

The initial research at Ghent University was focused on the experimental optimization of engine operation strategies for maximum power and efficiency, with ultra low nitric oxide emissions [2-4]. The focus shifted to numerical research with the development of a thermodynamic model of the engine cycle, the GUEST-code (Ghent University Engine Simulation Tool) [5, 6]. Such a model of the engine cycle enables a cheap and fast optimization of engine settings for operation on hydrogen. Several sub models are necessary to solve the conservation equations of energy and mass: a combustion, a turbulence and a heat transfer model among other things. The last one is important to simulate accurately the emissions of oxides of nitrogen which are influenced by the maximum gas temperature.

These emissions will occur in hydrogen internal combustion engines at high loads and they are an important constraint for power and efficiency optimization.

Several heat transfer models for internal combustion engines exist in the literature. The models of Annand [7] and Woschni [8] are mostly used. They have however been developed for fossil-fuelled engines and they have been cited to be inaccurate for hydrogen engines [9-11]. The purpose of the current research is to investigate the cause of the difference in the heat transfer process and to indicate the missing components in the heat transfer models. We have measured the heat flux in a spark ignited engine with a commercially available heat flux sensor. The engine was run on hydrogen and methane to be able to compare the heat transfer process of hydrogen with that of a fossil fuel. The separate influence of the compression ratio, the ignition timing and the air-to-fuel equivalence ratio on the heat transfer of both fuels has previously been described [12, 13]. This paper compares measurements on hydrogen and methane with the same indicated power output. The power output for hydrogen was varied by altering the air-to-fuel equivalence ratio (λ). In contrast, a throttle was used in the intake manifold for methane to equalise the power output with the hydrogen measurements.

2 Experimental Equipment

The engine used for the measurements is a four-stroke single-cylinder spark ignited gas engine based on a CFR (Cooperative Fuel Research) engine operated at a constant speed of 600 rpm. It is equipped with port fuel injection (PFI) and has a variable compression ratio. The details of the engine are given in Table 1. A cross section of the CFR-cylinder is shown in Figure 1. Fuel injection and ignition timing are controlled by a MoTeC M4Pro electronic control unit.

We have used a commercially available sensor to measure the heat flux and wall temperature. It is a Vatell HFM-7 sensor which consists of a thermopile (heat flux signal, HFS) and an RTD (substrate temperature signal, RTS). The sensor has a response time of 17 μs. As the test engine is easily accessible, the heat flux sensor was installed in three different positions (P2, P3 and P4 as shown in Figure 1). These openings are placed at the same height in the cylinder wall and are equally distributed around the circumference of the cylinder. The spark plug was placed in position P1.

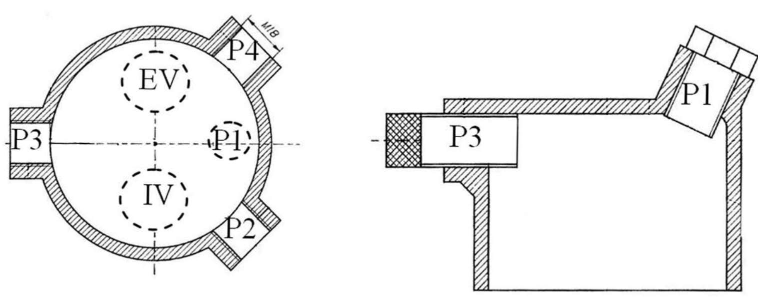

Figure 1: Cross section of the CFR engine, P1: spark plug position, P2-P4: sensor positions, IV: intake valve, EV: exhaust valve.

Table 1: CFR-Engine specifications.

Bore	82.55 mm
Stroke	114.2 mm
Connecting rod length	254 mm
Swept Volume	611.7 cm³
IVO	17 °CA ATDC
IVC	26 °CA ABDC
EVO	32 °CA BBDC
EVC	6°CA ATDC

In-cylinder pressures were measured with a water-cooled Kistler 701A piezoelectric pressure sensor and inlet pressure with a Kistler 4075A20 piezoresistive pressure sensor. This inlet pressure was used to reference the in-cylinder pressure around bottom dead centre (BDC) at the end of the intake stroke. A 12 bit data acquisition card was used to sample both the heat flux and pressure signals. It is triggered by a crank angle encoder every 0.5 °CA. This results in a sampling rate of 7.2 kHz. Gas flows were measured with Bronkhorst Hi-Tec F-201AC (fuel) and F-106BZ (air) flow sensors. Type K thermocouples were used to measure inlet and exhaust gas temperatures.

3 Results and Discussion

Three different air-to-fuel equivalence ratios for hydrogen were selected (λ = 1, 1.5 and 2). These three levels of mixture richness correspond with three different engine loads. The in-cylinder pressures are plotted in Figure 2 with a solid line in black, red and blue. An air-to-fuel equivalence ratio of 2 corresponded to an indicated work output (W_i) of 287J, which resulted in an indicated mean effective pressure (imep) of 4.7 bar. An air-to-fuel equivalence ratio of 1.5 gave 327J (imep=5.3 bar) and the stoichiometric combustion (λ=1) resulted in 376J (imep=6.1 bar). These three engine loads were repeated for methane and the results are plotted in Figure 2 as well, with a dotted line and in the corresponding colours of black, red and blue.

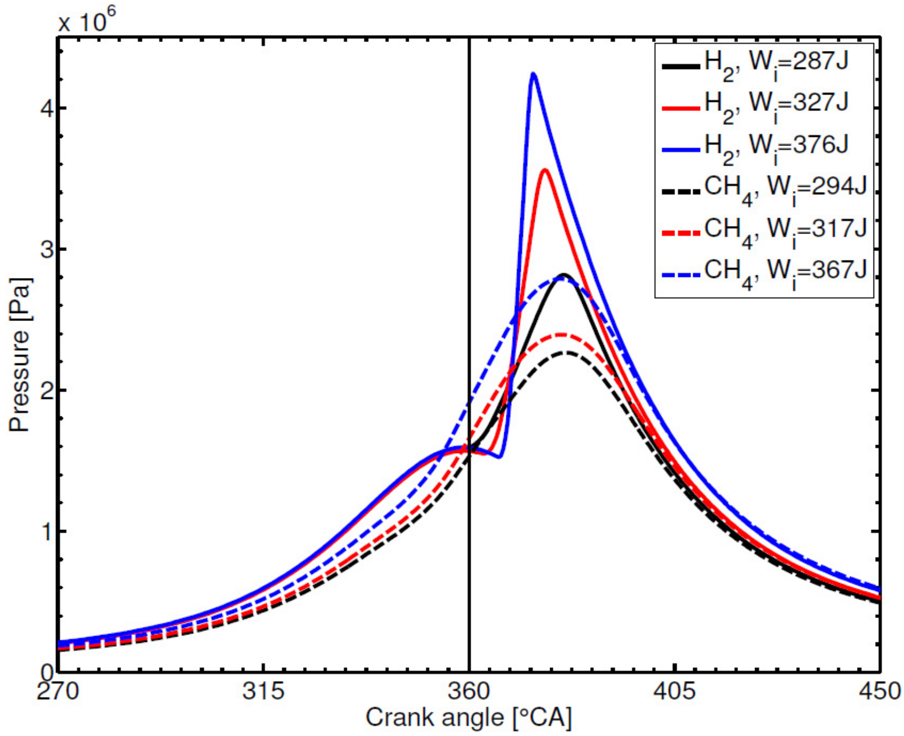

Figure 2: The pressure traces demonstrate the difference in combustion behaviour. Hydrogen burns faster than methane which causes the pressure trace to soar and to reach a higher maximum.

Methane combustion does not allow a variation of the air-to-fuel equivalence ratio in a wide range so a throttle in the intake manifold had to be used to decrease the power output, λ is kept equal to one. The throttle position can be varied between 0 and 90°. A change in the position between 0 and 70° does not have an effect on the power output because of the very small engine speed (600 rpm) and hence small air flow into the engine. A further small change in the throttle position has a large effect on the power output, so it is difficult to equalise accurately the power output with the hydrogen measurements. The throttle position of the methane measurement with a work output of 294J was 77°, that of 317J was 76° and that of 367J was 74°.

The pressure traces in Figure 2 show the difference in the combustion characteristics between hydrogen and methane. The hydrogen mixture burns very fast which causes the pressure to peak in a short time, the peak pressure goes up to 42 bar. Methane burns slower and this results in a wider pressure trace and a lower peak, up to 28 bar. The combustion properties have an influence on the chosen ignition timing. All the measurements were taken with ignition timing at MBT (minimum spark advance for Maximum Brake Torque). This MBT-timing is 23° ca before TDC for methane (not affected by a throttle variation) and it varies between 4° ca before TDC (λ=2) and 6° ca after TDC (λ=1) for hydrogen.

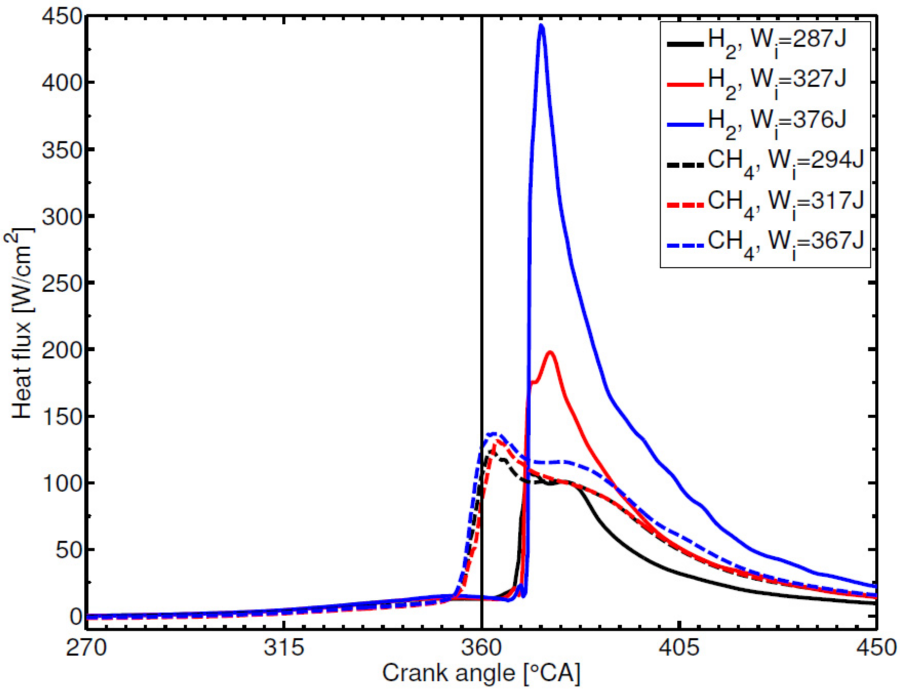

Figure 3: Varying the engine load by 23% results in a variation of 80% in the heat transfer of hydrogen and only 13% in that of methane due to the difference in load control.

The corresponding heat flux measurements in position P2 are plotted in Figure 3, those of hydrogen with a solid line and those of methane with a dotted line. The initial rise in the heat flux traces is caused by the flame passage over the measurement position. Although the flame speed is slower for the leanest hydrogen measurements (black colour), the initial rise occurs at the same moment of the stoichiometric measurement (blue colour) due to the advanced ignition timing. The fast and short combustion of the stoichiometric hydrogen mixture generates a high peak in the heat flux trace. This peak greatly reduces with decreasing mixture richness. The peak in the heat flux trace reduces with 80% if λ is changed from 1 to 2. The resulting power output decreases with 23%. In contrast, the heat flux traces of methane remain almost the same. Reducing the in-cylinder mass has a large effect on the resulting power output, but not on the heat transfer. The heat transfer does decrease when the load is reduced, but not as much as expected. The extra turbulence generated by the throttle could be the cause, because the same trend was visible in measurements under motored conditions [12]. The mixture richness on the other hand has a great influence on the heat transfer process. The peak in the stoichiometric heat flux trace of hydrogen is 3 times higher compared to methane, but it is smaller if λ is equal to two. The difference in the heat transfer process is reflected in the indicated efficiency of the engine. To demonstrate this, an estimate of the total cycle heat loss is calculated assuming that the heat flux at P2 represents the heat flux over the entire cylinder wall. Each sampling point of the heat flux trace is multiplied with the available in-cylinder surface at that instant and all these values are summed up to calculate the total cycle heat loss. These results are given in Table 2 together with the details of the measurements. For hydrogen the total cycle heat loss decreases from 597J to 235J if the power output is reduced from 367J to 294J, which is a reduction by 61%. The heat loss through the cylinder walls for methane reduces from 386J to 343J which is only a reduction by 11%.

Table 2: Details of the measurements.

fuel	ignition (°ca BTDC)	λ	throttle	W_i (J)	imep (bar)	η_i (%)	heat loss (J)
hydrogen	4	2	WOT	287	4.7	29	235
methane	23	1	77°	294	4.8	25	343
hydrogen	-2	1.5	WOT	327	5.3	26	353
methane	23	1	76°	317	5.2	25	329
hydrogen	-6	1	WOT	376	6.1	23	597
methane	23	1	74°	367	6	26	386

The indicated efficiency is lower for hydrogen in the case of the highest power output, 23% compared to 26% for methane due to the higher heat loss. The high efficiency caused by the fast combustion process of hydrogen counters partially the high amount of heat loss through the cylinder walls. Although there is a difference of 10% in the total cycle heat loss between hydrogen and methane at this power output level, there is only a difference of 3% in the indicated efficiency. The indicated efficiencies for both fuels are almost the same for the middle power output. The indicated efficiency of hydrogen is higher than that of methane for the lowest engine load, 29% compared to 25%. All this demonstrates the advantages of hydrogen as a fuel. The combustion properties enable a high efficiency for low engine loads, because there is no need to use a throttle. The efficiency is lower for the highest engine load in this case, but supercharging in combination with external gas recirculation could be a solution to attain high engine loads without high heat losses [14].

4 Conclusion

This paper has presented heat flux measurements in a spark ignited engine. The engine was run on hydrogen and methane to compare the heat transfer of hydrogen and a fossil fuel. Measurements with the same power output have been put side by side. The results showed that the heat flux of hydrogen decreased substantially if the equivalence ratio (and therefore the engine load) was reduced. In contrast, the heat flux of methane did not decrease that strong if the in-cylinder mass was reduced to attain lower engine loads. The peak in the heat flux was much higher for hydrogen compared to methane for the highest power output, but it was lower for the lowest power output. The mixture richness clearly has a large influence on the heat transfer process in contrast to the in-cylinder mass which was controlled by a throttle in the intake manifold. Total cycle heat losses have been calculated out of the measured heat flux traces. This paper has shown that the trends in the heat flux losses were reflected in the indicated efficiency which was lower for hydrogen compared to methane for the highest power output, but it was higher for the lowest engine load. The extremely high heat losses generated by the combustion of a stoichiometric hydrogen-air mixture will have to be reduced to improve the engine's efficiency at high loads.

Acknowledgements

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Implications of Combustion Parameters on the Performance of a Hydrogen-Fuelled Research Engine

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Abstract

This paper highlights part of the continuing R&D activities being carried out in the Engines and Unconventional Fuel Laboratory of Indian Institute of Technology for several years. Several engine configurations have been built up and widely tested to generate optimum performance and low-emission characteristics without any symptoms of undesirable combustion phenomena such as backfire and rapid rate of pressure rise. The results described in this paper centre round the experiments conducted on a research engine to study the effect of some critical operating parameters such as air-fuel ratio, ignition timing on the cylinder pressure and heat release rate using neat hydrogen gas. During these tests it was observed that an appropriately designed timed manifold Injection(TMI) system was extremely effective not only in getting rid of backfire, but also in ensuring ultralean operation resulting in drastic reduction in NOX emission level. An integrated control of several operating parameters showed that the if the engine was operated with fixed injection duration, peak pressure and rate of pressure rise showed an increasing trend with advanced spark timing. This could be due to the high burning velocity of hydrogen.

1 Introduction

The world today is caught between two major crises arising out of depletion of fossil fuels and rapid environmental degradation due to combustion of fossil fuels. The hydrogen fuel provides an ultimate solution to these twin problems. High flame speed, minimum ignition energy, wide range of flammability limits and high calorific value are some of the distinctive properties of hydrogen which make it suitable for use in internal combustion engines. Oxides of nitrogen, the only pollutant of concern, can be drastically reduced by lean operation even though it reduces power output. Exhaustive experiments have been conducted on a research engine to study the effect of some critical operating parameters such as air-fuel ratio, ignition timing on the cylinder pressure and heat release rate.

2 Hydrogen as an Alternative Engine Fuel

Research and development activities related to hydrogen engine are being pursued in the Engines and Unconventional Fuel Laboratory of Indian Institute of Technology, Delhi, for a period of close to three decades [1-2].Hydrogen has several typical properties which make it suitable for use in internal combustion engines. This paper discusses on those aspects of system development and optimization, which are critical to smooth engine operation without any combustion related problems. Low minimum ignition energy and wider flammability range of hydrogen facilitates ultra lean operation of engine resulting in higher thermal efficiency and lower NOx emissions.

The smaller quenching distance of hydrogen (0.064cm) can increase the tendency for backfire since the flame from a hydrogen-air mixture more readily gets past a nearly closed intake valve, than a hydrocarbon-air flame. The burning speed of hydrogen is 2.37–3.25 m/s and it is nearly an order of magnitude higher than that of methane or gasoline (at stoichiometric conditions)[3]. Thus hydrogen fires burn quickly and, as a result, trend to be relatively short-lived.

Hydrogen - Air combustion is associated with some well-known undesirable combustion phenomena such as flashback, pre-ignition, and knocking [4-6]. Studies by C.A. MacCarley *et. al* [7] have shown that the hydrogen injection techniques such as direct cylinder injection and port fuel injection greatly reduce the chances of backfire. The results of the present investigation are in close agreement with some of these results .In the present set of experiments, timed manifold injection has been observed to be the most appropriate fuel induction mechanism for neat hydrogen-operated SI engine systems [8]. It has been shown that the timed manifold injection increase thermal efficiency and reduces NOx emissions for a neat hydrogen-operated SI engine.

3 Experimental Test Rig

Tests were carried in a single cylinder 4 stroke water cooled spark ignition research engine. The experimental setup consists of three parts: The Engine, the Dynamometer and the Electronic Control Unit. Timed manifold fuel injection was developed to supply the fuel to the engine. The schematic layout of the experimental setup developed in IIT Delhi is shown in figure 1.

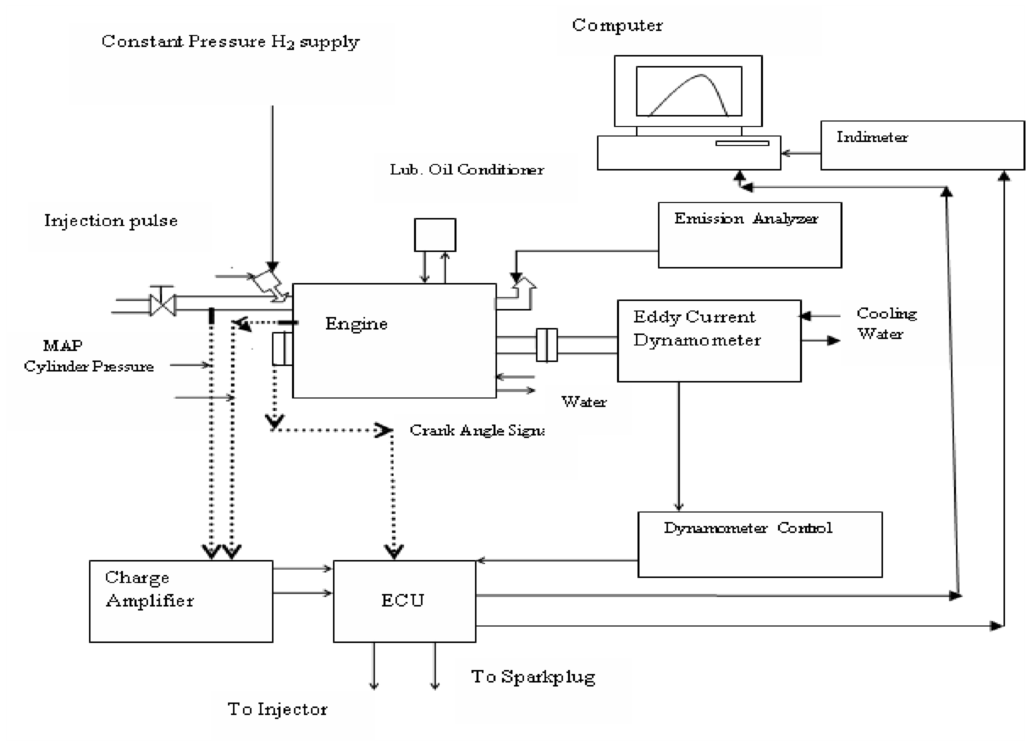

Figure 1: Schematic Diagram of Experimental Setup.

4 Results and Discussion

Comprehensive test were conducted on AVL research engine which was operated with WOT condition at different speeds for fixed equivalence ratio. The effect of speed on the torque is shown in figure 2 for baseline gasoline and hydrogen fuel. As it is clear from the graph the torque is relatively higher for gasoline operation in comparison to hydrogen fuel. This could be due to the fact that gasoline-air mixture was in stoichiometric condition whereas hydrogen – air mixture was leaner during the tests. Thus the energy content per unit volume is more in gasoline in comparison hydrogen fuel.

Figure 3 shows variation of thermal efficiency with engine speed at wide open throttle condition(WOT). The Break thermal Efficiency (BTE) is observed to be more for hydrogen operation due to high burning velocity in comparison to low burning velocity of gasoline-air mixture.

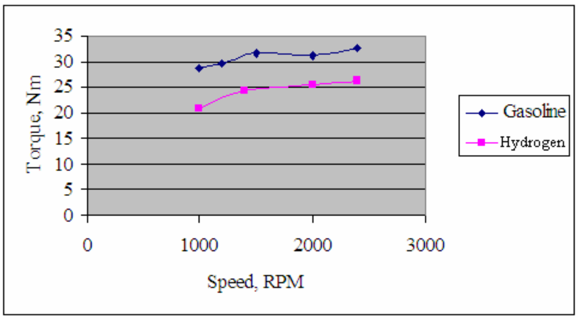

Figure 2: Engine Speed Vs Torque at WOT for gasoline and hydrogen fuels.

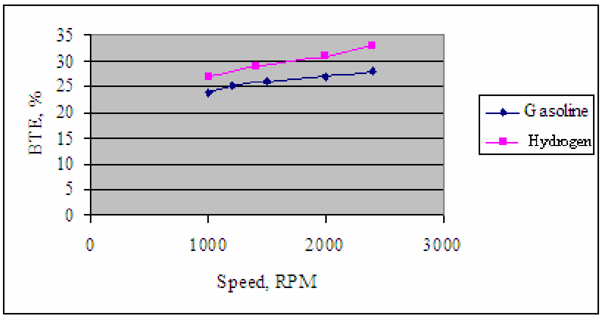

Figure 3: Engine Speed Vs BTE at WOT for gasoline and hydrogen fuels.

The engine was also operated at constant engine speed and fixed duration of injection. The increase in cylinder gas pressure and heat release rate was studied by varying the spark timing at this condition. From figure 4 and 5, it is observed that the cylinder gas pressure is less for the hydrogen operation than gasoline due to lower equivalence ratio and higher flame burning velocity. From the graph it is clear that for hydrogen the spark advancement is lesser compared to gasoline for smother engine operation without knocking. Knocking was observed when we increase spark timing beyond 26 deg of crank angle.

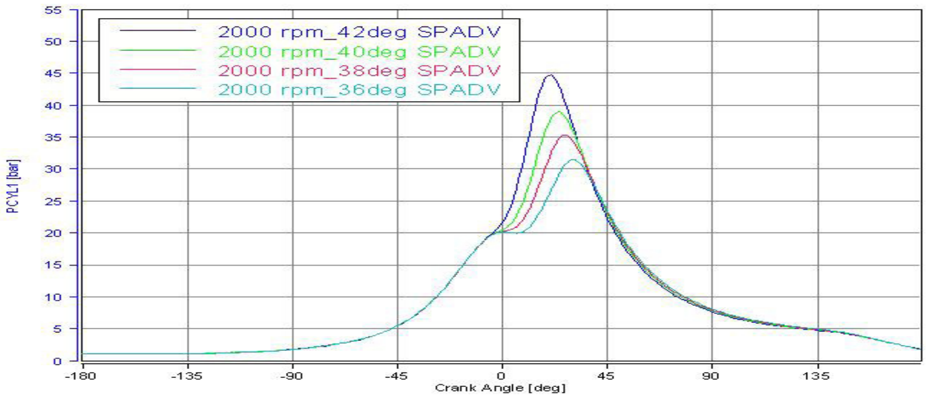

Figure 4: **Variation of cylinder gas pressure with crank angle at different ignition timing for gasoline fuel.**

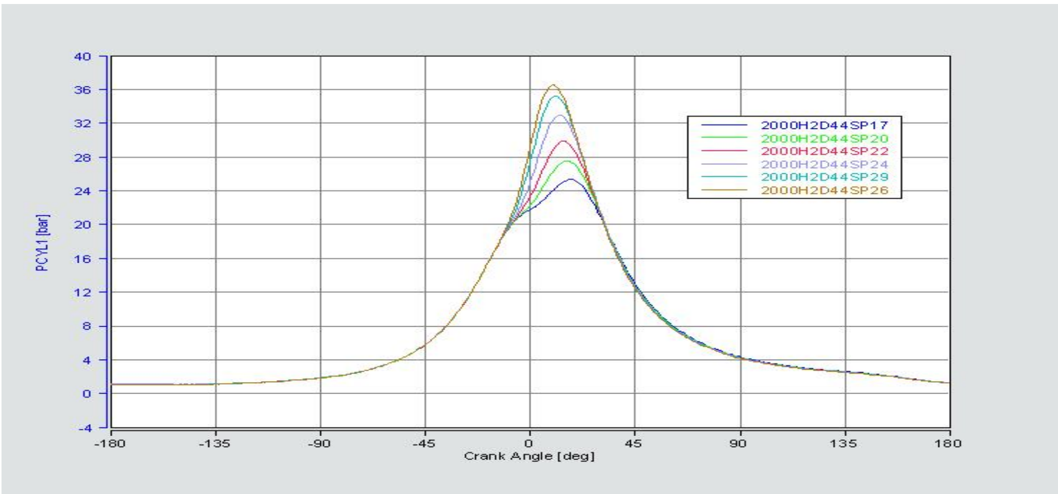

Figure 5: **Engine cylinder pressure Vs crank angle at different ignition timing for hydrogen fuels.**

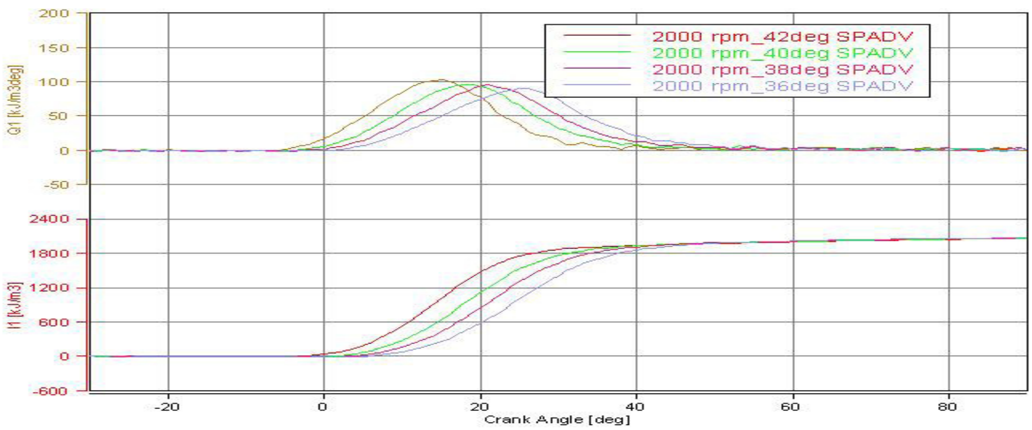

Figure 6: **Effect of Spark advance on Heat Release Rate at 2000 RPM engine speed.**

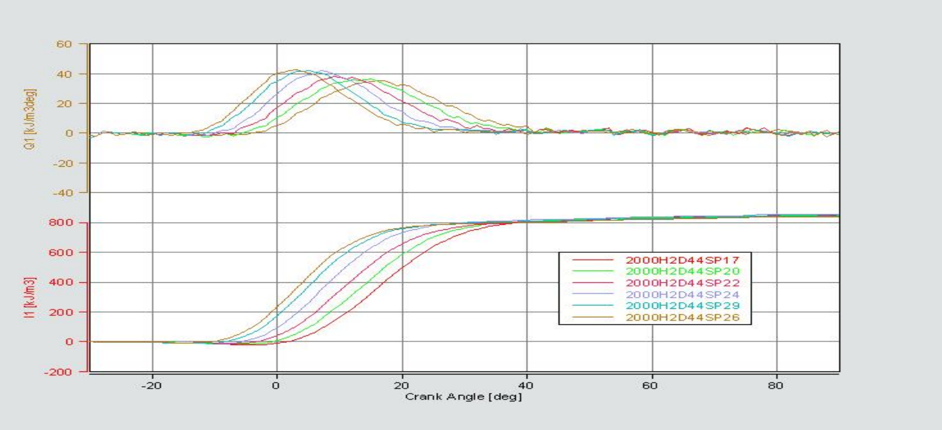

Figure 7: Effect of Spark advance on Heat Release Rate for hydrogen fuel.

From Figures 6 and 7 shows that the effect of spark timing on the heat release rate at 2000 rpm for gasoline and hydrogen fuels. Heat release will be less in hydrogen operated engine because of lean mixture is about 0.5 to 0.6 equivalence ratios in comparison to stoichiometric fuel air in the case of gasoline operation.

5 Concusions

Tests have clearly shown that hydrogen can be a used in the existing designs of internal combustion engines without any major modification in the existing engine. An appropriately designed timed manifold injection system can ensure neat hydrogen SI engine without any undesirable combustion phenomenon such as backfire. BTE will be more for hydrogen operation due to higher burning velocity and improved combustion in comparison to gasoline air mixture. Cylinder gas pressure is more for gasoline operation due to stoichiometric fuel air mixture burning.

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Sewage Sludge Based Producer Gas of Rich H_2 Content as a Fuel for an IC Engine

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Abstract

The manuscript presents investigation on hydrogen rich gas combustion in an internal combustion (IC) engine. The gas is obtained from gasification process of sewage sludge which is by-product of waste water treatment in a municipal sewage treatment plant. Recently introduced EU regulations of environmental protection do not allow to use such sludge as a soil fertilizer or substance for landfilling the ground due to its biological toxicity. On another hand, this sludge contains organic content of approximately 45-55% and from this point of view the sludge looks as an attractive material for fuel production through its gasification. This technology, primarily applied for wood gasification, has been also successfully implemented for gasification of sludge. It was found that the producer gas obtained in this way is rich of hydrogen content even up to 25%. This is because of high water content in the sludge that provides favorable conditions for steam reforming resulting in increase of hydrogen in the products of gasification. The high hydrogen content in the producer gas can lead to improper combustion particularly when the combustion takes place in the internal combustion engine. That improper combustion might appear as combustion knock and it is the main problem for the engine in which hydrogen is used as a fuel [1]. Onset of the knock during combustion contributes to rapid increase in heat transfer to the piston crown causing the piston to be quickly overheated that leads to surface erosion and damages. Additionally, engine body vibration coming from the knock significantly shortens engine durability. Conclusions from this investigation provide good premises for combusting the sludge producer gas in the IC engine without any improper combustion anomalies, thus considers this gas as worthy fuel for a stationary engine driven a power generator. The presentation shows results of producer gas combustion in both the spark-ignited and the compression ignition engine with particular focus on engine working cycles repeatability and potential knock onset. Additionally, these two quantities for methane, biogas (consisted of 65% CH_4 and 35% CO_2) and hydrogen combustion has been also determined. It was conducted for making comparison between these gases and the sludge based producer gas with respect to applying them as fuels for the IC engine.

1 Sewage Sludge Characteristics

The sewage sludge utilization is important because of the following:

- greenhouse effect (methane emission),
- stink (fermentation and putrid processes),
- bacteriological contamination of water and soil when sludge is landfilled.

It has been stated that the organic content in the municipal sewage sludge is high enough to justify its further thermal utilization. The organic content in the sludge can exceed more than

50% by mass after its drying [2,3]. Then, it can be satisfactory gasified in the gasification reactor. As a result of this thermal treatment the sewage sludge can be neutralized and the producer gas is generated. In the table 1 there are properties of dry and wet sludge. The table 2 contains properties of the exemplary producer gas with high H_2 content in terms of hydrogen combustion knock investigation.

Table 1: Municipal sewage sludge properties [2].

Property	Percentage	Municipal Sewage Sludge	
		Wet	Dried
Moisture	%	79 - 80	11.3 - 13.2
Ash	%	7.1 – 8.8	30.5 - 36.3
Sulphur	%	0.30 – 0.31	1.29 -1.30
LHV (Low Heating Value)	MJ / kg	0.62 - 0.67	10.9 - 11.4

Table 2: Composition of the producer gas.

Composition of the producer gas	Percentage by volume	Percentage by energy content
Hydrogen	16 %	50 %
Carbon monoxide	13 %	19 %
Carbon dioxide	16 %	0 %
Methane	3 %	31 %
Nitrogen	52 %	0 %
Molar Weight	26.04 kg/kmol	
LHV	3.4 MJ/Nm^3	
A/F stoic (by volume)	0.98 Nm^3/Nm^3	

2 Gasification System

Chemical energy contained in the sewage sludge will be converted to electrical energy and heat in the steps as follows (Fig 1.):

- gasification of the sewage sludge after preliminary drying,
- burning the producer gas in a CHP set including the IC engine driving a power generator for electrical energy production.

Usage of this gas as a fuel for the IC engine makes several difficulties due to low calorific value and unstable composition of the producer gas during sludge gasification. It contributes to unsteadiness of engine work [4]. There is also problem with tar content in the gas, however, it can be overcome through applying scrubbers and filters.

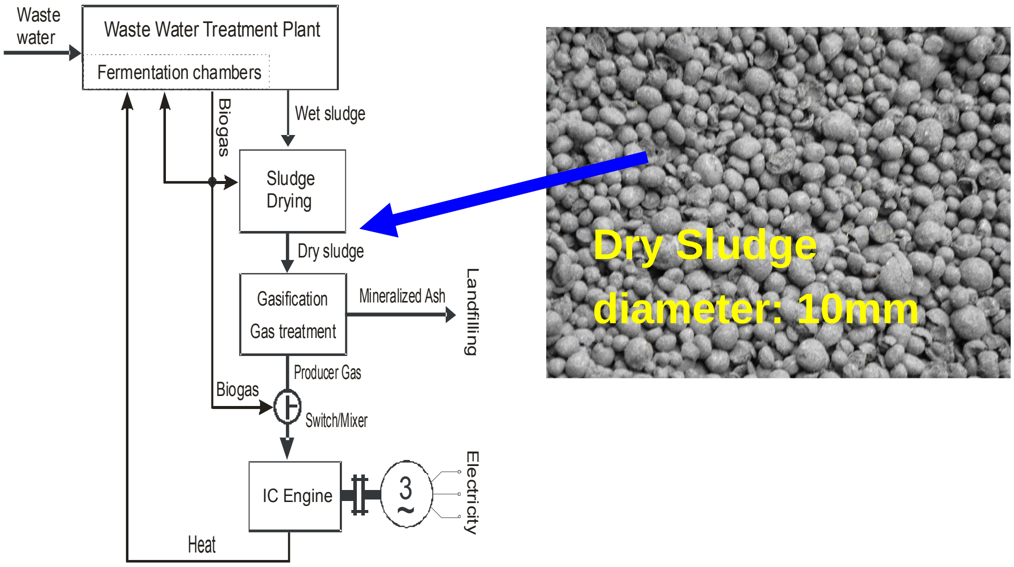

Figure 1: Diagram of sludge thermal utilization.

3 Combustion in the Internal Combustion Engine

The engine applied for the research:

a) modified Deutz FL511 to work as the spark ignited (SI) engine, swept volume: 825 cm^3, compression ratio CR = 8 or 12,

b) modified Deutz FL511 to work as the dual fuel compression ignition (CI) engine with diesel pilot of 15% (with respect to its nominal dose), swept volume: 825 cm^3, CR = 17 [5].

Exemplary in-cylinder pressure traces from 100 consecutive combustion events vs crank angle and averaged in-cylinder pressure vs cylinder volume are presented in the figures 2.a and 2.b. respectively. As plotted, the green coloured pressure traces come from retarded spark timing in the SI engine. On the contrary, red pressure traces are for spark timing which was too advanced.

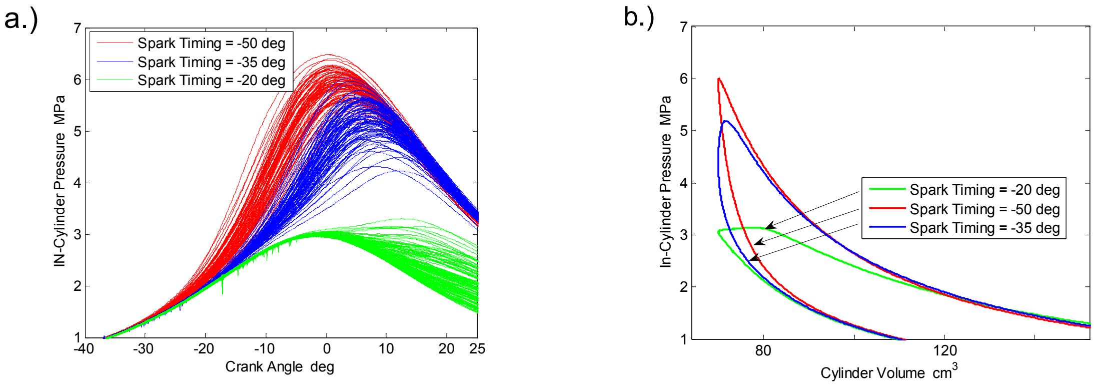

Figure 2: a) In-cylinder pressure history (superimposed 100 working cycles) for producer gas combustion in the SI engine at spark timing -20, -35 and -50 deg ATDC, CR=12, Relative air number λ=1.1, b) averaged p-v plots determined from the test series shown in the fig.2a.

As presented in the figure 3 the producer gas combusted at CR=12 is less sensitive to spark timing than the same gas combusted at CR=8.

The unrepeatability of engine work cycles can be expressed by the coefficient of variance of IMEP (COV IMEP). It is defined as follows:*COV IMEP %= standard deviation of IMEP / mean of IMEP*100%.*

The COV IMEP is depicted in the fig.4. As presented the high work cycles unrepeatability is observed for producer gas combustion at CR=8.

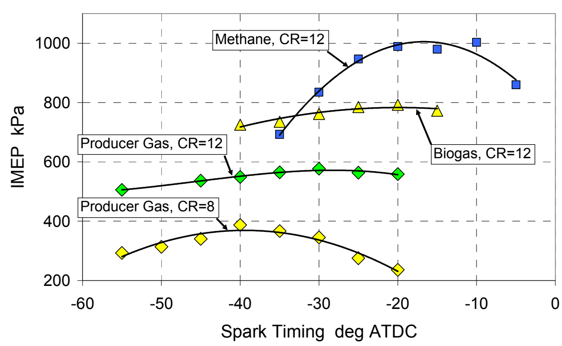

Figure 3: IMEP vs spark timing for the SI engine at nearly stoichiometric combustible mixtures.

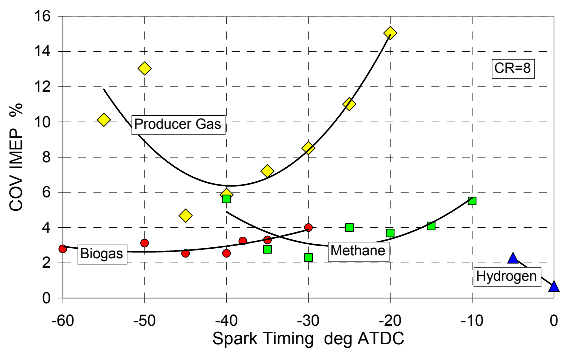

Figure 4: COV IMEP vs spark timing for the SI engine at CR=8 and nearly stoichiometric combustible mixtures.

Another potential problem concerns knocking during combustion. The knock combustion is abnormal combustion typical for SI engines and is mainly caused by spontaneous self-ignition of the combustible mixture during proper combustion process at its end phase. Intensity of the combustion knock can be expressed by peak value of high frequency oscillations of the in-cylinder pressure. Such the knock intensity was determined and presented in the fig.5. As seen, the producer gas is resistant to combustion knock even if it contains significant amounts of hydrogen, which, at favorable conditions, is prone to generate extremely high pressure oscillations during its combustion in the engine.

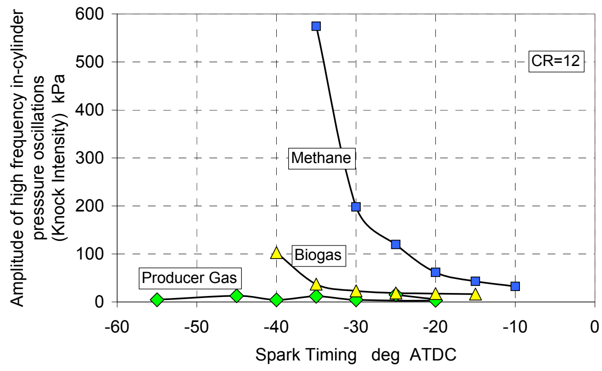

Figure 5: Knock intensity vs spark timing for the SI engine at nearly stoichiometric combustible mixtures.

Investigation presented here also includes gaseous fuels combustion in the dual-fuel CI engine with diesel pilot for ignition. Several in-cylinder pressure – crank angle plots are presented in the figure 6. Due to low calorific value of the producer gas both the peak pressure (fig.6) and the IMEP are relatively low when compared with methane or biogas combustion.

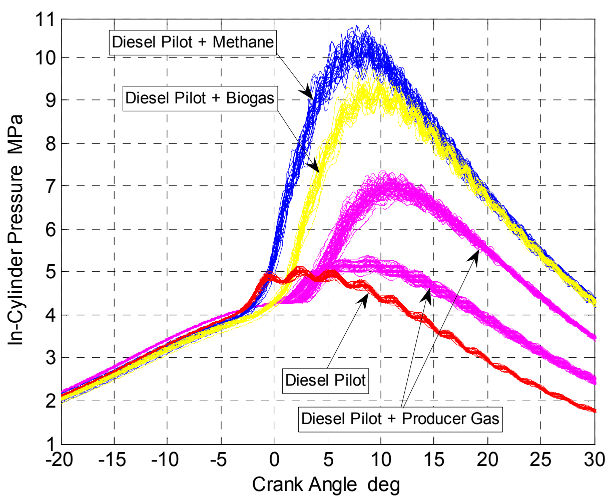

Figure 6: In-cylinder pressure history for various gases combustion in the dual fuel CI engine with diesel pilot at CR=17.

The summary of the knock intensity for several gases burnt in the SI and CI dual-fuel engine is depicted in the fig. 7. As indicated, potential knock can generate pressure oscillations of at least several hundreds kPa. Intensity of these pressure oscillations below the knock limit can come from fast and non-stable combustion and it does not have symptoms of end-gas autoignition as it is typical for combustion knock.

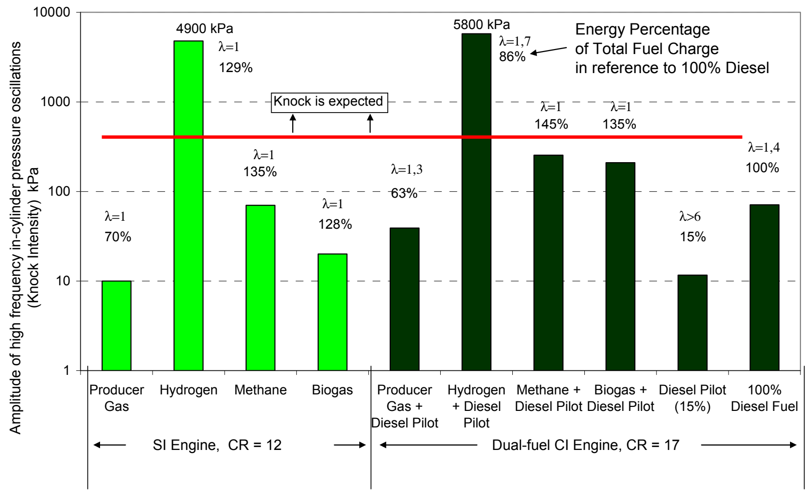

Figure 7: Knock intensity for various fuels combustion at the optimal spark timing in the SI engine (green) and the dual fuel CI engine (black), λ – relative air number.

4 Conclusions

- High unrepeatability (expressed by the COV IMEP) of engine work cycles is observed during producer gas combustion at relatively low compression ratio of 8 in the SI engine. It is mainly caused by both high content of incombustibles (CO_2, N_2) in the producer gas and relatively low in-cylinder air-gas temperature at ignition.
- The highest knock intensity is observed for hydrogen combustion. It reaches 5 MPa even if hydrogen is combusted under diesel conditions at lean combustible mixture terms. Knock intensity of producer gas combustion appears as negligible in comparison to hydrogen knock, even if the producer gas contains H_2 of 16% (50% by energy).
- Due to significantly high COV IMEP of producer gas combustion in the SI engine, better way is to combust it in the dual-fuel (CI) engine.

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H_2 Gas Turbine – a Stepping Stone to CCS

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Marcus H. Scholz, GE Energy - Europe

Abstract

Innovative coal technologies are as indispensable to preventive climate protection as coal is to satisfying the world's thirst for energy. With its Clean Coal Power strategy, RWE faces the challenge of preventing climate change and is now introducing further elements of this strategy. In this respect, carbon capture and storage (CCS) play a key role if CO_2 reductions more substantial than is possible by merely increasing efficiencies are to be achieved.

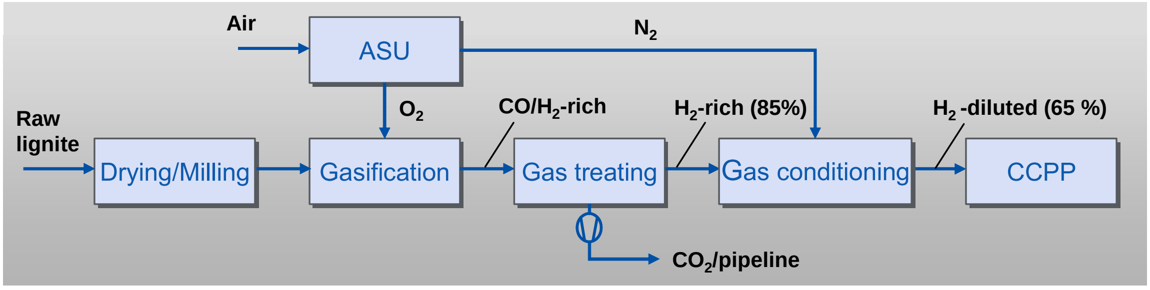
The 450 MW IGCC CCS project, focusing on capture and storage of the CO_2 from a fossil fired power plant, is part of RWE's overall strategy aimed at developing and implementing Clean Coal Power

Integrated Gasification Combined Cycle (IGCC) combines chemical process and power technologies to meet future requirements of fuel flexibility in a carbon-constrained environment. IGCC can operate on a multi-fuel basis with various coal types and waste fuels and produce valuable products beyond electricity generation via poly-generation, thus can be seen as a vehicle to introduce the hydrogen economy.

Over the past 10 years, the most common application of gasification technology has been in the process and chemical industry as well as in the power industry, using a variety of feedstock for the production of chemicals and electric power..

In parallel the power generation industry has increasingly evaluated IGCC solutions to prepare for a regulatory shift towards Carbon Capture & Storage (CCS) requirements, and to use this technology as a sustainable means of converting coal to electricity.

Coal gasification and associated fuel gas process treatment units provide the mechanisms inherently needed to effectively separate carbon components on a “pre-combustion” basis (IGCC CCS), leaving essentially carbon free hydrogen available for use in energy storage, transport or for combustion within a combined cycle power plant. Figure 1 shows the typical key components of an IGCC CCS power plant using the example of RWE’s 450 MW demonstration projekt.



> **Coal drying & milling**	WTA drying technology, roller mills.
> **ASU:**	Conventional concept, large size (3600 t/d O_2).
> **Gasification:**	Entrained flow gasification (1,000 MW $_{th}$, 40 bar) quench mode.
> **Gas Treating:**	Sour shift, H_2S/CO_2 capture, SRU, CO_2 compr.
> **Gas Conditioning**	Dilution with N_2, H_2O
> **CCPP:**	F class GT technology, Diffusion burners

Coexistence of proven technologies and new developments.
Above all the demonstration of their interaction is decisive.

Figure 1: Concept of the 450 MW IGCC CCS demonstration plant.

Rhenish lignite from the opencast mines serves as the fuel. In a first process step, its moisture content is reduced from approx. 55% to 12% using RWE's own WTA drying technology. Subsequently, the lignite is ground by roller mills according to gasification requirements. An entrained-flow gasifier with a dry lignite inlet and a thermal capacity of approx. 1,000 MW, operated at a pressure of approx. 40 bar, is employed for gasification. The hot, CO/H_2-rich raw gas is quenched to approx. 200°C using water. The resulting high portion of steam is used in the subsequent shift stage to convert the CO into more hydrogen and CO_2.

The hydrogen-rich gas left over after the H_2S/CO_2 separation process is conditioned with N_2 from the air separation unit and if necessary with steam to create moderate combustion conditions and meet the legal requirements for NO_X values. The conditioned fuel gas is used to generate electricity in the CCPP unit. The capacity of the gas turbine (F class), which has a share of approx. 300 MW in the total electricity generation capacity of 450 MW, determines the capacity of the overall process. Thus, the process design largely corresponds to the concept of the HTW (high-temperature Winkler) demonstration plant that RWE already operated on an industrial scale from 1986 – 1997 to produce synthesis gas/methanol from lignite. The essential technical challenges of the new project consist in demonstrating the interaction of all individual processes and achieving normal power plant availability.

Gas turbines have been applied to a wide range of syngas application with varying hydrogen fuel content. Based on that experience, it is expected that combustion turbines will likely become the primary hydrogen energy conversion unit for the foreseeable future. Worldwide, GE gas turbines continue to demonstrate their proven, reliable performance on hydrogen bearing fuels, including existing Gas Turbine installations, which operate on high hydrogen fuels up to 95% hydrogen by volume. Table 1

Table 1: Industrial H_2 gas Turbine experience with >50% H_2 by volume.

Project / Site	GT Model	No. Units	Fuel Gas	Features
Geismer, US	MS6001B	1	PG	up to 80% H2
Refinery, US	MS6001B	1	RFG	12 - 50% H2
Korea	MS6001B	1	PG	up to 95% H2
Tenerife, Spain	MS6001B	1	RFG	~70% H2
Cartagena, Spain	MS6001B	1	RFG	66% H2
San Roque, Spain	MS6001B	2	RFG	70% H2
Antwerpen, Belgium	MS6001B	1	RFG	78% H2
Puertollano, Spain	MS6001B	2	RFG	up to 60% H2
La Coruna, Spain	MS6001B	1	RFG	up to 52% H2
Rotterdam, NL	MS6001B	1	RFG	59% H2
Germany	MS6001B	1	IGCC	62% H2
Vresova, CZ	MS9001E	2	IGCC	46.8% H2
Fawley, UK	MS9001E	1	RFG	~50% H2
Georgia Gulf, US	MS7001EA	3	Blend	Methane + 50% H2
Milazzo, ITA	MS5001P	1	RFG	30 - 50% H2
Ref., India	MS5001P	1	RFG	50% H2
Paulsboro, US	MS5001P	2	RFG	20 - 60% H2
Ref., Int'l	MS5001P	1	RFG	Propane + 60% H2
Reutgerswerke, US	MS3002J	1	PG	60% H2
NUP	MS3002J	1	TG	~60% H2
Donges, US	GE10	1	RFG	76% H2
Refinery, Jordan	PGT10	1	RFG	82% H2

RFG = Refinery Gas, TG = Tail Gas, PG = Process Gas, IGCC = Syngas

GE continues to expand on this experience and to develop advanced gas turbine platforms, including F-class units operating on synthesis gas.

The early F-class gas turbines have been operating for over 12 years on hydrogen bearing fuels up to 45% hydrogen content by volume. Table 2.

Table 2: F-class H_2 Operation experience.

		Wabash, US	Tampa, US	Singapore	Delaware, US
Turbine		7FA	7FA	2x6FA	2x6FA
H_2	(% Vol)	24.8	37.2	44.5	32.0
CO	(% Vol)	39.5	46.6	35.4	49.5
CH_4	(% Vol)	1.5	0.1	0.5	0.1
CO_2	(% Vol)	9.3	13.3	17.9	15.8
N_2+Ar	(% Vol)	2.3	2.5	1.4	2.2
H_2O	(% Vol)	22.7	0.3	0.1	0.4
LHV	BTU/ft^3	209	253	241	248
	kJ/m^3	8,224	9,962	9,477	9,768
T_{fuel} F/C		570/ 300	700/ 371	350/ 177	570/ 299
H_2/CO Ratio		0.63	0.80	1.26	0.65
Diluent		Steam	N_2	Steam	H_2O/ N_2
Equiv BTU/ft^3		150	118	116	150
	kJ/m^3	5,910	4,649	4,600	5,910

Several small modifications of existing Gas Turbines, designed for natural gas, have been applied to account for the higher mass flow of syngas fuel with diluents.

Those hardware changes, including Combustion system, Hot Gas Path and general features have been implemented in the F-class Gas Turbine platform for GE´s 6F, 7F and 9F Syngas products. As a validation tool, the large tests facilities in Greenville, South Carolilna, provide full pressure, temperature, and flow conditions, as such replicating engine conditions. They also allow for a wide range of fuel blending capability for H2, N2, CO, CO2, and H2O, and to monitor dynamics, emissions, ignition, under full and part load characterization. Figure 2

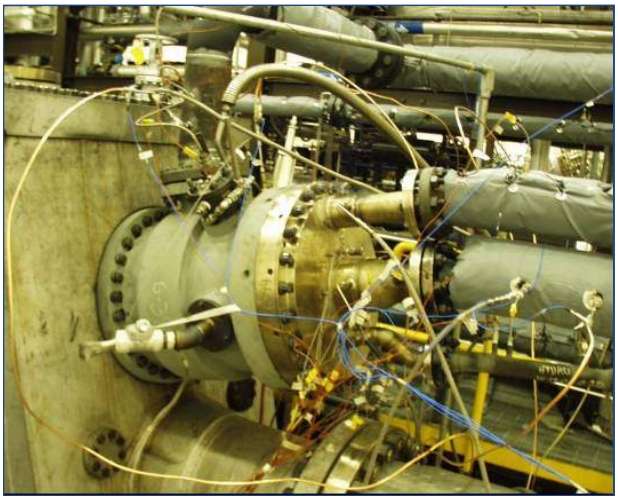


Figure 2: Syngas Test cell for full-scale equipment development.

This results in high fuel flexibility to allow for capabilities with hydrogen fuels for a wide range of carbon capture application, ranging from straight syngas combustion up to 90% CCS.

Since increasing firing temperature and cycle operating pressure are the principle drivers for improving Gas Turbine Combined Cycle and IGCC plant efficiencies, GE continues to drive technology enhancements with the latest F-class Gas Turbines designs. Successful operating experience, combined with continuous R&D efforts, provide efficient solutions for syngas and H2 fuels required by the carbon-constrained generation environment.

It is expected that policy makers will consent to tighten Carbon Dioxide emissions on a global basis in the near future and General Electric has meanwhile advanced the IGCC plant concept to take into considerations the lessons learnt from recent project activity, including the currently ongoing construction of the largest IGCC plant at Duke Energy, with over 620MW electric generation capacity.

Effect of Hydrogen Addition on Combustion and Emissions Performance of a Spark-ignition Gasoline Engine at 800 rpm and Lean Conditions

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1 Introduction

The use of hydrogen as an additive to enhance engine performance has been widely tested. Wang et al. [1] ran an HCNG engine with different hydrogen volumetric fractions at lean conditions. He found that the cyclic variation was decreased with the increase of hydrogen addition. Ma et al. [2] studied the effect of hydrogen addition fraction on the cycle-by-cycle variation, combustion process and emissions characteristics of a CNG engine with hydrogen enrichment. Varde [3] ran a single-cylinder engine with the mixture of hydrogen and gasoline, and he found that the lean burn limit was extended and the flame propagation speed was increased with the addition of hydrogen. Apostolescu and Chiriac [4] studied the effect of hydrogen addition on the combustion process at mid-to-low loads, with the results showing that the cyclic variation and 10% to 90% burn duration were greatly reduced while hydrogen mass fraction varied from 1.5% to 3%. Li et al. [5] investigated the mechanism of toxic emissions foramtion from the gasoline-hydrogen mixture based on chemical dynamics of combustion. He found that the toxic emissions was reduced after hydrogen addition, especially at relatively lean conditions. Lucas and Richards [6] ran an engine with pure hydrogen at idle and found that the engine thermal efficiency increased by at least 10% and CO and NOx emissions were lower than the original one.The engine always suffers low thermal efficiency, high cyclic variation and toxic emissions at idle and low engine speeds, because of the increased charge inhomogeneity and high residual gas fraction. Engines always show high cyclic variation at idle, because of the high residual gas fraction and low fuel burning velocity at low speeds [7].Compared with gasoline, hydrogen has a relatively high flame speed, which is likely to reduce the combustion duration inside the cylinder and ease the cyclic variation.At the same time, only a hydrogen injection system is required to realize the hybrid hydrogen-gasoline engine, reducing the modifiction costs.However, few studies were reported about the effect of hydrogen addition on the performance of a gasoline engine at low operating conditions. In this paper, the test engine was run at three different enrichment levels and four excess air ratios, and the effect of hydrogen addition on engine combustion and emissions performance at 800 rpm and lean conditions was investigated.

2 Experimental

The experiment was carried out on a 1.6L, port fuel injection, four-cylinder, SI engine manufactured by BEIJING HyunDAI Motors. Four hydrogen injectors were mounted near the intake valve of each cylinder while keeping the original gasoline injection system unchanged, so that the injected hydrogen can be introduced into the cylinder faster and the backfire was effectively avoided.The injection timings and durations of hydrogen and gasoline were controlled and adjusted by a self-developed hybrid electronic control unit (HECU). The HECU communicates with the engine original ECU (OECU) to freely adjust injection timings and durations of hydrogen and gasoline via the commands from the calibration computer.This system has accomplished the cold start with pure hydrogen, part-load operation with the hydrogen-gasoline mixture and high load operation with pure gasoline.The spark timing of the engine was kept at TDC during the experiment.The engine is loaded with a GW160 eddy current dynamometer to control and measure engine speed and torque output. A FC2210 fuel mass flow meter is adopted to meter the gasoline mass flow rate.The cylinder pressure acquisition and combustion analysis system consists of a Kistler 2613B optical encoder, a Kistler 6117BFD17 pressure transducer with a spark plug and a combustion analyzer manufactured by Dewetron, Austria. The cylinder pressure transducer with a spark plug is screwed into the cylinder head of the 4^{th} cylinder to detect the combustion cylinder pressure and enforce its ignition.The optical encoder is connected to the front of the crankshaft producing 1800 pulses per rotation for obtaining crank angles and triggering the sampling of combustion pressure.The cylinder pressure transducer and optical encoder are connected to the DEWETRON combustion analyzer via the screened cables.Cylinder pressure and crank angle signals were sampled and treated via DEWE-CA combustion analysis software The exhaust emissions of NOx, HC and CO from the test engine were measured by a Horiba MEXA-7100D emissions analyzer. The air and hydrogen mass flow rates were monitored by a EPI-800 and a D07-19BM thermal mass flowmeters,respectively.

The experiment was conducted after the engine is fully warmed. The idle bypass vavle was 50% opened and the engine speed was 800rpm. Different excess air ratios (1.00, 1.18, 1.43 and 1.67) were acquired by reducing gasoline injection duration with the increase of hydrogen addition. The cylinder pressures of 300 consecutive cycles were sampled for the calculation of coefficient of variation in indicated mean effective pressure COVimep, 0-10% and 10-90% burn durations. The coolant and lubrication temperatures were kept at 90 and 95±1℃,respectively during the experiment to minimize their effects on the test results.

3 Test Results and Discussion

3.1 Brake thermal efficiency

Fig. 1 displays the variation of engine brake thermal efficiency with excess air ratio under various hydrogen addition fractions at 800rpm. It shows that the brake thermal efficiency of the original engine is

reduced sharply with the increase of excess air ratio. This phenomenon demonstrates that the lean combustion technology is not suitable to be applied on the low speed conditions of a pure gasoline fuelled SI engine, since the lean mixture is hard to be burned well under large resodual gas fraction and low combustion temperature. Especially when excess air ratio exceeds 1.43, it can be clearly seen that the original engine thermal efficiency decreased dramatically, which is attributed to the misfire of the mixture in the cylinder.

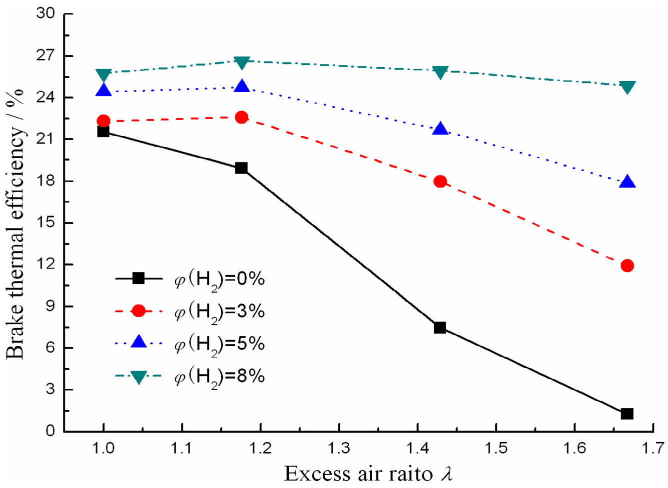

Figure 1: Brake thermal efficiency versus excess air ratio.

3.2 Combustion

The flame development duration CA0-10 and flame propagation duration CA10-90 versus excess air ratio at 800rpm are plotted in Figs. 2 and 3, respectively. CA0-10 and CA10-90 are both shortened with the increase of hydrogen enrichment level. For a specified hydrogen addition fraction, CA0-10 and CA10-90 are prolonged with the increase of excess air ratio. The reason can be attributed to the low combustion temperature caused by lean combustion. The flame velocity is reduced with the decrease of combustion temperature, so that the flame development and propagation durations are both prolonged with the increase of excess air ratio at a certain hydrogen enrichment level.

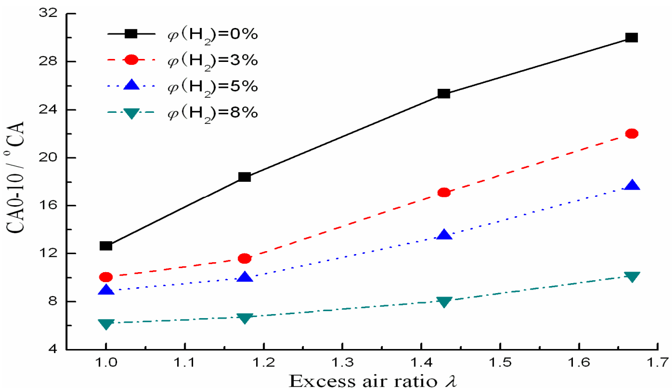

Figure 2: CA0-10 versus excess air ratio.

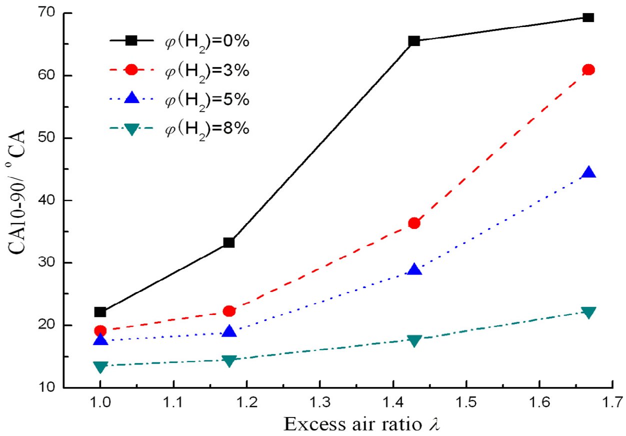

Figure 3: CA10-90 versus excess air ratio.

3.3 Cycle-by-cycle variation

Fig. 4 shows COVimep versus excess air ratio at 800rpm and various hydrogen addition levels.As it can be seen from Fig.4, when excess air ratio exceeds 1.43, COVimep of the pure gasoline engine is sharply increased to 65% due to the severe misfire. The high burning velocity of hydrogen decreases the engine combustion duration which is helpful on reducing the engine cyclic fluctation.When excess air ratio is greater than 1.43, the original engine encountered a serious misfire and caused a dramatical increase in COVimep.However, as the hydrogen-gasoline mixture has a wider flammability,the misfire can be effectively eliminated.

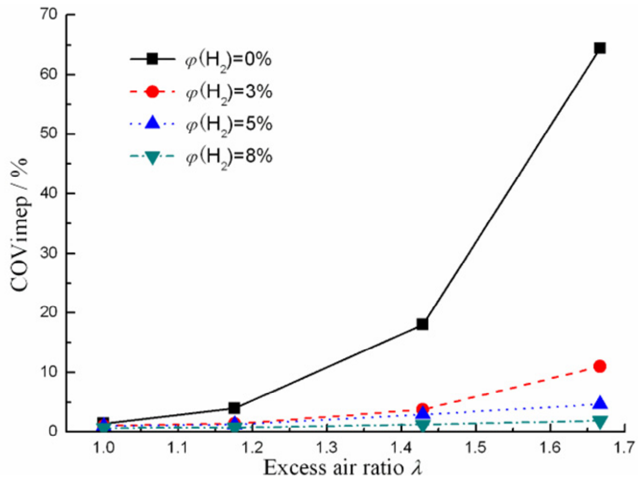

Figure 4: COVimep versus excess air ratio.

3.4 Untreated emissions

The variation of HC emissions with excess air ratio at 800rpm and different hydrogen fractions is shown in Fig.5. It can be seen that HC emissions decrease with the increase of hydrogen addition fraction at the same excess air ratio.For the original engine, HC emissions are obviously increased from 4206 ppm to 14331 ppm when excess air ratio is increased from 1.00 to 1.6 due to the serious partial burning and misfire of the pure gasoline engine at lean conditions.

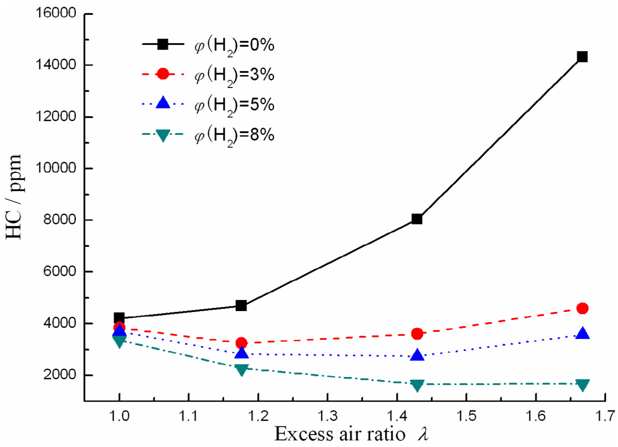

Figure 5: HC emissions versus excess air ratio.

Fig. 6 displays the variations of untreated CO emission with excess air ratio. From Fig. 6 we can see that under lean conditons CO emission dcreases with the increase of hydrogen addition. The decreased gasoline flow rate reduces the amounts of C atoms in the hydrogen-gasoline fuel mixture, and therefore contributes to the decrease of CO emission from the hydrogen-enriched gasoline engine.

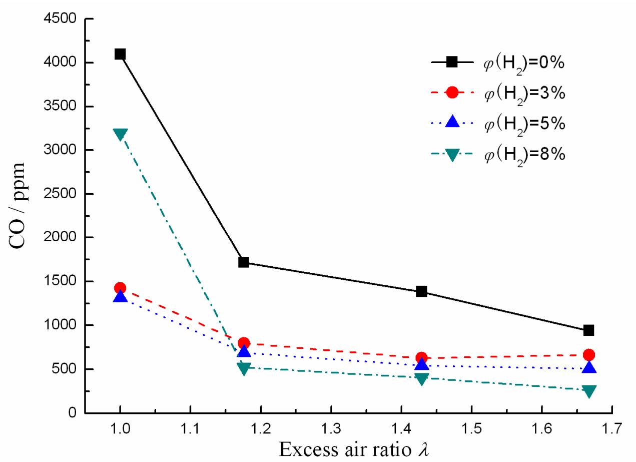

Figure 6: CO emission versus excess air ratio.

In Fig. 7 NOx emissions increase with the addition of hydrogen and decrease with the increase of excess air ratio.Especially at the stoichiometric condition, NOx emissions from the 8% hydrogen-enriched engine are nearly one time higher than those from the original one, because the fast burning velocity and high flame temperature of hydrogen tend to stimulate the formation of NOx.

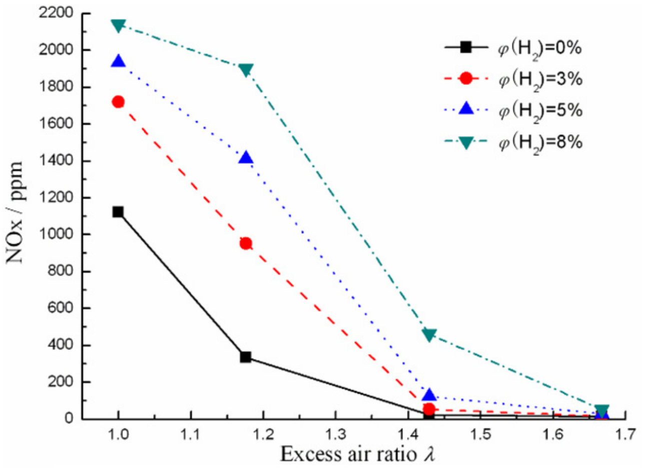

Figure 7: NOx emissions versus excess air ratio.

4 Conclusions

1).The brake thermal efficiency is greatly improved with the addition of hydrogen, especially at lean conditions;2). Hydrogen addition is helpful on decreasing engine flame development and propagation durations;3). The engine cycle-by-cycle variation and misfire is reduced with hydrogen enrichment;4).HC emissions are reduced while NOx emissions are increased with the increase of hydrogen addition for a specified excess air ratio.CO emission decreases with hydrogen enrichment level at lean conditions. However, when the engine runs nearly to the stoichiometric conditions, the 8% hydrogen-rich engine tends to expel more CO than 3 and 6% hydrogen-rich engine, but still lower than the original one.

Acknowledgements

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Development of a Common-rail Type High Pressure Hydrogen Injector with a Large Injection Rate and an Ability of Multiple Stage Injection

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Atsuhiro Kawamura, National Traffic Safety and Environment Laboratory, Japan

1 Introduction

It is definitely true that the fossil fuel depletion problem and the global environmental problem should be solved immediately. Vehicles used on the earth are required to use fuel produced renewably and have a power system to be of low pollution, high efficiency and high output power as well as compactness and lightness in weight. Though various types of vehicle are being studied in the world for those purposes, they have merits and demerits.

To overcome the problems in the transportation sector, vehicles powered by hydrogen fuelled internal combustion engines with direct injection system (hereafter written as DI-ICE) can be expected to be put into practice soon because the technologies are being used to this day. The engine and fuel supply systems now under development are shown in Fig. 1. In order to accomplish low emission, high thermal efficiency and high output power in the engine system, development of common-rail type high pressure injector with a large injection rate and ability of multiple stage injection is indispensable [1].

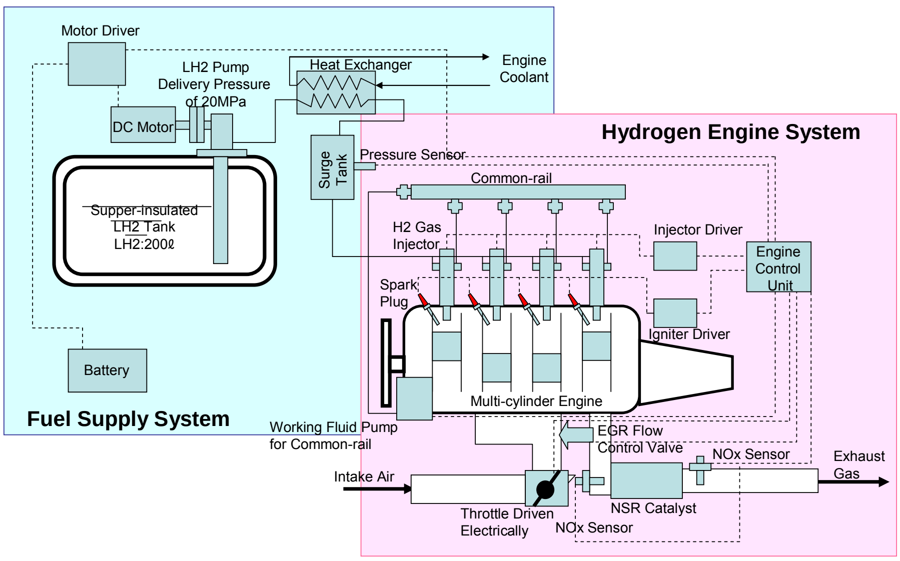


Figure 1: Hydrogen engine and fuel supply system.

There are several characteristics of hydrogen that makes this development difficult, such as small molecular size, low viscosity, low energy density, the gaseous state and some task work in precise machining processes.

This paper describes the features and key technologies of the injector obtained in the development, aiming for larger injection rate and less hydrogen gas leakage at the seating surface between the needle and the nozzle. Furthermore, the result is shown when a 4-cylinder 16-valve water cooled hydrogen fuelled direct injection engine with the developed four injectors installed was run according to the transient emission testing mode so called JE05 on an emission evaluation engine test bench.

2 Injector Developed, Injection Rate Measuring Device and Engine

The development of the injectors was carried out for the hydrogen fuelled truck engines. The injector developed and the device to measure the injection rate and the engine used were as follows.

2.1 Common-rail type injector

Basic requirements of injectors are high injection pressure, large injection rate, quick response, compact, controllability and durability for the DI-ICE mentioned above. To accomplish the requirements, studies were made on various injectors available on the market to find out the driving methods and materials in the design study. In the end, a compact common-rail type injector capable of electronic control was adopted. As the common-rail type injector system consists of a inner-cam type extremely high pressure pump, a common-rail where working fluid is kept at a constant high pressure and fed to the injectors and the injectors with electronic controlled solenoid valves capable of the very swift movement, it was conceivable that, as the matter of course, the common-rail type injectors were able to inject hydrogen gas at high pressure and make multiple stage injection with high response thanks to the very high operating pressure of working fluid.

As shown in Fig. 2 (a), the needle valve is close when the working fluid control valve is closed by the spring while the solenoid coil is deactivated. As shown in Fig. 2 (b), the needle valve is open when the working fluid control valve is opened by activating the solenoid coil. Namely, the activation and deactivation of the solenoid coil enables the needle valve to open and close respectively. It means that the activation and deactivating timings determine the opening and the closing timings, as well as the injection duration time. As a result, the injector can expectedly inject hydrogen gas at high pressure into the combustion chamber electronically. The solenoid coil, the spring and the working fluid control valve disassembled from a diesel fuel common-rail type injector on the market were used. As shown in Fig. 2, hydrogen gas is only fed to the needle valve at the high injection pressure while the working fluid control valve opens and closes in the same manner as a diesel fuel common-rail type injector does.

Table 1 shows the specifications of the injector developed and the hydrogen fuelled direct injection engine used for the JE05 mode emission evaluation. As the engine was the same with the diesel fuelled engine, a special effort was made for the installation of the additional feeding hydrogen pipe to the injector.

Table 1: Specifications of injector and engine.

Injector	Type	Hydraulic with Solenoid Valve
	Injector pressure	10～20MPa
	Working Oil	Diesel Fuel, 60MPa～
	Max Injection Quantity (at 3000rpm,30°CA)	400ml(N)/inj.
Engine	Engine Type	4-Cylinder
	Bore and Stroke	112×120 (mm)
	Displacement	1182cc/cyl
	Compression Ratio	13
	Valve Train	4-Valve SOHC

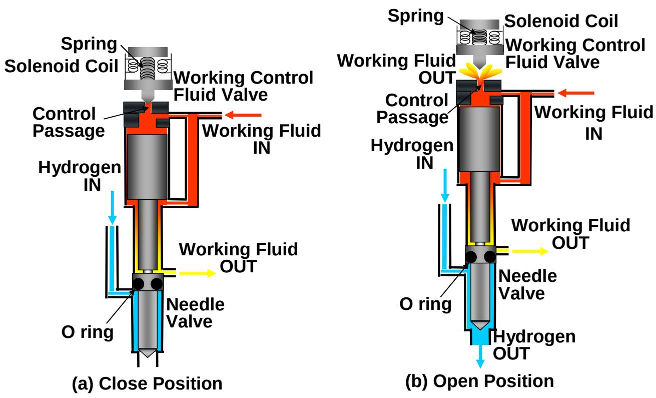


Figure 2: Injector behavior.

The maximum injection rate of the injector was determined by calculating from the condition of the stroke volume of 1.3 liters per cylinder, the volumetric efficiency of 80 % and the stoichiometric mixture strength. The minimum injection rate was determined by the hydrogen gas quantity capable of the engine idling. The allowable amount of hydrogen leakage through the seating surface between the needle and the nozzle was determined experimentally with a view to eliminating the abnormal combustion occurrence.

2.2 Injection rate measuring device and engine

A device was prepared to investigate the characteristics of the common-rail type hydrogen injector such as the injection rate, the functional behavior and the leakage from the seating surface into the combustion chamber. All the parts to make the device were employed from those used in the diesel fuel common-rail system except for the electric motor driving the inner-cam type extremely high pressure pump. Hydrogen gas at the injection pressure was supplied from high pressure cylinders. The pressures and temperatures of the hydrogen and the working fluid were recorded with a data logger. The following data were measured with an oscilloscope; the electronic command signal, the activating electric current generated in the injector electronic driver and the lift of the needle of the injector from the lift sensor embedded in the injector.

To know whether the injectors work functionally as expected in an engine operating condition, the four injectors were installed on the engine as described in Table 1.

3 Injector Performance and Endurance Life Improvements

3.1 Injector performance

To obtain high output power and high thermal efficiency by using hydrogen fuelled DI-ICE, it is necessary to have the injector make injection near at the top dead center in as short a period as possible. In order to obtain high injection rate, two measures were adopted. One was to enlarge the original diameter of 0.22 mm of the control passage which the working fluid control valve opened and closed. The other was to increase the angle of the tapper portion of the needle valve resulting in obtaining larger flow area. The enlargement in the diameter and the increase in the angle successfully enabled the injector to attain the injection rate of 400 ml(N)/1.67 msec. equivalent of 30 degrees crank-angle at 3000 rpm as shown in the specifications of the injector in Table 1. It was also found in the experiment that the injection rate would not be increased without fail when the diameter became more than 0.29 mm. It was conceivable that the maximum lift of the working fluid control valve was smaller than 0.073 mm. For purposes of combustion control in DI-ICE, the multiple stage injection is of great promise.

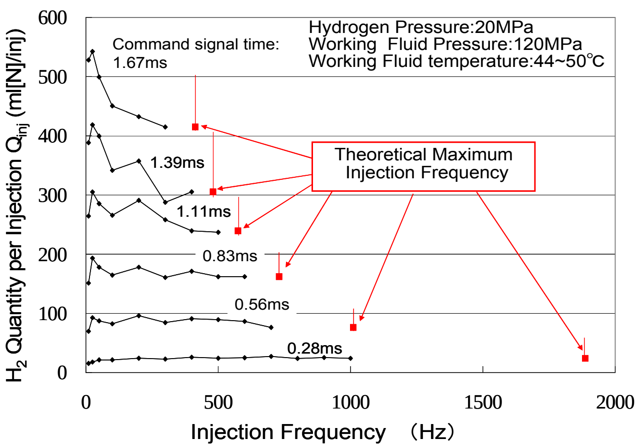
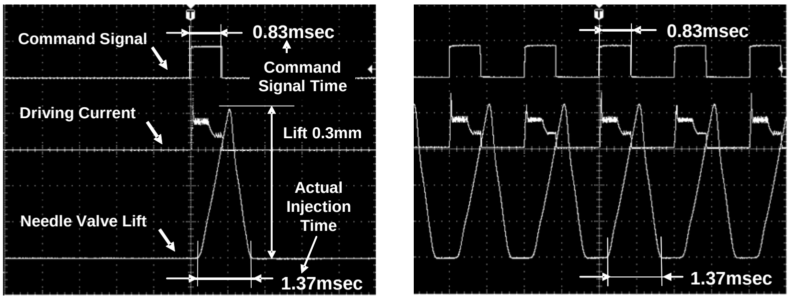


Figure 3: Effect of injection frequency on hydrogen quantity per injection.

As known well, common-rail type injectors are good at the multiple stage injection. It is very important to know to what extent of injection frequency the injector can perform correctly. Figure 3 shows the results of hydrogen quantity per injection Qinj. ml(N)/inj. by varying the command signal time such as 0.28, 0.56, 0.83, 1.11, 1.39, 1.67 msec. In most cases, the measurement was given up because the flow rate was beyond the capacity of the measuring device so that all most measurement stopped on the way to the theoretical maximum injection frequency. Figure 4 shows the command signal, the driving current and needle valve lift at the actual injection time of 1.37 msec. in cases of 10 Hz injection frequency (a) and 500 Hz (b). It is found in the figure that the needle valve lifts make no difference between injection frequency of 10 Hz and 500 Hz. It is quite evident in Fig. 3 and 4 that the developed injector can make multiple stage injection at very high frequency.



(a) Injection Frequency : 10Hz (b) Injection Frequency : 500Hz

Figure 4: Needle valve lift behavior in comparison between injection frequency 10 Hz and 500 Hz.

3.2 Endurance life improvements

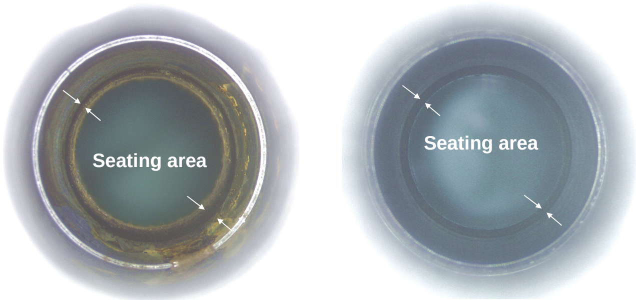
When the developed injector is used for experiments and practical use, the consideration to the endurance life is inevitable. As explained in Chapter 2, the common-rail pressure works on the seating surface of the needle valve, namely, the increase of the common-rail pressure makes the seating surface pressure go up resulting in improving the sealing ability. On the other hand, the increase in the common-rail pressure results in smaller injection rate. As it is found that the relationship between the sealing ability and the injection rate is a trade-off manner, the appropriate common-rail pressure was determined experimentally.

It is said that, in case of high pressure hydrogen gas injectors, metal-to-metal contact sealing is subject to leakage of hydrogen gas at high pressure and that the leakage won't stop. To stop the leakage, a little lubricant on the sealing surface largely helps to stop the leakage of hydrogen gas at high pressure. However, the lubricant may generate pollutants such as hydrocarbon, mono-carbon oxide and carbon dioxide resulting in losing the attraction of hydrogen fuelled engines and moreover it may influence combustion of hydrogen-air mixture. As a result, this fails to have this kind DI-ICE called a true hydrogen fuelled DI-ICE. Therefore, the metal-to-metal contact sealing was intentionally employed for the injector sealing while focusing on the seating surface pressure, the precise machining and the surface treatment.

To look for long endurance life, improvements in the following subjects were carried out, expecting 100 hour endurance life.

1. Precise machining of needle valve and surface treatment

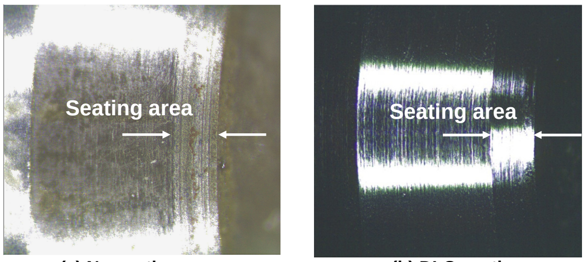
Circularity and flatness of the seating surfaces of the needle and the nozzle were improved by much more precise machining. In addition, circularity and cylindricity of the sliding portion of needle valve stem and coaxiality of the seating portion of the needle valve and the nozzle were also improved. As a result, no leakage through the seating surface was found definitely after 3-hour breaking in operation. The width of the seating surface of the nozzle was found to be uniform. As a result, the sealing for hydrogen gas at high pressure reached a practical level. Figure 5 shows the photographs of the seating surfaces of the nozzles; (a) leakage case and (b) no leakage case.



(a) Leakage case **(b) No leakage case**

Figure 5: Photographs of the seating surfaces of the nozzles.

A surface treatment was carried out on the surface of the tapered portion of the needle valve to keep the original contour. The surface treatment carried out was a diamond-like carbon (hereafter written as DLC) coating. The DLC used was an amorphous carbon containing hydrogen with which a sliding friction test showed good results (Ref. 2). Figure 6 shows the photographs of the seating surfaces of the needle valves; (a) No coating, (b) DLC coating.



(a) No coating **(b) DLC coating**

Figure 6: Photographs of the seating surfaces of the needle valves.

2. Precise machining of needle valve stem and surface treatment

For the increase in sealing ability at the seating surface of the needle valve and the nozzle, the clearance at the portion of the needle valve stem was decreased and furthermore circularity and cylindricity of the sliding portion of needle valve stem were improved. In addition, it was necessary to decrease the sliding friction at the portion of the needle valve stem for a stable needle valve lift. To decrease the sliding friction, the surface treatment with the DLC coating mentioned above was made. In Fig. 7, there appears a SEM photograph of the needle valve with DLC coated on, taken after the experimental engine operation. The needle valve stem used in the experimental engine operation was originally damaged and, after that, coated with DLC to investigate whether the DLC coating could stand the actual engine operation or not. As the result of SEM observation, there was no coating damage such as separation. It was found in the experiment that the coating had enough adhesion and endurance. It was also found that the coating could allow the tolerance in the clearance at the portion of the needle valve stem to be loose.

It has been clarified that the DLC coating worked well for experiments and practical use even in the circumstance of hydrogen gas. For further improvement, more study on the surface roughness of the needle valve stem and good coating structure is necessary.

Figure 7: SEM photograph of the needle valve with DLC coated on.

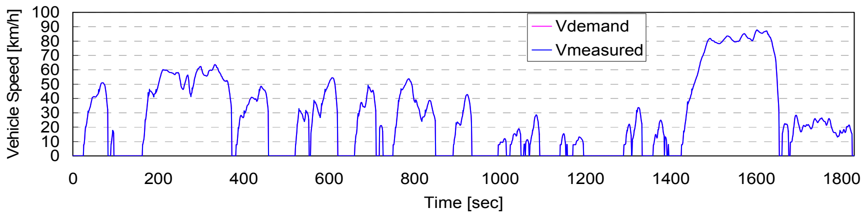


Figure 8: Comparison between vehicle speeds V measured and demanded.

3. Sealing between hydrogen gas and working fluid

High pressure hydrogen gas was applied to the portion of the needle valve and the nozzle in this injector. Injection of the hydrogen gas was made by up and down movement of the needle valve. For the sealing between hydrogen gas and working fluid, a rubber O ring with a nylon backup ring was employed. The surface of the rubber O ring was usually torn off. In this experiment, the sliding surface roughness and the sliding clearance were adjusted smaller than those of the design standards. However, though there was no improvement in the tearing-off of the O ring as usual, the sealing worked well. For the future, structural design change may be necessary to overcome the tearing-off.

4. Engine operation in the emission evaluation transient mode JE05

The JE05 mode operation was actually carried out by using the four developed injectors mounted on the engine described in Table 1. The JE05 mode is a transient operation simulating a real driving. The mode has been used for the emission test of the new long-term regulation since 2007 settled by the Ministry of Land, Infrastructure, and Transport (MLIT) of Japan Figure 8 shows the comparison of the vehicle speeds V measured and demanded. The measured one followed well the demanded one. It means that all the injectors synchronized well with the JE05 mode owing to the high response and the high injection rate of the injectors. In the engine operation, the working fluid was pumped up by an electric motor driving the inner-cam type extremely high pressure pump independent of the engine.

4 Conclusions

The followings are found in the development of the common-rail type hydrogen injectors by using the diesel fuel common-rail system on the market.

Compact common-rail type hydrogen injectors were successfully developed. Hydrogen fuelled engines with high engine performance have been realized by using the injectors developed. It is found that the injectors are good for hydrogen DI-ICE.

The injectors could bring about high injection rate and multiple stage injection.

DLC coating made a large contribution to the endurance life. And the injectors are expected to have the endurance life more than 100 hours.

Machining improvements in circularity, flatness and coaxiality made it possible to use the metal-to-metal sealing even when hydrogen gas was used at high pressure.

By using the injectors developed, a transient operation could be successfully done with a multi-cylinder engine according to JE05 mode. It was found that all the injectors synchronized well with the JE05 mode owing to the high response and the high injection rate of the injectors.

It is largely expected that the common-rail type injectors developed surely bring about further advancement in hydrogen fuelled DI-ICE.

Acknowledgements

This study was carried out under the Next-generation Environmentally Friendly Vehicle Development and Commercialization Project (EFV21) of the Ministry of Land, Infrastructure, and Transport (MLIT) of Japan. The authors greatly appreciate the assistance of this organization and its personnel. And also, many thanks are sincerely expressed to all involved staffs of National Traffic Safety and Environment Laboratory, and Hydrogen Energy Research Center of Tokyo City University for their devoted support.

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TA Transportation Applications

Systems Analysis and Well-to-Wheel Studies

Thomas Grube, Bernd Höhlein, Christoph Stiller, and Werner Weindorf

Abstract

Energy systems analyses provide powerful assessment frameworks for research and development projects involving new energy technologies. These analyses rely on the description of state-of-the-art technologies and incorporate scenarios on future developments in the energy sector in order to identify the benefits and weaknesses of the technologies under consideration. This chapter presents selected assessment highlights relating to hydrogen and fuel cell technologies for transportation. With respect to fuel cell system cost, noble metal requirements are of utmost significance. The corresponding balances for fuel cell vehicles will be introduced. Moreover, the relevance of dynamic powertrain simulation for the evaluation of energy process chains in transportation will be discussed. In a further part, the methodology and results of well-to-wheel analyses of energy use and greenhouse gas emissions will be discussed, followed by an assessment of relevant hydrogen-focused well-to-wheel studies of different world regions as well as a comparison and interpretation of key findings.

Sustainability of Transport Fuels

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1 Introduction

Given the magnitude of transportation fuels to be provided by renewable energies in the future, a sustainability framework that goes beyond greenhouse gas emissions is essential in order to avoid backlashes in other environmental categories. Major environmental issues include greenhouse gas emissions, air pollutants, biodiversity and protection of natural habitats. Water consumption already goes beyond environmental concerns touching human and geopolitical issues alike. Social and local economic sustainability are further topics that are already vividly discussed in the context of biofuels production (see the 'food vs. fuel' debate).

As a result, the European Union target of 10% renewable energies in transport by 2020 is conditioned by a comprehensive set of sustainability criteria. This is currently under strong political debate as e.g. the assessment of potentially disastrous indirect land use changes clearly falls short when addressing individual bioenergy projects only.

This paper presents the sustainability criteria and approach of the European Union as laid out in the EU Renewables Directive. Furthermore, aspects going beyond the EU Directive are discussed and typical values for selected criteria are presented.

Focus is put on the comparative assessment of primary energy potentials, greenhouse gas emissions, land-use and water intensity of different fuel and power train options including biofuels, electricity and hydrogen.

2 EU Renewable Energy Directive

On 23 April 2009, the European Union has voted on the EU Renewable Energy Directives (EU-RED [1]). The RED includes a comprehensive set of sustainability criteria to apply for EU Member States' mandatory share of 10% of renewable energies in transport fuel by 2020. The Directive will have to be implemented in EU Member States' law by end of 2010. Article 17 stipulates "go/no-go" criteria for greenhouse gas emission reductions, land with high biodiversity and land with high carbon stock. Article 18 stipulates reporting obligations (to be further defined) on soil, water, and air protection; social issues; availability of foodstuffs; land rights; etc. The sustainability criteria apply to geographic origins both from within the EU as well as import from third countries. For the time being, the focus is set on sustainability issues related to the cultivation of biomass for bioenergy. However, paragraph 4 of article 3 states that "all forms of energy" is included to make up for the 10% target. Hydrogen is explicitly mentioned in the 1st paragraph of article 5 to be considered for the calculation of the Member States' share of renewable energies.

It is expected that certified transport fuels will gain a premium in Europe. For the time being, hydrogen energy stakeholders are largely unaware of this novel policy framework. Opportunities for renewable hydrogen in transport have yet to be explored.

3 Energy Potentials

The potentials for producing electric power from renewable energies in Europe noticeably exceeds current consumption (see Figure 1). Distinguishing between direct power production and biomass-based power generation, Figure 1 clearly shows that bioenergy is strongly limited in potential: direct power generation (left) exceeds current consumption by more than a factor of two, while the biomass power generation potential (right) is around 10% of consumption. A similar relationship holds true for transport fuels.

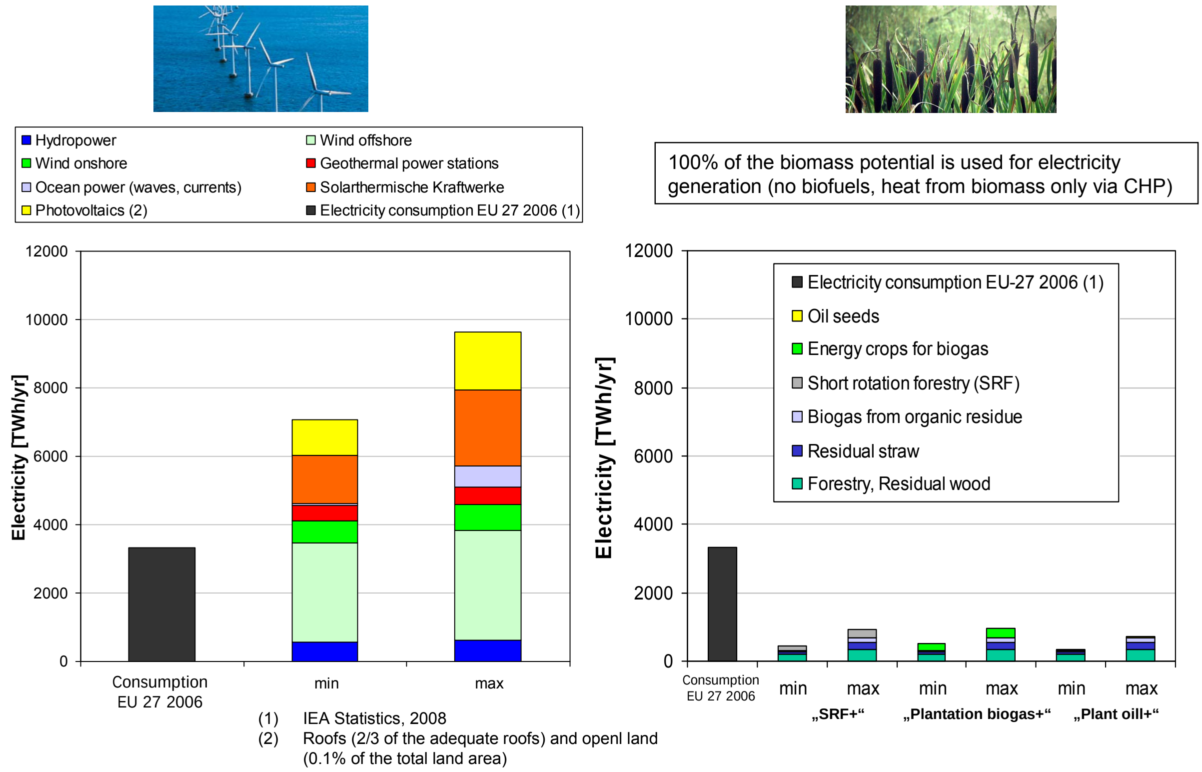


Figure 1: Energy potentials for direct renewable electricity production (left) and bio-based electricity production (right) in Europe.

4 Greenhouse Gas Emissions

Greenhouse gas emission (GHG) reductions of biofuels, hydrogen and electricity compared to conventional transport fuels have large bandwidths. A 100% reduction is feasible if renewable power or suitable biomass pathways are used. Unfavourable biomass pathways provide only insignificant greenhouse gas emission reductions compared to mineral oil-based fuels (see Figure 2 based on analyses by the authors [2]). Including land-use changes can drive up GHG emissions to levels significantly above conventional fuels, e.g. palm oil emissions are up to 25 times the emissions of fossil-based diesel if land use changes are accounted for.

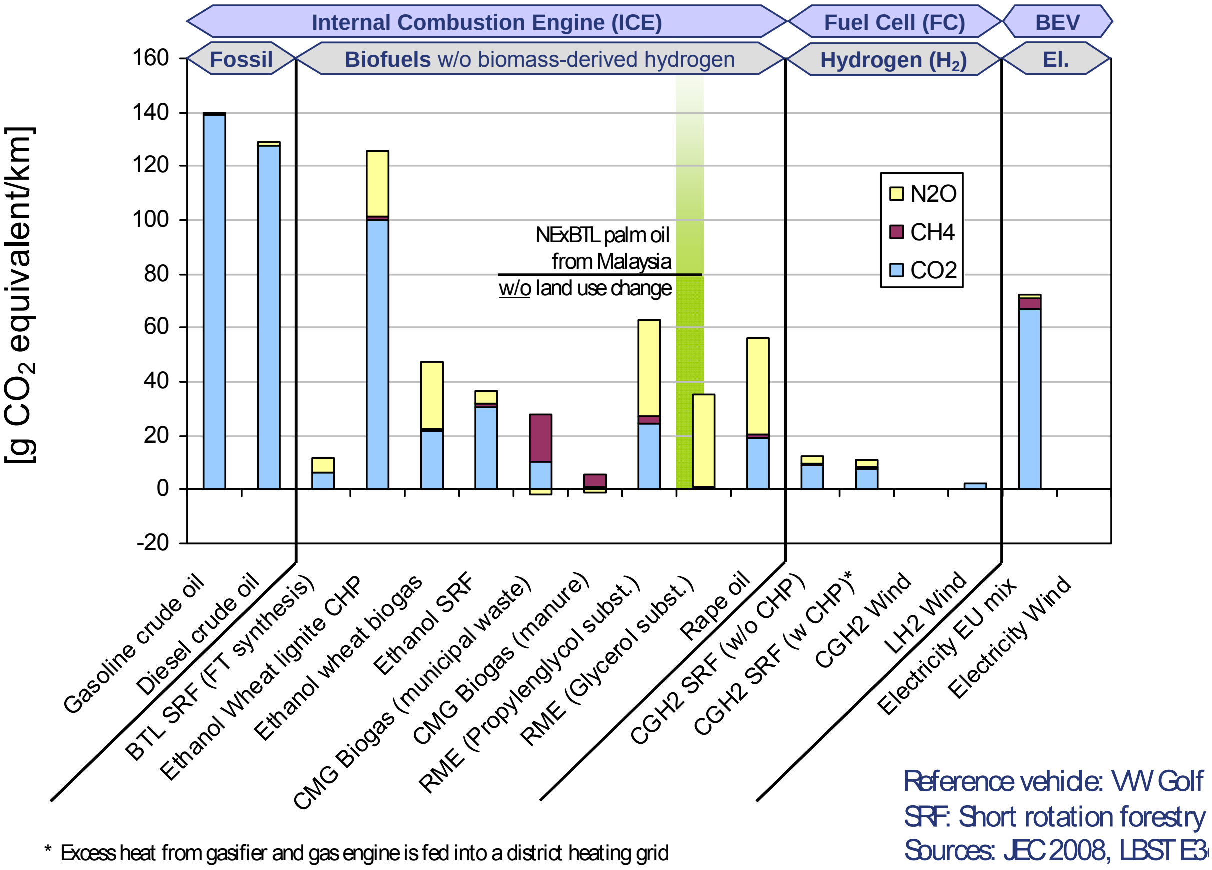


Figure 2: Greenhouse gas emissions "well-to-wheel" (without land use change).

Note that battery electric vehicles do not fulfill all performance requirements, notably cruising range, which gives them a bias towards better GHG emissions.

5 Air Pollutant Emissions

Air pollutants have come more into focus again in recent years with pollutant concentration levels in urban areas not improving, in spite of stricter emission limits for vehicles. Hence, stricter air quality requirements are being enacted in European. The latest move is the EU Directive on Ambient Air Quality and Cleaner Air for Europe [3].

Critical for human health are high pollutant concentrations in urban areas. Figure 3 depicts the nitrogen oxide emissions by place of occurrence for the same fuels as Figure 2 for GHG emissions. As can be seen, emissions are reduced significantly by renewable hydrogen and renewable electricity, while biomass-based fuels do not reduce pollutant emission levels. It has to be noted, that the future EURO6 emission standard (best case for internal combustion engines) has been taken into account for Figure 3. Today, the EURO4 emission standard applies with significantly higher tank-to-wheel (TTW) emissions.

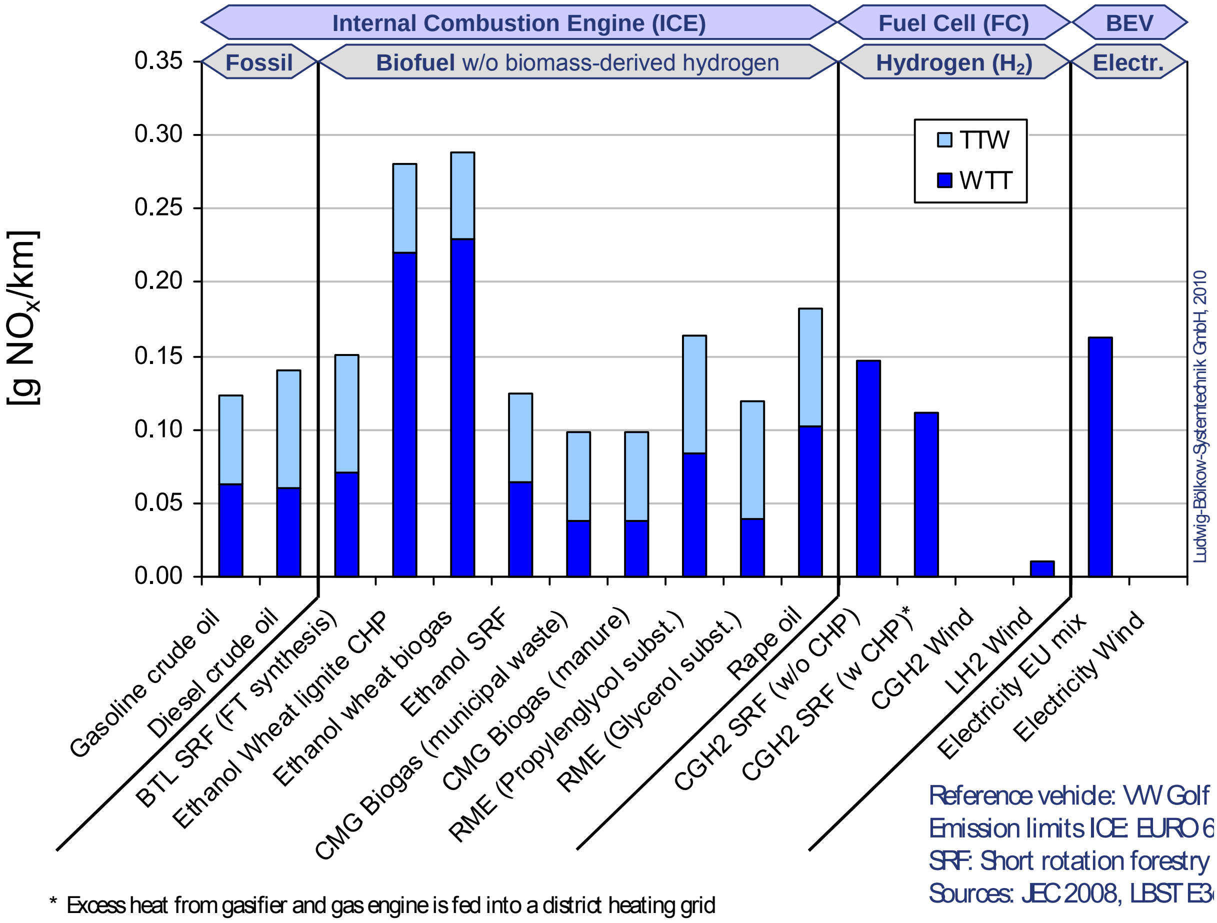


Figure 3: **Nitrogen oxide emissions “well-to-wheel”, based on VW Golf with EURO6 emission standard (applicable from 2014).**

6 Land-use

The European goal of substituting 10% of transport fuel consumption by alternative fuels by the year 2020 is designed to essentially be met by biofuels. Assuming all biofuel crops to be grown in Europe, this would require substantial land areas. Figure 4 relates these to the total arable land available in EU-27. Conventional biofuels would require some 25-35% of arable land, while second generation Biomass-to-Liquids would require 20%. Preliminary values for algae-based fuels indicate that around 5% would be required under very strong irradiation conditions, while under central European conditions this value goes up to 25%. Direct renewable power for hydrogen fuel cell vehicles or battery electric vehicles requires less than 5% of arable land in the EU. It should be noted here that algae can be grown on non-arable lands (similar to photovoltaics) and that wind power still allows for agriculture on the land covered.

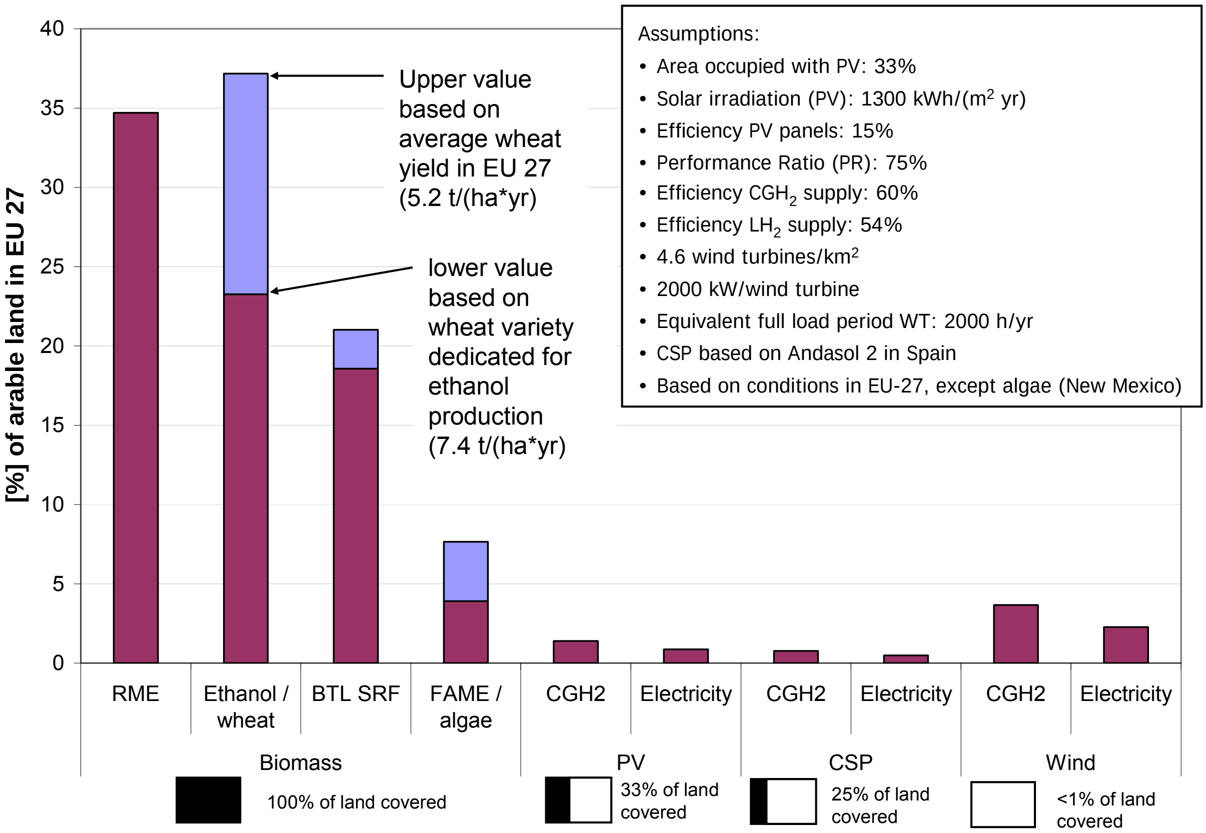
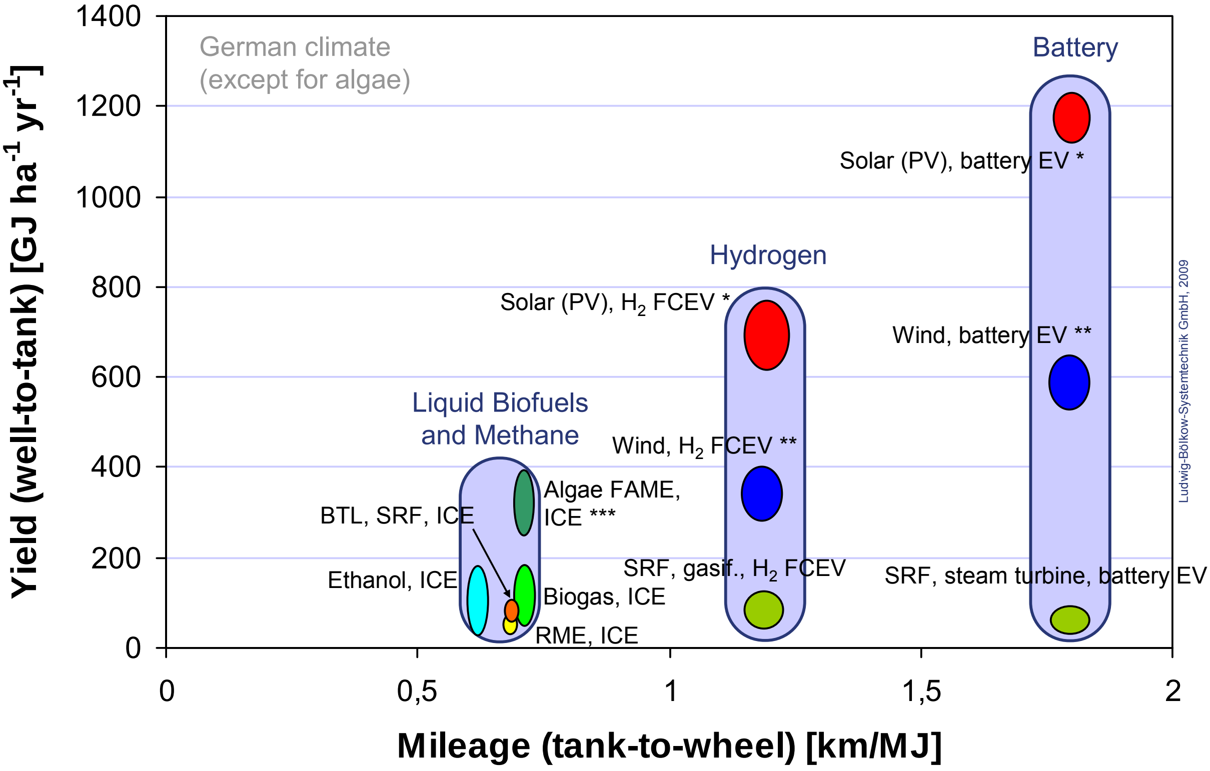


Figure 4: Land-use of various transport fuels in terms of share of arable land required for achieving the EU of a 10% substitution of conventional fuels by 2020.

Figure 5 maps vehicle mileage against fuel yield per hectare. A clear grouping results with liquid biofuels showing lowest yields as well as lowest mileage; hydrogen fuel cells showing medium values; and battery vehicles highest. This is a clear indicator that battery electric vehicles would be the best solution if they achieved the performance levels of conventional or hydrogen fuel cell vehicles.

Fuel cell-electric vehicles have a head start compared to pure battery-electric vehicles in terms of operating performance (range, temperatures, etc.). Demonstration projects are required to validate whether the very high expectations set on battery technology can be delivered under real-world conditions. Despite economic challenges for both technologies, the key question should not be “Which technology’s gonna make it?”, but rather “Which shares between batteries and fuel cells perform best in future hybridised drive-train concepts for the various transport applications and mobility patterns?”.



*) One third of the area is occupied with PV panels
**) more than 99% of the land area can still be used for other purposes e.g. agriculture
***) region with high solar irradiation

Figure 5: Mapping of key performance criteria “mileage” versus “yield” for different fuels and drive-train options under German conditions (except for algae).

7 Water Intensity

Analyses based on average or typical values of water requirements show that biofuels production in general consumes several orders of magnitude more water than electrolytic hydrogen production, or electricity generation from solar thermal power plants (see Figure 6). This is aggravated if inefficient irrigation systems are used for cultivation (flood, spray, furrow, and drip irrigation in increasing order of efficiency). The agricultural sector is responsible for some 60% of world water consumption. Sea water desalination for electrolytic hydrogen production only requires 0.13%-0.16% of the power consumption of the electrolysis process itself [4], [5]. "Grey waters", i.e. water consumed in manufacturing the production machinery and infrastructure have not been taken into account. It is assumed that they are negligible, similar to "grey energies".

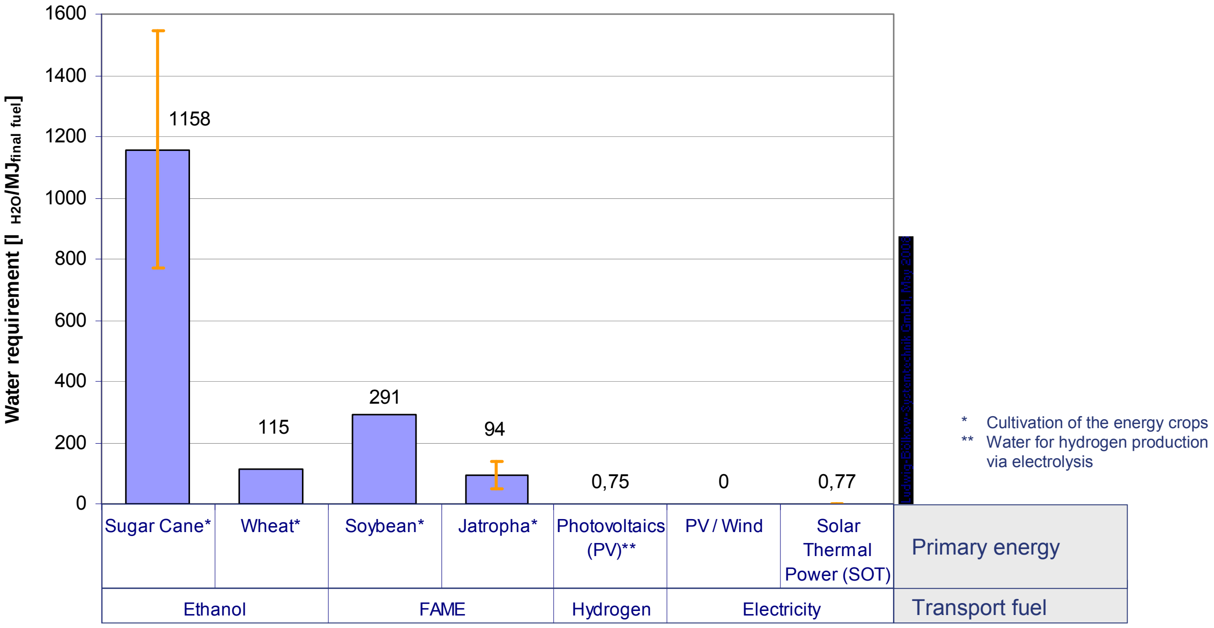


Figure 6: Water requirement for the cultivation of various crops used for biofuels, for electrolytic hydrogen production, and for renewable electricity generation.

8 Conclusions

It is shown that biofuels are most complex, most critical, and provide the lowest potential, but can be used as a 'drop-in' substitute not requiring new infrastructures or vehicle propulsion systems. Battery electric cars are most efficient, can rely on abundant renewable electricity potentials, but have a limited operating range (battery swapping to be validated) and require new recharging infrastructure build-up. Hydrogen and fuel cells provide it all – great primary energy potential, high environmental performance based on renewable energies, and a sufficient operating range – but require pro-active infrastructure build-up. Therefore, all solutions are needed at different scales and for different applications while avoiding exaggerated expectations.

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WTW Analyses and Mobility Scenarios with OPTIRESOURCE

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1 Overview

Today´s road transport is facing a number of challenges which will only be overcome if new sustainable and competitive solutions for fuels and powertrains can be realized. One issue is to take decisions for the choice of fuels and drive train technologies which have to be developed. The variety of options is huge: biodiesel, ethanol, DME, methanol, methane (either in natural gas or produced from biomass), hydrogen and electricity are only a portion of the alternative fuels. Hybrid electric vehicles, plug-in hybrids, electric vehicles with battery and and electric vehicles with fuel cell are the vehicle technologies which are currently being discussed. Not only maturity of the different technologies for fuel production and distribution as well as vehicle technologies are to be considered when selecting those technologies which should be promoted by politics and industry. Very important criteria like well-to-wheel energy consumption and green-house-gas emissions as well as production potentials of the fuels are of utmost importance. Daimler has used the software tool OPTIRESOURCE to investigate the impact of introduction of alternative drive trains and fuels on future energy consumption and GHG emission in different scenarios for the German car park. In the presentation detailed results of these scenario calculations will be shown. Emphasis is given to electric vehicles, such as battery electric vehicles and fuel cell electric vehicles.

2 Introduction

Security of fuel supply, air quality and climate change are the main reasons for the need of the introduction of alternative fuels and alternative drive trains for transport applications, especially road transport. A considerable number of options and solution is currently being developed, some are already on the road. Due to the variety of different fuel and drive train options it is not easy to asses the effects of these solutions on total energy consumption and the environment. Several studies concerning the energy consumption and green-house-gas (GHG) emissions of different transport options have been carried out and published. As the matter is very complex, only experts are able to interpret the results of such studies. Furthermore, results showing the benefit of a particular solution in terms of fuel consumption and GHG-emissions for a single car do not show the effect of the introduction of the technology in total. In order to enhance the understanding of such effects, Daimler decided to develop a software tool for the visualization of single energy chains for road transport applications and build up of scenarios for mobility. The software uses data for energy consumption and GHG-emissions from WTW-studies which already have been carried out. In the first version, most data were taken from the EUCAR/CONCAWE/JRC-WTW-study . As this study did not cover all possible options, data for some drive train options have been created by the Ludwig Bölkow System Technology GmbH and integrated in Optiresource®. The software can either be used to compare single energy chains in the query mode or to investigate the impact of new fuel and drive train options on total energy consumption and GHG-emissions. More information about Optiresource® can be found on http://www.optiresource.org. Furthermore, a public version of the Optirsource® query mode is located on the Daimler website on http://www.daimler.com/go/optiresource.

3 Software Description and Data Sources

The base philosophy of the Optiresource®-Car software is to use existing data implemented in a purpose-made database. The database plus the user interface constitute the Well-to-Wheel (WtW) system. All data from the study and these of the additional chains were incorporated in the database of the visualization software. This database contains the data defining the different energy paths from Well-to-Tank (WtT) and Tank-to-Wheel (TtW) in terms of energy efficiency, greenhouse gas emissions or any other available parameter. The users do a query to the database and get the results in terms of a visualization of the absolute or relative values of energy consumptions and GHG-emissions of each path. The way the query is done and the way the results are displayed depends on the kind of user. The data base stores and elaborates the data, the user interface manages how the query is done and how the results are displayed.

3.1 Query mode

The user chooses the quantities he likes to see (energy, GHG or both in the first version), the time period to which these quantities refer (2002, 2010 or both for the first version) and the energy chains. To select the energy chains, the user can select one or more primary energies and/or one or more processes, one or more fuels and/or one or more powertrains. It is possible to select all the chains with one single command. The selection can be done in a random way (the sequence of the choices is free). The system automatically pre-selects all the possible choices, according the selections made in the previous step. At the end of the query, the results are displayed in a bar diagram. The system is already designed to include the choice of various geographical contexts. A typical result of a query is shown in figure 1.

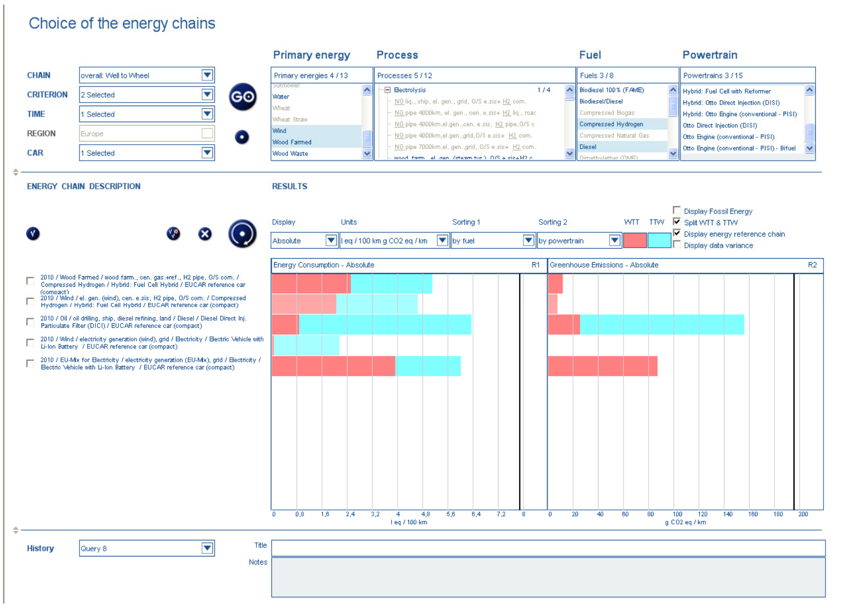

Figure 1: Example for the visualization of WTW-energy consumption and GHG-emissions in the query mode.

3.2 Scenario mode

In this modality the user defines the energy mix, the composition of the vehicle fleet (type, km/year driven and quantities) and the technical improvements of a certain geographical area. As an alternative, pre-set scenarios can be up-loaded and modified. The results show what happens in that area in terms of quantities related to the technology (e.g. l/100km, MJ/100km, miles/gallon, GHG/km, GHG/mile) or any other available quantity in comparison with the present situation of that area. Figure 2 shows the result of a typical scenario produced with Optiresource.

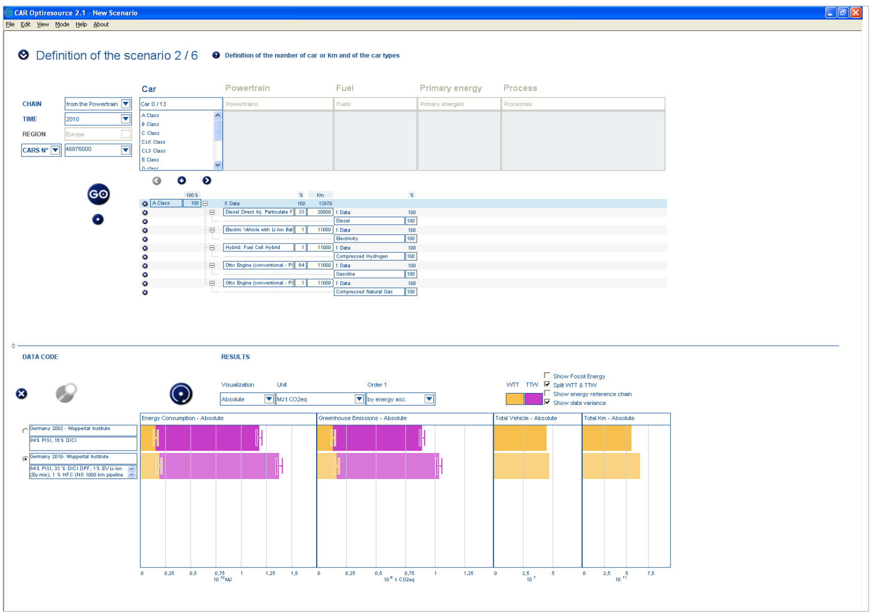

Figure 2: Example for the visualization of results from the scenario mode.

4 Description of Investigated Scenarios

4.1 Basic Scenario and Reality Check Scenario

Building scenarios for future road transport first needs a basic scenario in order to make reality checks and then compare results of the future scenarios with the basis. The base scenario consists of 50 million compact class cars, each of them driving 12,000 km per year. The driving pattern was also simplified: it has been assumed that the cars are always driven in the New European Drive Cycle. The share of diesel engines in the base scenario is 23%, the share of gasoline engines is 77%. All other drive trains are disregarded in the base scenario. Table 1 displays the parameters chosen for the base scenario.

For reality check we have also used Optiresource® to obtain the respective calculated energy consumption and GHG emissions for all passenger cars in Germany. The numbers used for this scenario were taken from a publication of the DIW and are shown in table 2.

Table 1: Parameter list for Base Scenario.

Car type	Mileage/car	Number of cars	Driving Pattern	Drive Train	Fuel
Compact class	12,000	38.5 Mio (77%)	NEDC	Otto engine (Port injection)	Gasoline from crude oil
Compact class	12,000	11.5 Mio (23%)	NEDC	Diesel engine (Direct Injection with particle filter)	Diesel from crude oil

Table 2: Parameter list for Reality Check Scenario.

Car type	Mileage/car	Number of cars	Driving Pattern	Drive Train	Fuel
Compact class	10,900	36.0 Mio (79%)	NEDC	Otto engine (Port injection)	Gasoline from crude oil
Compact class	19,500	9.6 Mio (21%)	NEDC	Diesel engine (Direct Injection)	Diesel from crude oil

4.2 Alternative scenarios

Currently, a number of different options for future mobility are in discussion, some of those being already on the road to some extent, some others being still in the development phase. We have investigated scenarios for four different future scenarios. Detailed description of the scenarios will be shown during the presentation.

5 Results

5.1 Energy use and GHG emissions for Reality Check Scenario

As already explained in the description of the basic scenario, we have used a simplified scenario. As simplification always causes uncertainties, we have checked the accuracy of the model results by comparison with real data for passenger cars in Germany in the year 2005. Table 3 shows the data obtained with Optiresource® as well as the published data.

Table 3: Comparison of Optiresource® results with data for Germany.

	Total energy consumption for passenger cars tank-to-wheel (TTW) (MJ)	Energy consumption per 100 km TTW (MJ/100km)	Total GHG emissions from passenger cars TTW (tons)	GHG emissions per km TTW (g_{CO2eg}/km)
Data for German passenger cars in 2005	1.48×10^{12}	255	110×10^{6}	189
Results from Optiresource® for simplified scenario for Germany 2005	1.22×10^{12}	210	92×10^{6}	158

The comparison shows that both TTW energy consumption and TTW-GHG emissions of the Optiresource® scenario and real data differ in the range of 15%. Considering the simplification of the inputs for the scenario, using only one car type, deviation is rather small. The fact that the Optiresource® results are lower than real data can be explained with the different ages of the vehicles. In Optiresource® the data for the 2002 compact class reference vehicle were used, whereas the cars being actually on the road show a broad distribution of ages and are mostly equipped with older engines with somehow higher fuel consumption and CO_2-emissions. Other main reasons are the variety of vehicle types on the road and the real driving patterns which also differ from the NEDC. Taking all this into account, the results obtained with Optiresource® give a fairly good correlation with reality.

5.2 Alternative scenarios

The electrification of road transport is one of the major efforts taken in the automobile industry. It is expected that fuel cell electric vehicles (FCEV) and battery electric vehicles (BEV) will be introduced in the market within the next five years. The impact of different market introduction scenarios of FCEVs and BEVs will be shown during the presentation.

Infrastructure Issues of Decoupled Hydrogen/ Electricity Production with Carbon Capture and Storage

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1 Introduction

On the way to establish a large scale “hydrogen economy”, the undertaking of consequent upfront infrastructure costs is generally anticipated as the main obstacle. Indeed, a high risk of stranded investment exists while no demand market has been proved on the end-user side. In order to reformulate this “chicken-or-egg” dilemma, the present work explores a possible transition path based on existing mid-term energy options for electricity generation.

For a conceivable fossil-fuelled electricity production strategy with CO_2 capture, the location of available storage options could play a key role for plant siting, as expensive CO_2 transport infrastructure might be required in some configurations. The possible spatial separation of electricity generation and centralised fossil hydrogen production with CO_2 capture and storage allows an additional degree of freedom in the system in enabling the transport of hydrogen instead of electricity.

In this study, we analyse energy conversion and transport tasks associated with the plant locations offered by this enhanced scheme. By considering various scenarios for Germany, we describe different gasification/ reforming options with CO_2 capture and estimate their cost, including where new infrastructures are required.

2 Methodological Approach and Limits of Analysis

2.1 General system definition

Different options for the installation of new fossil-fuelled electricity generation facilities within Germany are discussed. We consider imported hard coal and natural gas as primary energy carriers, the former being delivered at existing harbours in the Benelux or in the north of Germany whereas the latter is directly sold at the power plant gates to electric utility consumers. For reasons of simplification, we assume that no secondary energy carrier enters our system. Secondary energy carriers considered here are high voltage electricity delivered to the big energy consumption areas identified below and optionally gaseous hydrogen as an intermediate. We do not formulate any assumption on the final use/ conversion of the electricity.

The modelled fossil-fuelled power or gasification/ reforming plants are equipped with carbon capture systems. The captured CO_2 will have to be transported to underground storage options.

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Costs associated with all processes modelled in our system are evaluated to make different pathways comparable. Upstream CO_2 emissions like contributions of primary energy carrier exploration and transport are not assessed here.

Accordingly, this study should neither be regarded as a Well-to-Wheel study nor as a Life-Cycle-Assessment but aims at analysing conversion and transport options.

2.2 Conversion tasks

In a conceivable fossil-fuelled electricity production strategy with CO_2 capture, we selected the hard coal Integrated Gasification Combined Cycle (IGCC) and the natural gas Combined Cycle (NGCC) technologies. The pre-combustion capture process envisaged for the IGCC produces a hydrogen rich gas as an intermediate product. Instead of burning it in a syngas combined cycle, it can be further cleaned to make hydrogen available as a product of a gasification power plant. We also retained the natural gas reforming option with carbon capture as an alternative for hydrogen production. The hydrogen can fuel a combined cycle for central decoupled electricity generation.

2.3 Plant locations

The choice of power plant location is classically driven by the main operational constrains[2], namely the proximity of water courses (or sea) able to meet the process cooling needs, the possibility to deliver the fuels and to export the relevant secondary energy carrier. In addition to these criteria, the present study explores the relevance of siting carbon capture power plants nearby a CO_2 storage option (for Germany, as a rule, carbon dioxide storage options are not located near existing power plants or import/ exploration sites). The decoupled hydrogen/ electricity production is also envisaged to add a further degree of freedom to the system. As an example, we detail in Table 1, the allowable plant locations for the hard coal alternative in the base case of one seaport, one consumption centre and one storage option. Figure 1 depicts illustrative examples.

Table 1: Power plant locations and associated processes – hard coal alternative.

Power Plant	Power Plant Location	Electricity	Note
IGCC	Seaport	Coupled	Consumption Centre and/ or Storage Option in some scenarios
Gasification to H_2	Seaport	Decoupled	Storage Option in some scenarios
IGCC	Consumption Centre	Coupled	Seaport and/ or Storage Option in some scenarios
H_2 Combined Cycle	Consumption Centre	Decoupled	
IGCC	Storage Option	Coupled	Consumption Centre and/ or Storage Option in some scenarios
Gasification to H_2	Storage Option	Decoupled	Seaport in some scenarios

2 In addition to usual building requirements: site accessibility and constructability under sustainable economical and environmental conditions together with the successful completion of the permitting process.

2.4 Transport tasks and infrastructures

Transport tasks required by the conversion processes and plant locations retained in this study are listed in Table 2, together with the associated infrastructure. This provides the basis of the scenario comparison proposed in this article.

Table 2: Transport tasks and associated infrastructures.

Transport	From\To	through	Network Status
Hard Coal	Seaport\Power Plant	Rail/Ship	Existing
Natural Gas	- \Power Plant	Pipeline	Existing
Hydrogen	Power Plant\Consumption Centre	Pipeline	To be built
CO_2	Power Plant\Storage Option	Pipeline	To be built
Electricity	Power Plant\Consumption Centre	HV Network	Existing

Keeping short every transport route is crucial to avoid losses and/ or additional costs. For that purpose, we used an internally developed Geographical Information System (GIS) to optimise transport distances. This tool finds optimal paths through the given set of the existing German infrastructures (waterways, railways, highways, high pressure natural gas grid and high-voltage transmission network). Transport distances along the existing networks referred to in Table 2 can be measured directly whereas we assume that CO_2 or H_2 pipelines will align the combined existing routes, thus reflecting allowable right of way and local geographic conditions (relief, protected area…) constraining any new infrastructure construction.

3 Model Description and Assumptions

When new infrastructures or power plants have to be built, capital costs are calculated according to the annuity method. Operation and maintenance costs are added to this annual charge.

Costs and performances assumed for the study reflect a plausible status for the year 2030. This is in line with expectable timeframe for designing, gaining necessary consents, building and commissioning the technologies selected here.

To ensure continuity with previous works, all reported costs refer to the year 2000. Likewise, primary energy import prices suit the scenario ranges selected in Hake et al. (2009) [1]: 3,5 respectively 5,9 $€_{2000}/GJ_{LHV}$ for hard coal and 7,0 respectively 11,9 $€_{2000}/GJ_{LHV}$ for natural gas (low respectively high prices). An emission price is also set to 31 $€_{2000}/t_{CO2}$ in line with Umweltbundesamt (2009) [2] scenarios.

A literature review of future expectable hydrogen and electricity generation costs was performed for the proposed power plants equipped with CO_2 capture. Our model proved to fit those expectations after usual fuel price/ inflation/ currency corrections.

Hard coal transport costs per barge and/or rail are modelled following the framework described in Prognos (2006) [3] for Germany. Actual natural gas transport fees against delivery location and volume are difficult to access, moreover taking into account the various locations of existing gas import options in Germany. Therefore, this study estimates the cost of natural gas sold at the power plant gate[3].

Hydrogen transport costs are based on the model from Yang & Ogden (2007) [5] [Yang & Ogden, 2007], crosschecked with other sources. CO_2 transport and storage costs for Germany are set within the range reviewed in Wietschel et al. (2010) [6].

In the absence of accurate information on electricity transport fees through the high voltage network, costs are estimated on a simplified energy loss basis (Neither existing network reinforcement nor construction are accounted for). It should be noted that such electricity transport refers to the high voltage transport network and do not allow for distribution to the final energy consumer (The same would apply for hydrogen, should it be derived at the exit of a transport pipeline[4]).

4 Scenarios and Results

We present a selection of significant scenarios investigated for this study.

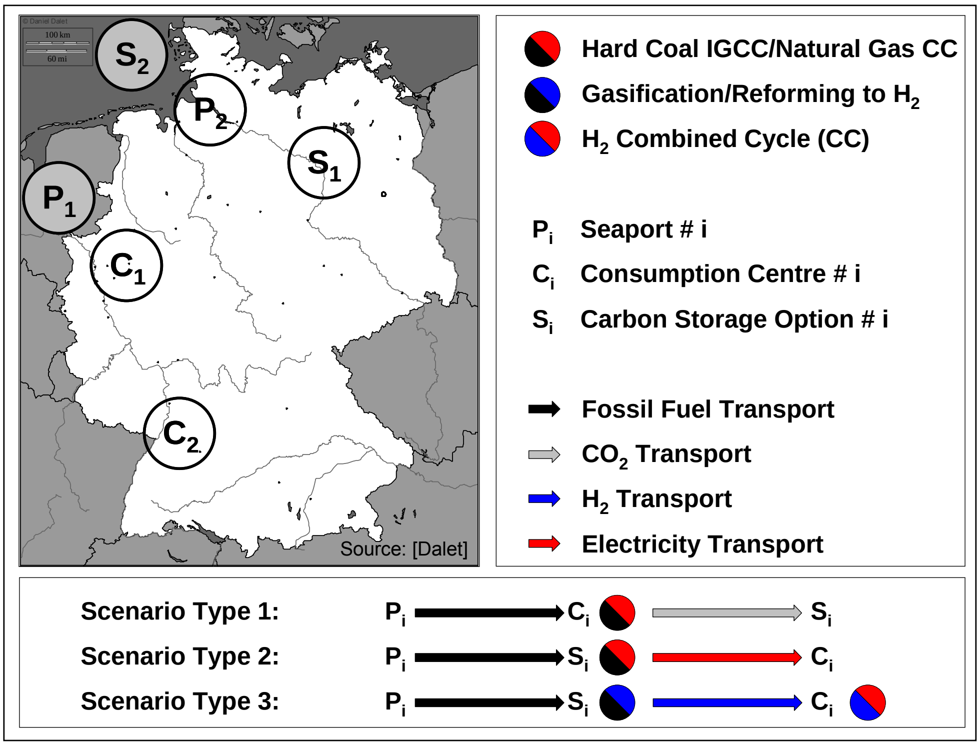

Figure 1: Selected locations and definition of three types of scenarios [7].

Figure 1 summarizes the conversion tasks, plant locations and transport tasks associated with these scenarios (See also the base combinations of locations and tasks listed in Table 1 and Table 2). Scenario Type 1 refers to the fossil fuel conversion at the consumption centres

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[3] From the difference between border and utility delivery prices, gas transport within Germany can be roughly estimated to increase its sell-price by 9 to 13% (including profit margin), Bundesnetzagentur (2009), [4]

[4] Central delivery at the pipeline exit, gaseous state – 3 to 4 MPa in our case.

whereas scenario Types 2 and 3 correspond to the fossil fuel conversion nearby carbon storage options, into electricity or hydrogen respectively.

From Figure 1, a scenario naming convention is defined for this article. As an example the abbreviation “Coal/Type 1/P_1/C_1/S_1” is referring to “Primary energy Coal/Scenario Type 1/Seaport #1/Consumption Centre #1/Carbon Storage Option #1”.

4.1 General trend and implications

Representative base scenarios are compared in Figure 2 for the hard coal and gas alternatives. The cost of electricity produced and transported to consumption centres stays within a similar range for all three types of scenarios proposed and mainly differs in the resulting transport tasks. The costs associated with an additional hydrogen generation step (and transport infrastructure) seem to be moderate. Despite good efficiencies and reasonable investment costs, the natural gas case is penalised by high shares of fuel costs in the final electricity costs. This is even more emphasised for scenarios of high energy prices depicted by the thin bars in Figure 2.

We also note that the question of transporting electricity instead of hard coal is more open with carbon capture and storage power plants, as additional CO_2 transport costs arise when fossil fuel is converted near to energy consumers. A more refined model of electricity transport costs would be required to address this point (reflecting high voltage network access costs, possible additional capacity needs…).

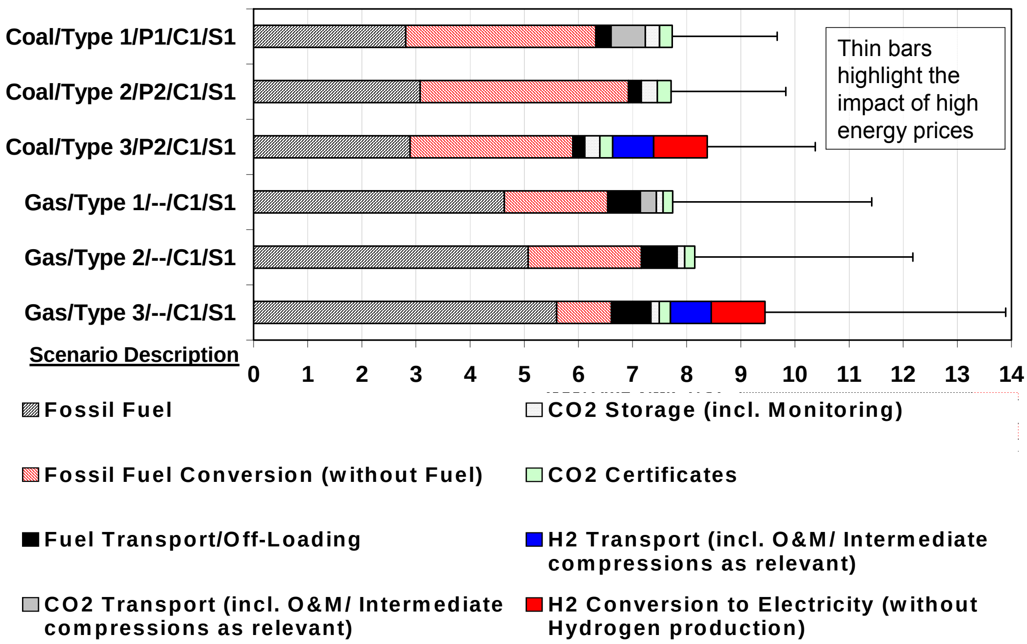

Figure 2: Costs of electricity (Eurocent$_{2000}$/kWhe) at consumer centres (High voltage – excluding distribution) for selected scenarios.

Types of scenarios are defined in Figure 1; Seaport for hard coal P_1: ARA (Amsterdam, Rotterdam, Antwerpen); P_2: Hamburg; Consumption Centre C_1: Ruhr area; Carbon Storage Option: S_1: Onshore Aquifer

4.2 Alternative locations

The impact of different locations for consumption centres and storage sites has been evaluated for the hard coal example. We propose in Figure 3 the comparison of two consumption centres, namely the Ruhr area (C_1) and Karlsruhe area (C_2). The overall cost of electricity is reasonably affected by the almost doubled transport distances for hydrogen and CO_2. The pipeline starting/ ending at Karlsruhe were forced to cross the Ruhr area to suit an expectable future pipeline demand in this big consumption centre. This penalising assumption reflects plausible pipeline routes but should be balanced by the possibility to mutualise pipeline costs with other users.

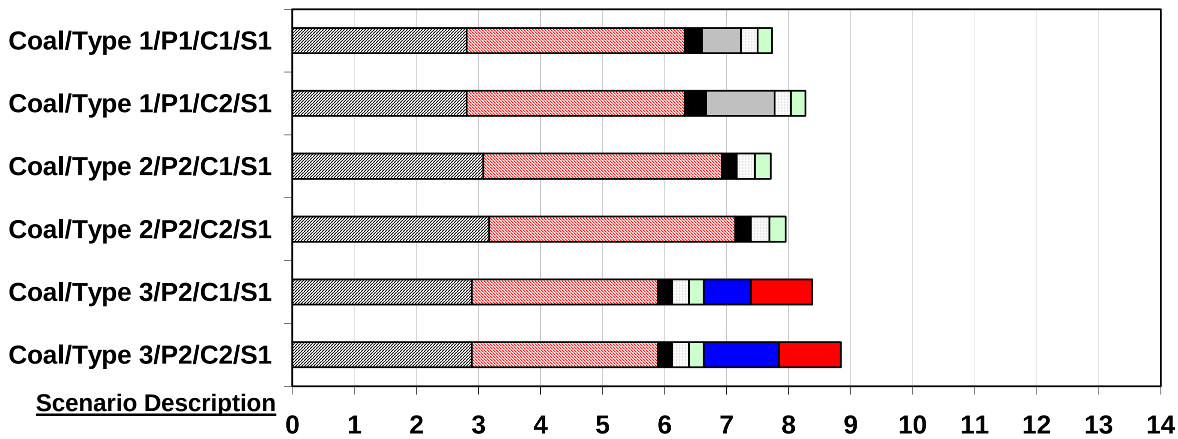

Figure 3: Costs of electricity (Eurocent$_{2000}$/kWh$_e$) at consumer centres (High voltage – excluding distribution) for selected scenarios.
Consumption Centre C_2: Karlsruhe area; Other assumptions and keys as defined in Figure 2

Alternative carbon storage locations were also analysed. Under our assumptions, choosing the offshore aquifer option S_2 would be slightly more expensive than the onshore aquifer option S_1. All scenarios would be penalised by the expected higher costs for offshore pipelines and sequestration. Moreover, for scenarios Types 2 and 3, the fossil fuel conversion would occur near to a seaport (not at the storage location directly) and require the construction of CO_2 transport pipelines (offshore) which were avoided for scenarios Types 2 and 3 associated with an onshore storage option.

5 Conclusion

Taking climate protection constrains into account, the CO_2 emissions of fossil fuelled power plants have to be captured and safely stored. Such a strategy implies the construction of a sufficient infrastructure. For fossil-fuelled electricity generation with CO_2 capture, siting power plants near to carbon storage options should be considered further. Electricity or hydrogen can be transported to make these emission-free secondary energy carriers available near to consumers. In addition, it seems that moderate additional costs could allow the implementation of a first level hydrogen transport infrastructure instead of building a CO_2

transportation network. This could be a smooth way to finance and facilitate the transition to a future larger “hydrogen economy”. On the long term, this infrastructure would be in place for the transport of a non fossil H_2 generation.

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Potential of Hydrogen-Oxygen Fuel Cells in the Transportation Sector

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1 Introduction

To cope with the increasing demand on individual mobility the efficiency of the powertrain of the car has to be increased significantly compared to the state of the art. At the same time the energy demand of the vehicle has to be lowered by mass reduction and by lowering the resistances (air drag, rolling resistance).

In this context the application of an electric motor (EM) within the powertrains opens a large potential for efficiency improvements and the availability of a new torque characteristic which leads to a wider range where the nominal power is available.

To provide the energy demand of the EM electricity has to be released from an onboard storage device (battery) or has to be generated (fuel cell, auxiliary power unit APU) based on a chemical energy carrier. The design of the adequate energy-storage-device or a mix of several storage devices is among other factors a question of the required autonomy and performance of the vehicle, requested emissions level of the vehicle operation, the costs and also from the available infrastructure for fuelling.

For the electricity supply of the board net via APU hydrogen as well as hydrocarbon-based fuels can be considered as fuels. For HC-based fuels a reformer is needed or the application of a direct methanol fuel cell is another option. If the FC is considered as propulsion unit for the vehicle direct stored hydrogen can be seen as the only appropriate option.

For both option the refill time of the tank is not a limiting option given that the fuel for some 100 km range can be transferred with a few minutes to the vehicle.

2 Powertrain Based on a PEFC

An electrical powertrain comprising only a fuel cell is a possible configuration and there has been some vehicles running, demonstrating the feasibility of such a concept. In the last years the majority of the solutions for passenger cars were combinations of an energy storage device and a fuel cell. The main advantages are (i) the power demand of the vehicle can be split in a continuously available power and a peak power which has to be provided only for a limited time. (ii) If an energy storage device in form of a battery or a supercapacitor unit is available braking energy can be recuperated. (iii) The dynamic requirements to the fuel cell system can be partially decoupled from the power demand of the driver.

Plug-in concepts can be realized for these hybrid-kind powertrains where the battery can be charged from the grid as well as from the fuel cell.

3 Use of Pure O_2 Compared to Air as Oxidation Media in a PEFC

The operation of a PE-FC-system, which is using direct H_2, is mainly influenced by the selection of air or pure O_2 as oxidation media. The differences are manifested on the cell respective the stack level, at the level of the auxiliaries for the system and in the integration and characteristics of the system in the vehicle integration.

We are looking at the three levels in the following:

3.1 Cell/stack level

Within the cathode side the gas flow in the case of pure is lower because the nitrogen is not present. For every mol of O_2 consumed by the reaction a mol of product gas (H_2O) is produced. In case of liquid water the product gas volume will shrink further.

Consequence: Gas channels n the cathode side can be made less high, resulting in the potential to reduce the thickness of the bipolar-plate on the cathode side.

With the pure O_2 the reaction-resistance on the cathode is diminished. The characteristics of the voltage –current curve is more flat over a large area.

Consequence: There exists a potential for increased power density at higher voltage. To realize this potential the heat transport and the electricity resistance has to be in line with the increased specific power density.

Since the conflict of transporting the gaseous educts and the product-gases is less severe in the case of pure O_2-usage, the requirements of the porosity and structural composition of the gas-diffusion layer (GDL) is less demanding.

Consequence: Cheaper materials can be use for the GDL on the cathode-side.

Using air as oxidation media face the challenge that at specific locations the air is polluted with unknown molecules at varying concentrations. Therefore the absence of air, the pollutant concentration at the electrode-interface, or in the GDL can be reduced in a large extend. The only source of pollutants could be impurities carried by the oxygen.

Consequence: Pollutant based degradation on the cathode side can be limited significantly by using pure O_2.

3.2 Fuel cell system (auxiliaries) level

Since the oxygen content of air is approximately 21%, the air is often compressed to gain enough O_2 for the reaction. Using pure O_2 enables to reduce or avoid entirely some of the auxiliaries. No air compressor is needed. The compressed O_2 can be fed directly from the pressurized O_2 tank.

In combination with the avoidance of a compressor also no charge air cooler is needed, which reduce the total heat-exchanger area required in a vehicle.

The output O_2 can be recirculated and combined with fresh gas. Since the cathode-exhaust is in most cases in a saturated state. Therefore there can be designed a system without an additional humidifier of the oxidation gas.

Using pure O_2 helps to reduce the volume of the air ducts. The pressure level of the O_2 can be chosen higher than air. Consequently further reduction of the pipe diameters can be achieved. A significant volume is attributed to the air filter which is not required in the O_2 case.

Consequence: Reduced volume and mass of the auxiliaries (no compressor incl. its electrical motor, no oxygen humidifier, charge-air cooler, air ducts, air filter).

The absence of an air compressor reduces the noise level dramatically at least in the cases of a high pressure compressor. The compressor is normally the source of the highest noise level and defines significantly the noise reduction efforts towards the environment and the passenger compartment. Beside the noise, also the vibration level of the fuel cell system is heavily influenced by the characteristics of the compressor.

Consequence: Less effort to spend to separate noise and vibrations from the fuel cell system to the passenger compartment and the environment.

The fact that H2 and O_2 are both stored as pressurized gases in the vehicle in case of pure O_2-application the pressure level of operation can be varied in a much wider range than in case of air. This can be used to increase the efficiency for a specific requested power (higher voltage level with higher pressure level).

Consequence: Wider power range > 1:20 by application of a variable system pressure range.

The power output of an H_2 - O_2 fuel cell system is not disturbed by operation at variable altitude. In high altitude the air based system has to provide more compression energy for the same O_2 output resulting in a lower net-power output of the fuel cell system

Consequence: No adaptation for high altitude operation is required for O_2 – systems.

The lower resistance on the cathode side for the O_2 operation leads to higher efficiencies and therefore the cooling requirements for the total system can be reduced for the same net-output power.

Consequence: Lower heat-exchanger needed in the vehicle.

The absence of an electrical driven air-compressor as a large mechanical inertia in the gas supply path leads to a much higher dynamic behaviour of the FC-system. The nominal power output can be reached within < 100 ms.

3.3 Vehicle level

The increased efficiency of the stack as well as of the system the fuel demand for a specified range is reduced significantly compared to an air system. Since efficiencies above 60 – 62% are possible for a wide range this reduction can be as large as 15 – 20%. In comparison with the air system an additional pressurized tank is needed for the O_2. This tank is in principle half the size of the H_2 storage. In particular this has to be adjusted depending on the maximum pressure as well as in relation of the real gas properties. In fact at a pressure level of 200 bar the gas properties of O_2 favour a smaller tank.

In vehicle applications short start-up times are important. The fuel cell system based on O_2 favours minimal starting time. The gases can be provided out of the storage tanks at a required pressure level nearly without delay. In addition the simplicity of the fuel cell system can be used for smallest gas volumes outside the stack as well as for low thermal capacity of the auxiliary components. Together with the low thermal heat capacity of the stack, based on its high power density, the heat-up time of the system from start-temperature to the nominal temperature can be kept reasonable short.

3.4 Infrastructure level

It is true that at the logistic side two gases are needed to be fed to the vehicle. If we take into account that most of the low-CO_2-emitting energy paths are transported via electricity the use of an electrolyses-process offers an option to produce H_2 and O_2 at the same time in the needed quantities. In case of harvesting intermittent renewable energies like wind or sun via PV, the use of decentralized electrolysers offers a way to transmit larger amounts of this energy into fuels without the explicit need to install reserve capacity in the grid.

Impact of Industry Strategies and Consumer Attitude on Growth of the Hydrogen Vehicle Fleet and Corresponding Refuelling Infrastructure

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Summary

Hydrogen is seen as a major energy carrier for future transport. For this to be actualized, the parallel roll-out and growth of the hydrogen passenger car fleet and corresponding refuelling infrastructure must be guaranteed. Within the THRIVE project[1] ('Towards a Hydrogen Refuelling Infrastructure for Vehicles') a tool called THRIVE ALLOCATE has been developed to simulate the interdependent rollout of hydrogen cars and refuelling infrastructure in both temporal and spatial domains. The behaviour and strategies of three major actors involved – consumers, fuel suppliers and car manufacturers – are modelled and their impacts analysed. The model has proven to generate plausible results by combining assumptions in consistent ways, which in this study are considered to reflect low to high industry ambition levels. Simulations of base case scenarios show H_2 car penetrations ranging from about 5% to 35% of the total passenger car fleet by 2050. However, extension of the initial H_2 refuelling network, the introduction of H_2 cars via the lease car market or a change in consumers' refuelling behaviour might lead to hydrogen car penetrations of 60% or even more.

1 Introduction

THRIVE ALLOCATE is the core of the project THRIVE. This study tackles the chicken-and-egg dilemma from a demand-pull rather than technology-push perspective, simulating interdependent rollout of cars and infrastructure taking real-world conditions into account. Further projects can use this study's results and tools to help identifying potential regions, relevant stakeholders as well as economic and environmental impact of different technologies and strategies involved. Consequently it can help evaluating actions to be taken for a successful introduction of hydrogen as alternative transport fuel for passenger cars.

In this paper we present the working principles of THRIVE ALLOCATE, the storylines behind the scenarios and give an insight into sensitivities towards industry strategies and consumer attitude. More detailed information on the model, input parameters and other analyses carried out in the course of the THRIVE project can be found in [1, 2].

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[1] THRIVE is a 3-year research project led by ECN and joined by TNO (representing research institutes), Shell and Linde Benelux (representing industry).

2 THRIVE ALLOCATE

2.1 General Working Principles

In the real world consumers purchase cars mainly based on the car's price and characteristics (brand, model, safety, range, etc) as well as the local and countrywide availability of the fuel and its price [3]. These criteria are influenced by car manufacturers, fuel suppliers and policy makers (regulations, taxes, subsidies, …). THRIVE ALLOCATE, a MATLAB® based dynamic model, simulates the consumer's purchase behaviour on zip code level and annual basis for any defined timeframe. It starts, amongst other parameters, from an initial hydrogen refuelling network and the total number of cars being sold in a particular year and zip code (Figure 1, step 0.). Coefficients, varying from 0 to 1 depending on the availability of fuel cell electric vehicle (FCEV) models and fuel, reflect the fraction of car buyers addressed. These coefficients are multiplied with the total number of cars sold in a year and zip code resulting in the total number of FCEV sold in each zip code in that particular year (Figure 1, step 1.). Subsequently it evaluates the number of new hydrogen refuelling units necessary to meet the countrywide demand (Figure 1, step 2). These units are optimally allocated to meet the local demand and to attract new consumers as much as possible (Figure 1, step 3.). Hence, the model creates its own new starting situation (Figure 1, step 0) and proceeds with the next iteration, i.e. the next year. Costs are not considered in the simulation as we assume that rollout of H_2 and FCEV on large-scale will only take place if the option is fully cost-competitive from an end-user perspective. But, as H_2 and FCEV will initially be relatively expensive, the financial consequences of assuming this "level playing field" are evaluated by post-processing simulation results in separate cost models [1, 2, 4, 5].

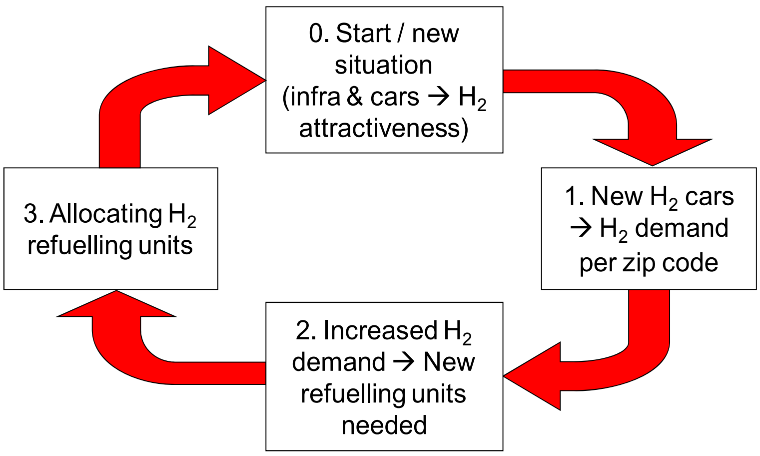


Figure 1: THRIVE ALLOCATE: Model schematics.

2.2 Description of Input

General parameters and starting points [1, 2]

- Spatial resolution: Zip codes (NL: ~4000) & drives time between zip codes
- Number of non-hydrogen passenger cars per zip code & potential fleet increase
- Annual car replacement rate resulting in annual car sales for each zip code
- Current conventional refuelling station network (location, characteristics, …)

Fuel Supplier Strategies

- Initial refuelling station network

  To start a simulation the model requires an initial hydrogen station network (initial "seeds"), for example resulting from large-scale demonstration projects. Based on population density, visibility and size of current refuelling stations and considerations such as availability of space and safety, we differentiate three "seeding scenarios": "Careful" (17 seeds in 2015), "Reactive" (17 seeds in 2015, 44 additional seeds by 2019) and "Proactive" (17 seeds in 2015, 88 additional seeds by 2019).

- Required refuelling unit utilisation:

  Each fuel supplier strives towards optimising the utilisation of his assets in order to stretch costs over a larger amount of fuel sold. As it takes time for hydrogen demand to develop, refuelling units are initially underutilised. As stricter the fuel industry is with regard to required increase of utilisation, the more time it will take before new refuelling units are installed and the slower the fuel availability will increase. Hence, the market for FCEV cannot develop quickly either. However, if fuel suppliers were convinced to receive a positive return on their investments, they might relax their utilisation requirements, expand their refuelling networks faster and consequently create a higher market potential for FCEV. Three strategies are differentiated: "Careful", "Reactive" and "Proactive" (see Figure 2). They are based on the development of successful natural gas vehicle markets in Brazil and Argentina.

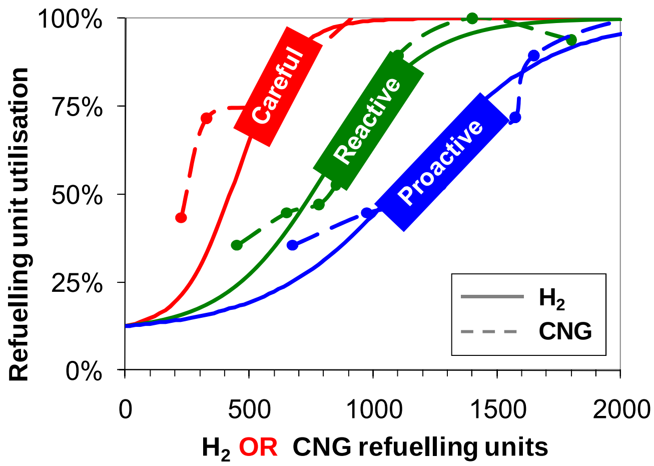


Figure 2: Fuel Supplier Strategy: Required utilization.

<u>Car Industry Strategies</u>

Dutch car market statistics show that around 100 car models deployed by 20 brands cover around 90% of the annual car sales in the Netherlands. Consequently we assume that each introduced FCEV model addresses on average 1% of all car buyers. By following statements of car manufacturers in press and discussions we assume that six brands will enter the market by 2015 with one FCEV model each. By 2030, we estimate that 20 brands have introduced at least one model. The three different strategies (again distinguished into "Careful", "Reactive" and "Proactive") are modelled based on varying FCEV deployment schemes.

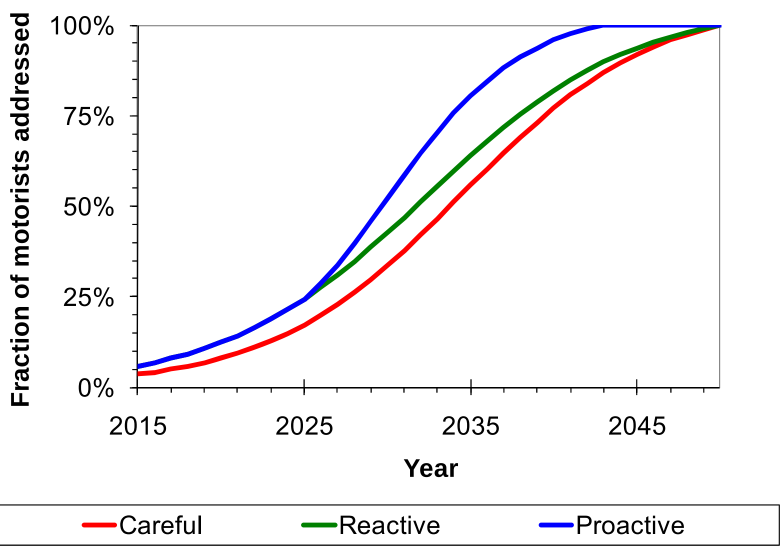


Figure 3: Car industry strategies: FCEV model deployment schemes.

<u>Consumer attitude and refuelling behaviour</u>

3000 Dutch motorists were questioned on their attitude towards alternative fuels and their current refuelling behaviour by TNS-NIPO [1, 6]. This survey is part of the THRIVE project and used to model the consumers' refuelling behaviour. Figure 4 illustrates the resulting "Drive-time-function" (solid line). Assuming that people stick to their current (usual) refuelling behaviour, the solid line reflects how far they are willing to drive (in minutes) from their home to refuel their car. The dashed line reflects a more eager attitude of people who are willing to drive further. It is derived from combining the TNS-NIPO results with another survey [2, 7]. The Drive-time-function is used to determine the local fuel availability for each zip code. Refuelling stations located closer to the consumer are more attractive for refuelling and therefore contribute more to the consumer's perception of local fuel availability. Compared to usual consumers, eager consumers perceive a better local fuel availability due to their willingness to drive further. To their awareness, more refuelling stations are locally available.

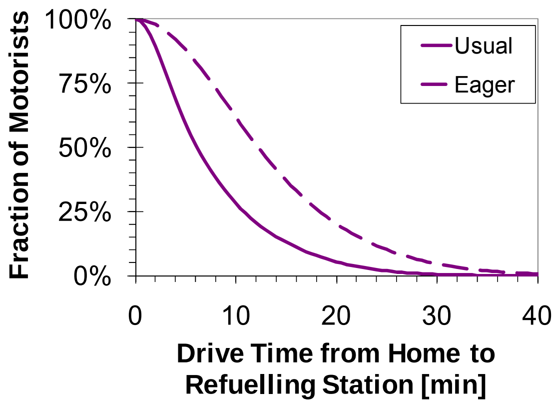
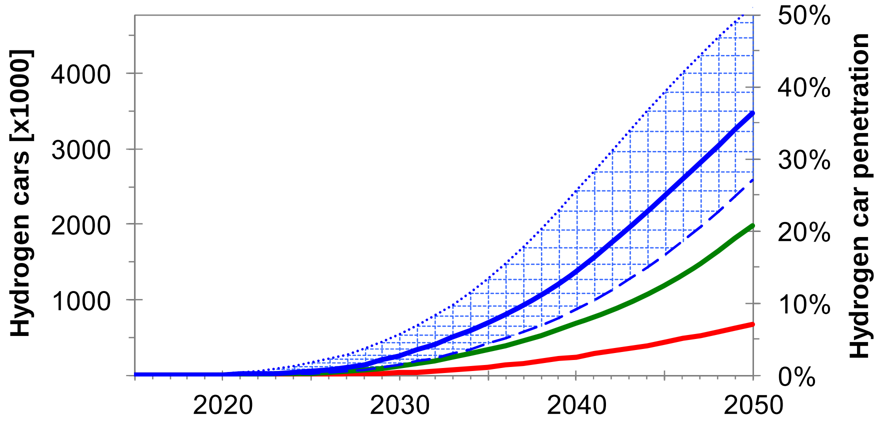


Figure 4: Refuelling behaviour and "Drive-time-function".

2.3 THRIVE Storylines

The input parameters presented in the previous sections reflect plausible consumer behaviour and industry strategies for the Netherlands as analysed within the THRIVE study. However, THRIVE ALLOCATE is capable to run any combination of assumptions and variation of input. But not every combination of assumptions makes sense. For example: If car manufacturers do not pursuit highly ambitious strategies and deploy FCEV models only on small scale, the fuel supplier industry probably won't install a large initial network of refuelling stations and vice versa. Three scenarios are developed based on coherent model assumptions on actor behaviour reflecting low, medium and high ambition levels that represent a certain trust of industries in the success of hydrogen as transportation fuel. But, even with equally careful, reactive or proactive actors on all fronts, there are still uncertainties left, which are not included in the scenarios but rather treated as sensitivities (see Figure 5).

3 Results



Scenario	Low	Medium	High		
Variation	Standard	Standard	Standard	Eager	Delayed

Figure 5: Simulation results for car fleet penetrations of FCEV. Solid lines show the results for the base case scenarios based on coherent industry ambition levels. The upper, dotted line is based on the high scenario and illustrates the effect if consumers are willing to change their refuelling behaviour. The lower, dashed line is also based on the high scenario and indicates the effect of a delayed FCEV model deployment by car manufacturers.

4 Discussion and Conclusions

THRIVE presents an integrated perspective for the deployment of hydrogen cars and corresponding refuelling infrastructure. THRIVE ALLOCATE simulates consumer-driven rollout influenced by industry market strategies reflecting different ambition levels. As its working principles can be translated to other technologies as well, the concept of THRIVE ALLOCATE could be adjusted to research chicken-and-egg dilemmas in other fields too. However, in case of hydrogen as transportation fuel for the Netherlands, THRIVE ALLOCATE shows that meaningful penetration requires a widespread upfront availability and visibility of H_2 stations, fast expansion of hydrogen refuelling station network and rapid deployment of different FCEV models. Simulations of base case scenarios show H_2 car penetrations ranging from about 5% to 35% of the total passenger car fleet by 2050. Studying sensitivities on extending the initial H_2 refuelling network, the introduction of H_2 cars via the lease car market or a change in consumers' refuelling behaviour indicate that up to 60% of all cars could run on hydrogen by 2050. Nevertheless, transition takes time and requires an approach on large scale to be successful: even with coherent, specific and long term policy stimulation it may well take over a decade before penetration becomes significant. Therefore, large scale demonstration projects and policy instruments have to be prepared now and have to be in place before market introduction to stimulate a smooth transition from demonstration to commercialisation.

Acknowledgements

We gratefully acknowledge the Dutch Ministry of Economic Affairs and Agentschap NL for their financial support within the EOS-LT program contract number EOSLT06025.

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Hydrogen Fuel Cell Battery Electric Vehicles (HFCBEV) *vs.* Battery Electric Vehicles (BEV) – *A Birmingham Experience*

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This paper describes the development, design, testing and commissioning of five HFCBEVs on the University of Birmingham campus (Figure 1). The HFCBEVs were tested to evaluate performance, range, efficiency and system cost and were compared to 'pure' lithium-ion BEVs (Mitsubishi iMiEV, 47 kW electric motor, 58 MJ of battery storage, 1100kg, £26,700 – Figure 2) and conventional internal combustion engine (ICE) diesel vehicles. The 11 kW electric motor in these HFCBEVs were powered directly by an inexpensive 1.5 kWh lead acid battery pack (£1,000) which was constantly charged up by a 1.2 kW Proton Exchange Membrane (PEM) fuel cell (Ballard Nexa, £4,000) running on a 350 bar hydrogen composite tank (Class III, Dynecell, Dynetek Industries, £4,000). The electrolytic grade hydrogen (99.999%, Green Gases Ltd) was delivered by an Air Products refueller (Series 100) and refuelling 0.6kg of hydrogen took an average of 3-5 minutes (for). The hydrogen consumption of the HFCBEVs was 10.0 $g.km^{-1}$, giving an energy efficiency of 0.71 $km.MJ^{-1}$ (77 mpg of diesel equivalent) with up to 60 km range on full throttle with an acceleration of 1.5 $m.s^{-2}$ and a top-speed of 30 mph (note that 80 km range would require either 0.94 $km.MJ^{-1}$ or a 0.8 kg hydrogen tank). The weight of the HFCBEVs is 525 kg with a load capacity of 200 kg.

The BEVs showed better efficiency (2.22 $km.MJ^{-1}$) with higher range (up to 130 km) and speed (80 mph) to that of the HFCBEVs. Overall, all hydrogen and 'pure' BEVs offered better efficiency and performance than ICE diesel vehicles. Finally, we clearly demonstrated that hydrogen PEM Fuel Cell can be used as an 'effective' range extender when used with some batteries. This paper reports the early results of these tests and follows from two previous publications [1,2].

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Figure 1: Hydrogen Fuel Cell Battery Electric Vehicles at The University of Birmingham (UK).

Figure 2: Battery Electric Vehicles (Mitsubishi iMieV) at The University of Birmingham campus (UK).

1 Introduction

In the UK, there is a substantial problem of increasing energy use in transport which takes about 30% of total energy usage, mainly fossil fuel based, with large CO2 emissions. Since North Sea oil and gas reserves have now been depleted, UK consumption exceeds the oil extracted. To diversify transport fuel is therefore a priority and two steps are being taken to use renewables:

1. To employ BEVs charged from the existing electricity grid;
2. To develop HFCBEVs to be refuelled from green hydrogen gas refuelling stations.

Currently, 110 BEVs are being tested in a project which started in 2009 and which runs through 2011 - the TSB funded CABLED [3] project (Coventry and Birmingham Low Emission Demonstrator). In addition, HFCBEVs have been tested on the University of Birmingham campus since 2008 and 8 further vehicles will be tested later in 2010.

Hydrogen fuel cell hybrid vehicles have been explored theoretically in a number of previous papers [4,5] but most operational hydrogen hybrids have been combustion which continue to emit NOx. The purpose of this study was to introduce a new design of lightweight hydrogen fuel cell hybrid on campus and to compare the hydrogen vehicles with 'pure' lithium ion battery electric vehicles.

2 Vehicles tested and Results

The HFCBEVs were designed with a fuel cell battery charger which topped up the lead acid accumulator when the vehicle was idle (Figure 3).

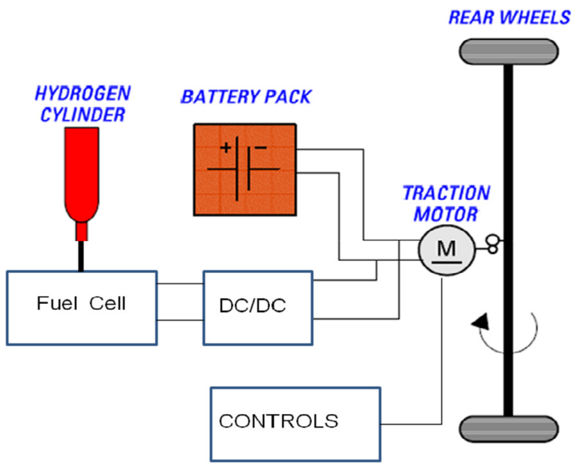

Figure 3: Mechanical drive system layout.

3 Characteristics of the PEM Fuel Cell stack

The 1.2kW Ballard Nexa PEM fuel cell was used, as it was compact and relatively low cost, and provided the durability required for the demanding operating environment. The stack efficiency quoted by Ballard was 38% (LHV) at full power and 48% at half power inclusive of parasitic loads. This was consistent with measurements taken from the stacks installed into the vehicle fleet. Table 1 below shows the characteristics of the 1.2kW Ballard Nexa. The Nexa fuel cell system is designed for operation on pure gaseous hydrogen. No fuel humidification is required. Hydrogen can be supplied at pressures ranging from 0.7 to 17 bars (gauge).

Table 1: Characteristics of the PEMFC stack.

Nominal power (at 0.55V per cell)	1200W
Heat dissipation	1600W (at rated net power)
Nominal operating point	26V (DC) x 46A (DC)
Efficiency (full load)[a]	32%
(50% load)	41%
Mass	13kg
Lifetime	2000 hours
Anode gas	99.999% H_2
Consumption (at full power)	17.5 SLPM
Pressure / Temperature / Humidity	7 to 17.2 bar/3-40^{o}C/0% -95%
Water emission	870ml/h (max)
Noise	72 dBA @ 1m

Overall, fuel cell reliability has been excellent to date, providing over 2,000 hours of operation across the fleet and 2,000 km travelled with no technical problems or observable degradation. Experimental *V-I* curves for the stacks in four of the vehicles are shown in Figure 5, and demonstrate that the PEM fuel cell performance is consistent between stacks and against manufacturer’s specifications – despite incidences of fuel starvation, excessive current draw, rapid power cycling, ambient temperature extremes and vibration/shock received during operation.

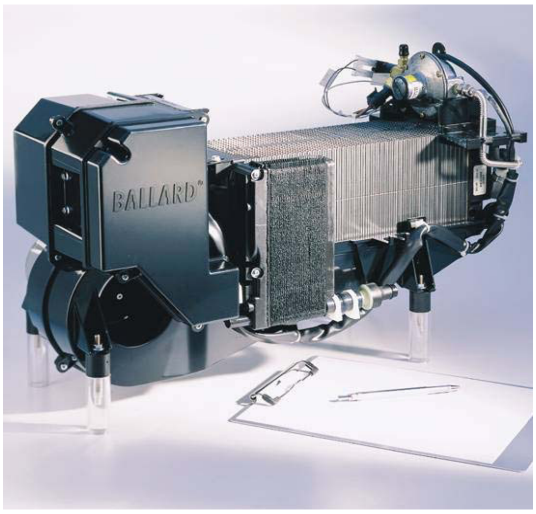

Figure 4: 1.2 kW PEM Fuel Cell Stack Ballard Nexa used in the five HFCBEVs.

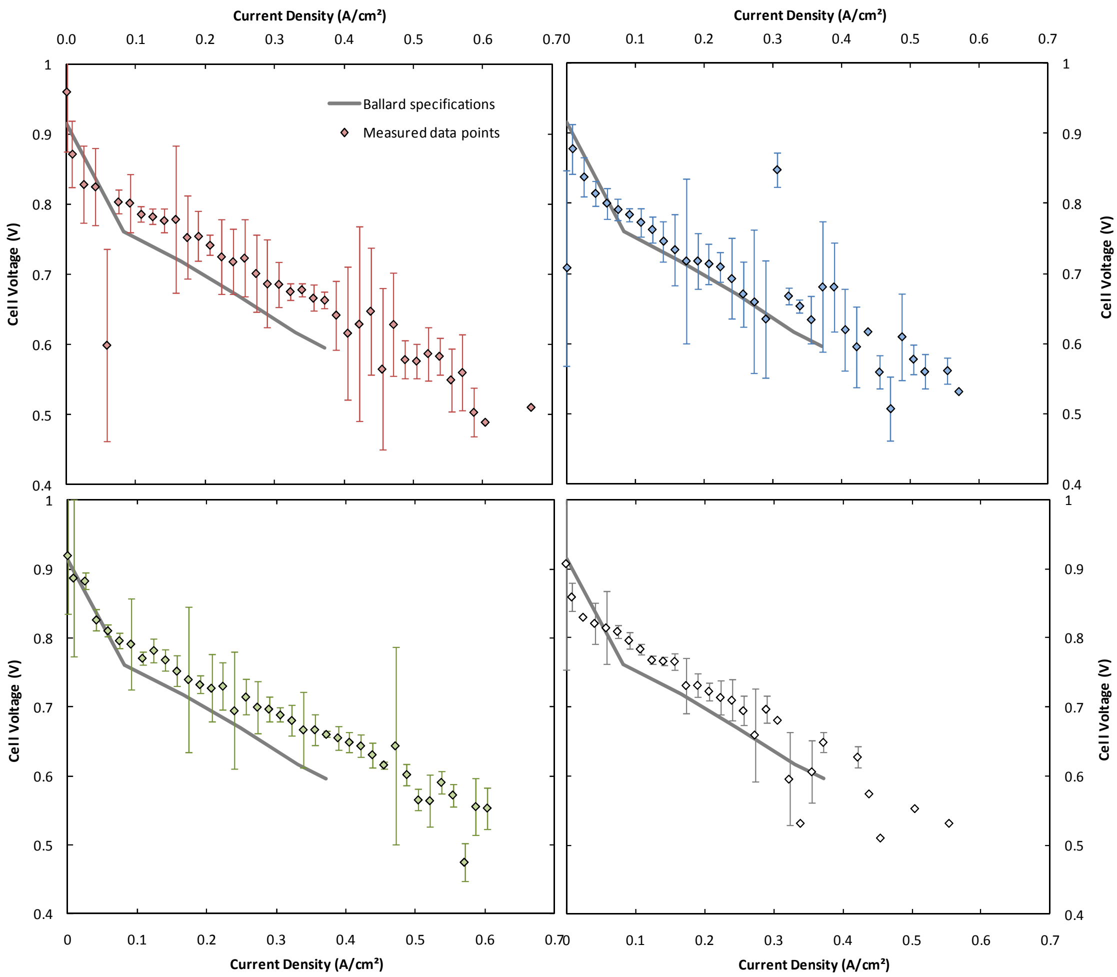

Figure 5: ***V-I*** **curves taken from the Ballard Nexa stacks installed in each HFCBEV.**

***Keywords**:* hybrid vehicle; hydrogen PEM fuel cell; 350 bar hydrogen; battery electric vehicle (BEV)

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Production of Biofuels – The Hydrogen Consumption as Performance Indicator in the Early Design Stage

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Abstract

Lately, biomass is more and more considered as a raw material in the processing of chemicals and fuels, but only few production processes are established until now. Instead, a lot of individual reaction alternatives are explored and very little information is available to predict their potential in integrated biorefinery concepts. In this contribution feasible production strategies for biofuels are systematically identified and subsequently analyzed applying Reaction Network Flux Analysis (RNFA) [1]. In the analysis, the hydrogen consumption is chosen as performance indicator to compare different scenarios. Based on the results, a classification of solutions is possible such that promising reaction pathways as well as bottlenecks can be detected. Thus, RFNA is an efficient tool to deal with complexity of the early design stage and to obtain first important information in terms of conceptual process development.

Keywords: *biorefinery, biofuels, Reaction Network Flux Analysis, hydrogen*

1 Motivation

Due to the limited availability of fossil resources, an increasing energy demand and rising carbon dioxide emissions, renewable raw materials are attaining a special interest in the transportation fuel sector. Whereas most approaches focus on the production of biodiesel or bioethanol, it is also possible to develop synthetic biofuels. Here components and blends with excellent fuel properties can be chosen, which can be efficiently produced from biomass feedstock. However, converting the oxygenated biomass into suitable fuels by removing oxygen in form of water requires large amounts of hydrogen. Therefore a sustainable hydrogen supply is of utmost importance. To meet this demand, research activities are run in the field of electrolysis (with sustainable electricity sources like solar or wind energy), photo- or thermophilic fermentation and steam reforming or pyrolysis of biomass. Especially, if biomass is considered as feedstock for both, hydrogen and fuel production, integrated biorefinery concepts must be evaluated in the early design phase. The problem complicates as only few (bio-)catalytic routes for the conversion of biomass are established, which in turn provides the opportunity for exploration and innovation. So the hydrogen need (among others) can be utilized as an evaluation criteria for the selection of synthesis routes. In this contribution we show how Reaction Network Flux Analysis (RNFA) can be applied to analyze integrated biorefinery concepts for the production of biofuels.

2 Approach

In the cluster of excellence “Tailor-made Fuels from Biomass” an interdisciplinary research approach is followed to develop sustainable production processes for synthetic biofuels [2]. By defining the optimal combination of fuel blend and low-temperature combustion engine, the engine efficiency should be improved while the emission ratio is reduced. Besides novel chemical synthesis routes are explored such that the functional structure of biomass is preserved. From the beginning, experimental work on reactions and catalysts should be accompanied by conceptual design to classify the large number of alternative production pathways according to the data at hand. For this purpose, Reaction Network Flux Analysis (RNFA) is applied [1].

This systematic approach for material flow analysis is derived from metabolic pathway analysis [3]. For the analysis of the different reaction pathways, all possible reactions are summarized in a network, where substances and reactions are represented by nodes and arcs respectively. Mole balances are performed for each node taking the stoichiometric coefficients into account. As a substance can generally be formed by one or more reactions, the corresponding system of equations is underdetermined such that room for mathematical optimization is given. If the yield of the target component b_{target} is supposed to be maximized, the linear optimization problem

$$\begin{aligned} &\max_{x,b} b_{\text{target}} \\ &s.t. \quad Ax = b \\ &\qquad x_j \le \eta_j \sum_{k,k \ne j} \nu_k x_k \quad \forall j \\ &\qquad x, b \ge 0 \quad , \end{aligned} \tag{1}$$

can be formulated where A is the matrix of stoichiometric coefficients. The molar flux through the network is x, while b balances the product and by-product formation at each node. In addition yield constraints are introduced to limit the conversion of certain reactions. Here, η refers to the molar yield of a reaction j and k is the set of fluxes entering or leaving the associated node.

The solution of the optimization problem identifies the best reaction pathway according to the chosen objective function, whereas a reaction pathway consists of the active reaction steps between starting and target molecule. For a comprehensive analysis it is necessary not only to know one, but all reaction possibilities. These can be detected by adequate mixed-integer programming techniques [4]. Once the flux scenarios are identified, they can be classified according to different criteria, which are either directly linked to the mass balance or expanded by economic, energetic or ecological aspects. Based on this knowledge bottlenecks as well as most promising reaction pathways can be detected and further research activities can be guided properly.

On the one hand the reusability of the network enables the fast calculation of case studies varying i.e. the biomass composition, reaction yields or the objective function. On the other hand promising solutions are pointed out by the successive analysis and can be refined by adding criteria of conceptual process design like separation index or energy demands. The combination of these two aspects offers the basis for a rapid evaluation of alternatives in the early design stage.

3 Application to Biofuels

RNFA is now applied to evaluate the production of different biofuels in integrated biorefinery concepts focusing on the hydrogen provision. Therefore a network covering reactions from biomass towards fuel components is constructed. Based on the literature [5, 6, 7], admissible reactions increasing the hydrogen to carbon ratio and decreasing the oxygen to carbon ratio at the same time are selected for the network, which finally consists of 125 reactions and 87 substances. For most reactions no yield predictions can be found in literature, such that a yield of 97% is assumed for these reactions accounting for unavoidable losses.

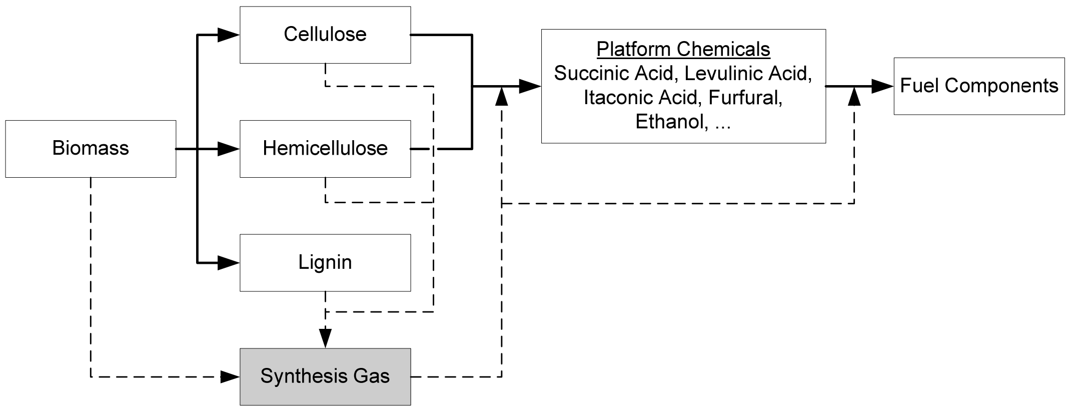

Figure 1: Processing scheme of biomass.

Figure 1 shows the underlying structure of the reaction network. In a first step biomass is decomposed into its main components cellulose, hemicellulose and lignin. While cellulose and hemicellulose can be transformed into platform chemicals, lignin can only be converted into synthesis gas. Further reactions describe the formation of synthesis gas using biomass, cellulose or hemicellulose. Instead of defining a particular processing technique for the production of synthesis gas, ideal conditions are assumed for gasification and subsequent purification. Synthesis gas itself can be returned to the network as hydrogen source or as a feedstock for the production of additional reactants like methanol such that biomass is the only feed to the network.

As the criteria for the selection of a suitable biofuel is still an open research problem, the energy of combustion is chosen as representative fuel property in this case study. Unfortunately, experimental values for the energy of combustion are not available for all substances such that they have to be calculated based on Joback's group contribution method [8]. According to this data, the five network components with the highest combustion energy are selected as target molecules.

For each target molecule the ten best reaction pathways are identified by solving the optimization problem (1). To account for changes in the biomass feedstock, two different scenarios are investigated. In the first scenario biomass has a high cellulose and a low lignin fraction (cellulose 75%, hemicellulose 15%, lignin 10%), while in the second scenario biomass with a low cellulose and a high lignin fraction (cellulose 40%, hemicellulose 35%, lignin 25%) is supplied. Lower and upper bounds on the individual fractions are set according to data provided by Huber et al. [5].

4 Results

The case verifies the assumption that the hydrogen need for the production of biofuels can be fairly high. Depending on the target molecule and on the production route, up to 6.5 mole hydrogen are required per mole product. Still, the hydrogen supply for direct use or for the production of additional reactants is not the limiting factor in any of the reaction pathways. In fact, the actual yield in the reaction steps from biomass to platform chemicals is so low that a sufficient amount of hydrogen can always be provided by the gasification of the residuals.

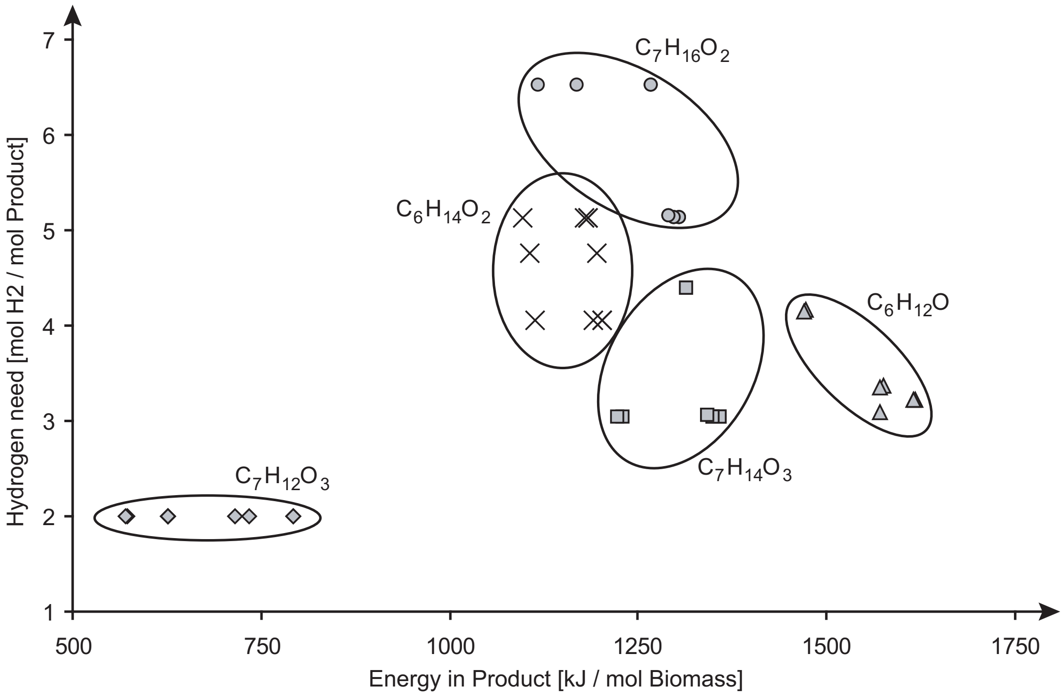

Figure 2: Comparison of production pathways for different biofuels (different symbols) starting from biomass with high cellulose content.

However, the production alternatives strongly vary in their hydrogen consumption such that it is a good performance indicator in terms of sustainable raw material utilization. Residuals can be recycled elsewhere (i.e. to meet the energy demand), if they are not needed in the hydrogen chain. Figure 2 shows the results for scenario one, where a feedstock with a high cellulose fraction is supplied to the network. For the different production routes of a target molecule, the hydrogen need is plotted against the amount of combustion energy, which can be obtained per mole of biomass. It can be seen that the reaction pathways are spread over a wide range, but obviously pathways with good energy efficiencies and low hydrogen demands are desired.

All target components have a similar molar energy of combustion, but the product yields of $C_7H_{12}O_3$ (3-(hydroxymethyl)-, ethyl ester-3-butenoic acid) are so small that it is not competitive with the other molecules. In this case great amounts of by-products are formed.

In contrast $C_6H_{12}O$ (dimethyltetrahydrofuran, DMTHF) outperforms the other substances in terms of energy at comparable hydrogen needs. Moreover, significant differences also exist between the alternative pathways producing the same target molecule. Especially, for $C_7H_{16}O_2$, $C_6H_{14}O_2$ and $C_7H_{14}O_3$ (1,4-dimethoxy-2-methyl-butane, 1,4-dimethoxy-butane, 4-methoxy-3-methyl-, methyl ester- butanoic acid) one can find solutions, which offer either a higher energy level at the same hydrogen demand or a lower hydrogen demand at the same energy level. Both examples show that target molecules cannot only be selected based on their combustion properties, but that their production routes must directly be taken into consideration.

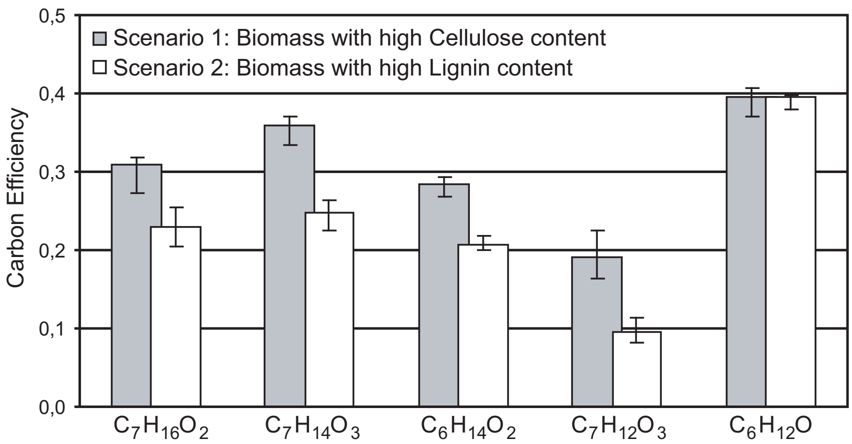

Figure 3: Carbon efficiency of selected target molecules for two feedstock scenarios. The "error bar" refers to variations in the production routes linking feedstock and target molecule.

For a further analysis of the two biomass scenarios, carbon efficiency is selected as a performance indicator, which relates the amount of carbon in the product to the one in the biomass feedstock. With a value below 40%, the carbon efficiency is very low for all the molecules. This is again due to the limited conversion in the reaction steps from biomass to platform chemicals.

In Figure 3 the mean values of the carbon efficiency are compared for both scenarios. The deviation from the average indicates the best and the worst production route. In most cases the carbon efficiency decreases, if the processed biomass has an elevated lignin fraction. The pathways are sensitive to these changes in the feedstock because lignin cannot directly be converted into functional compounds. DMTHF proves an exception to this rule. The average as well as the optimal values of the carbon efficiency remain largely unaffected, even though the composition of the feedstock changes. This can be explained by the fact that DMTHF can be produced on the basis cellulose and hemicellulose and the collective fraction of the two is not strongly affected by changes in the feedstock. Thus, if major changes in the feedstock are expected, this must be considered in the selection of target components and production routes.

As a result of this analysis, the component DMTHF is identified as most promising fuel candidate. It can be produced efficiently with a low hydrogen need and the reaction pathway is not sensitive to changes in the feedstock composition.

5 Discussion and Conclusions

Even though the hydrogen demand can be covered by gasification of residuals, the carbon efficiency is very low in all cases. Consequently, future research must focus on increasing the carbon efficiency. On the one hand the conversion from biomass to platform chemicals must be improved, on the other hand efficient processing techniques for lignin must be developed such that lignin can directly be transformed into chemicals while the hydrogen need is met by other sustainable resources.

The study clearly shows that crucial information can be deduced from RNFA. It allows a systematic analysis of reaction pathways in order to evaluate production routes for promising fuel candidates. While hydrogen consumption and carbon efficiency have been used in this study, many other (alternative or additional) performance indicators can be accommodated in a straightforward manner.

Acknowledgements

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TA Transportation Applications

TA.1 Fuel-Cell Power Trains

TA.3 Hydrogen Internal Combustion Engines

TA.4 Systems Analysis and Well-to-Wheel Studies

TA.5 Demonstration Projects, Costs and Market Introduction

TA.6 Electrification in Transportation Systems

HyNor – The Norwegian Hydrogen Highway

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1 Introduction

Hydrogen is one of the most promising energy carriers which can make the transport sector emission-free. The challenges related to hydrogen as an energy carrier are however not only technical. Due to the nature and purpose of transport, a number of refueling points or hydrogen stations are needed for it to be attractive as a fuel. The cliché “chicken and egg”-situation is often used to describe the dilemma of implementing new fuels such as hydrogen. Without hydrogen stations where people can refuel the cars, it is not profitable to produce the few cars that will be needed. Without many customers asking for hydrogen fuel and very few customers actually using the existing stations, the operators of the station will not want to build more stations due to the economical loss it presents.

Hydrogen has many years been looked upon as an alternative to conventional fuels, either because of energy security and/or environmental reasons. Norway has a long history of hydrogen technology, and especially on the production side, with big actors such as *Norsk Hydro*, making hydrogen from electrolysis for their fertilizer production. The interest for hydrogen has steadily been growing in Norway, already being considered an “energy nation”.

2 The HYNOR Project

In 2003 the interest parties from industry, government, environmental organizations and academia joined forces and initiated the HyNor project. Hydrogen was identified as one, or the one energy carrier which could give clean transport for the future, and a potential for Norway as an energy nation to also play an important part in the future “hydrogen society”. In order to demonstrate that the technology for the hydrogen infrastructure exists and to demonstrate that it is a viable alternative to the already existing fossil-based infrastructure, it was decided to build a “Hydrogen highway” from Stavanger in the west of Norway, along the southern coast, ending in the capital of Norway, Oslo, in the east. This road stretch is 580 kilometers long, and a certain number of sites, or nodes along the way were identified as important for having a hydrogen highway, and being able to drive a hydrogen car comfortably along the route without running out of hydrogen. Separate private-public project groups were established for all the nodes and a steering committee for the project leaders of each node was established to coordinate the efforts.

Figure 1: The HyNor-road with its six nodes. The Agder nodes still remain to be built. (HyNor)

The cities along the road account for more than half than half the population of Norway. The phase I (2003 -2009) project goal was to enable hydrogen driving on this road. On May 11th 2009 the two easternmost stations along the route in Drammen and Oslo were opened. A hydrogen and electrical vehicle rally was held at the opening, the participant cars driving the hydrogen road from Oslo to Stavanger. The rally illustrated the potential of the hydrogen vehicles and hydrogen refueling stations, all of which are publicly available. Three of the stations are multifuel stations with petrol, diesel, LPG and CNG in addition to hydrogen. Although a modern hydrogen vehicle can drive the entire hydrogen road without refueling along the way, in the south of Norway however, two stations still remain to be built to ensure hydrogen availability for a stretch of about 400 kilometers between Porsgrunn and Stavanger.

3 Hydrogen Refuelling in Public Environment

From the construction of the first station and throughout the project, all the hydrogen refueling stations has been designed as public fuelling stations. Three of them are integrated into commercial stations in retail environment, and for two of them they can be operated with a regular credit card. In order to achieve the level of high availability for the public from the start of the project, there has been a very strong focus on safety and commercial interface. Comprehensive training on emergency response and on hydrogen properties and safety has been done for personnel at station.

Another important factor for the HyNor project is demonstrating the various sources of hydrogen that exist, from industrial by-product to reforming of natural gas and biogas, to electrolysis from renewable energy sources. The first station which opened in Stavanger in 2006 has trucked-in reformed natural gas as its source of hydrogen, while the second station which opened at Herøya, Grenland gets hydrogen piped directly from a nearby chlorine-production plant, where hydrogen is one of the bi-products. The stations in Oslo and

Drammen currently get trucked in hydrogen from Grenland, but in 2010 the Drammen station will be provided with locally produced hydrogen which has its origin in biogas. The stations in Drammen and Oslo are also prepared for installing electrolysers locally when the demand gets high enough. As of 2010 all four hydrogen stations in Norway are still available and in normal operation, and are as such permanent stations.

4 Hydrogen- and Battery-electric Vehicle Rally

The rally that was held at the official opening of HyNor in May 2009, the "EVS Viking Rally", was a three day rally going from Oslo to Stavanger, with many different tests along the way, from eco driving to regularity tests and hill climbs. There were public events at all the stations along the way, and the rally sparked international attention. The finish-line of the rally was right outside the conference hall for the 24th Electrical Vehicle Symposium which was held in Stavanger from 11th to 13th of May 2009. Fifteen hydrogen vehicles participated in the rally. Celebrities such as His Royal Highness Crown Prince Håkon Magnus and Prince Albert of Monaco attended parts of the rally and the event. A new zero emission rally will be held in August 2010.

Figure 2: The opening of HyNor on May 11th. (Statoil)

5 HYNOR Phase II and International Collaboration

The HyNor project continues in a second phase, from 2010 to 2015. During Phase II four additional stations will be included in the project, increasing the density of stations in the Stavanger and Oslo area. There will be a strong focus on acquiring more vehicles, both cars and buses. International cooperation and collaboration will also be intensified, and in November 2009 a memorandum of understanding (MoU) was signed between HyNor and the Califorinan Fuel Cell Partnership (CaFCP). The collaboration with CaFCP will include market issues, safety and training of first line responders. HyNor is also part of the Scandinavian Hydrogen Highway Partnership (SHHP), which is a Nordic hydrogen infrastructure project which will enable driving a hydrogen vehicle all the way through Norway, Sweden and Denmark. In addition there will be a focus on adapting the technology used at the stations to what will become the market standards for hydrogen refueling stations.

The HyNor project has laid a solid foundation for further hydrogen projects, and in 2010 the EU-project H2-moves Scandinavia will commence in Oslo. It will lead to the introduction of 17 new hydrogen fuel cell vehicles and one new hydrogen station in Oslo within 2011. In addition there is progress on a bus project which also will be located in Oslo. The realization of the bus project will bring 5 hydrogen fuel cell buses to Oslo, and the final decision of the project will be in June 2010. As such, the increased activity and projects related to HyNor, makes it still more attractive as a project for early introduction of hydrogen as fuel for vehicles.

The Clean Energy Partnership – A Successful Cooperation Model

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Sybille Riepe, motum GmbH, Germany

1 The Partnership

The Clean Energy Partnership (CEP) emerged from the „Transport Energy Strategy VES", and was established in December 2002 as a joint political initiative lead-managed by the German Ministry of Transport and Industry. Its focus is clean mobility for the future – quiet and emission-free. The international cooperation of 13 partners – combining the car manufacturers, energy and technology companies and bus operators - GM/Opel, Berliner Verkehrsbetriebe, BMW, Daimler, Ford, Hamburger Hochbahn, Linde, Shell, Statoil, Total, Toyota, Vattenfall and Volkswagen – test the system compatibility of hydrogen in everyday use.

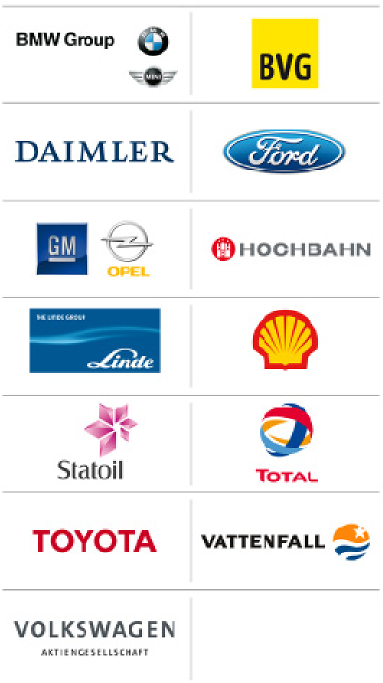

Figure 1

This includes the continuous operation of efficient hydrogen vehicles, their fast, safe refuelling, the clean and sustainable production of hydrogen, and its transport and storage in both its liquid and gaseous states. The increasing integration of renewable energy sources for hydrogen production is a clear objective of the CEP.

The Clean Energy Partnership is the beacon project of the National Hydrogen and Fuel Cell Technology Innovation Programme (NIP) in the transport sector. The NIP is implemented by NOW GmbH (National Organisation for Hydrogen and Fuel Cell Technology). The Clean

Energy Partnership is one of the biggest demonstration projects in Europe in the field of hydrogen technology.

Figure 2

2 The Leading Companies

The project is concentrating on validating technology in everyday conditions testing a broad variety of technologies. The partners participating in the clean energy partnership are competing enterprises in “real life” or work in totally different sectors without any common interest. In the CEP project they come together to jointly tackle the challenge of introducing clean transport technologies into society. The common interest in participating is their awareness that an accelerated development and demonstration of the innovative hydrogen technologies is necessary to come up with a successful solution for a clean transport. Each company on their own would not be able to progress in the way they do together. By sharing their knowledge and cost of development the learning curve can thus be followed faster as the experiences of the past years prove:

Already in 2004 a hydrogen filling station for both liquid (LH2) and gaseous hydrogen (GH2) has been integrated in a conventional public filling station for the first time in Germany. Offering LH2 and GH2 requires both, the delivery of trucked in hydrogen as well as the production on site. Several components in this project like compressors and liquid hydrogen pumps have been applied for the first time. Meanwhile the partnership has already travelled a distance of 837,000 kilometers by hydrogen - nearly 21 times around the world. Currently 44 hydrogen cars and 8 Hydrogen busses are being fueled at two stations.

3 Seven Steps for Clean Mobility:

1. The CEP is investing in infrastructure – 5 Hydrogen filling stations are planned till the end of 2011
2. The CEP is developing new vehicles – e.g. Daimler F-CELL B-Class, VW Tiguan HyMotion, Caddy Maxi HyMotion, Audi Q5 HFC, GM/Opel HydroGen4
3. The CEP is growing – new partners are Toyota and North Rhine-Westphalia
4. The CEP is a trailblazer in technological development – 700 bar refueling, State-of-the-art electrolysis technology, Hydrogen production using biomass
5. The CEP is increasingly relying on renewable energy – Increase the share of renewably produced hydrogen to 20%, hydrogen from a hybrid power plant and from biogenic waste, first CO2-free fuelling station at Berlin Brandenburg Airport
6. The CEP is spreading to other cities – e.g. talks with Baden-Württemberg.
7. The CEP pursues international alliances – exchange with the California Fuel Cell Partnership (CaFCP) on standardization processes and research results, networking with HyNor and Scandinavia

Figure 3

4 The SMEs Behind

Leading energy companies and OEM suppliers are in the visible partners in this project. However, the success of the necessary technology developments based to a great proportion on the support and the innovative power of small or medium sized enterprises (SME). It is their know-how and innovative power that was of great supportive value to this project.

A successful cooperation model enables an acceleration of the innovation process:

Big enterprises take the risk and provide the financial support to small and medium enterprises to develop and implement new innovative technologies. The knowledge remains with the small and medium enterprises who concentrate on their core competences as well as the big enterprises. Due to the diversity of technology suppliers and the emerging competitive environment, cost of the hydrogen technologies is expected to remain fair in the future. An example for the successful cooperation within the clean energy partnership is the technology development cooperation between Statoil and TOTAL as CEP partners and the

SMEs Andreas Hofer and SME Hexagon Composits, who developed and delivered the dry piston compressor and the storage units implemented at the TOTAL hydrogen station Holzmarktstraße in Berlin. The German wind energy company ENERTRAG has been integrated into the project by supplying hydrogen from wind energy that has been generated from electricity surplus. Here new business models have been developed and successfully tested and show the potential of co-operations between big and small enterprises in regard to technology innovation.

5 Outlook

CEP will enter the third phase from 2011 until 2016 focusing on market preparation for commercial hydrogen-powered vehicles. It will be a challenge to develop an overall infrastructure of hydrogen production and fuelling with relevant shares of renewable energy as well as the implementation of a significant number of vehicles – involving the effort of SME and leading companies.

Assessing Consumer Preferences for Hydrogen Driven Road-Sweepers

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1 The Demonstration Project “hy.muve”

The Swiss Federal Laboratories for Materials Testing and Research (Empa) and the Paul Scherrer Institute (PSI), two Swiss research institutions in the field of future powertrain technologies developed in collaboration with industrial partners a prototype fuel cell street-sweeper which is close to a pre-production series. The vehicle now undergoes operational testing on the streets of various cities in Switzerland.

In view of their driving profile (fleet operation from a fixed refuelling point, possibility to operate such vehicles in pedestrian areas and even indoor, etc.) road-sweepers appear particularly well suited for a soon niche market introduction of fuel cells and a possible early commercialization.

Besides technical investigation, the project called “hy.muve” (“hydrogen-driven municipal vehicle”) also serves as a research platform for socio-economic studies focusing on non-technical challenges for the implementation of fuel cell and hydrogen technology and its public acceptance. Promising market introduction strategies will be developed.

Figure 1: CityCat H_2 – The prototype fuel cell street-sweeper.

2 Niche Market Research

Only a few studies already exist analyzing the acceptance of hydrogen and hydrogen technologies in the general public (which include both potential users and non-users). Yetano Roche et al. (2009) recommend developing further the use of non-market valuation approaches for investigating demand for hydrogen fuel cell vehicles on a large scale, as strong and robust quantitative evidence is still relatively scarce. They also suggest a whole-system perspective, looking at hydrogen technologies in the context of other competing technologies. With our study we aim at making an important contribution to this field of research.

A sound knowledge about the current state of preferences and determinants of demand of consumers is required, as this is of great importance for introducing a new, innovative technology into the market, or niche market respectively. In contrast to a technological niche, a niche market is defined not around a particular technology, but around a set of performance attributes. Levinthal (1998, p. 220) characterizes niches as *“populations of (potential) consumers [that] are distinguished by the functionality they desire and their willingness to pay for these various attributes.”*

This begs the following questions: Which attributes are relevant for the purchase decision of street-sweeper users? Which trade-offs are they willing to make? Does a niche market for hydrogen driven street-sweepers exist? What preferences do the target groups beyond this possible eco-niche have? Innovators (the technology enthusiasts and environmentally active consumers) may not be representative for early adopters and the other target groups beyond the eco-niche, as they are more price-sensitive or less environmentally active (see figure 2).

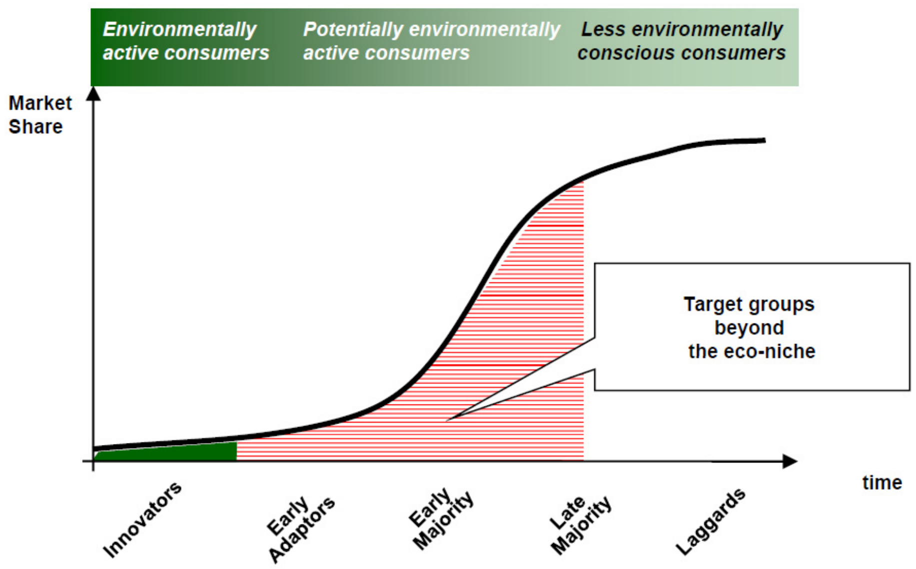

Figure 2: From eco-niche to mainstream market.
Source: Derived from Wüstenhagen (2000) & Moore (1999)

There are challenges in doing research for innovative, environmental products: When it comes to environmental issues people have a tendency to provide socially desirable answers. This means that the more direct they are asked, the more biased they will answer and this may lead to an overestimation of people's willingness to buy sustainable products. So what can be done? One possible solution is to use more sophisticated quantitative methods that avoid socially desirable answers like the choice experiment approach.

3 Choice Experiments in Eco-Innovation Research

Choice experiments have been widely used in market research for product innovation, and can be beneficial for eco-innovation research, too. Hence, we conducted an online survey with choice experiments implying 1'600 choice decisions by 160 respondents in Switzerland, to determine users preferred street-sweeper.

Our study extends previous research on consumer preferences in two ways.

First, most past research has been conducted about individual consumer (or household) preferences for alternative fuelled vehicles. This research focuses on fleet buyers' preferences, as fleet managers are a very promising target group for early testing and implementing of new drive train technologies (compare Nesbitt & Sperling (1998)). A grounded understanding of fleet purchase behaviour will lead to more effective marketing and policy strategies. Second, in addition to the typical vehicle-choice predictors (e.g. price) we also considered noise emissions.

In the choice experiment, the respondent is presented to a number of choice situations and asked to choose the most preferred. Specifically, respondents were provided with descriptions of three street-sweeper types: (1) conventional diesel vehicles (defined as the status quo), (2) vehicles which run on compressed natural gas/biogas, and (3) hydrogen driven ones. The use of different alternatives allows for the analysis of hydrogen in the context of other competing technologies.

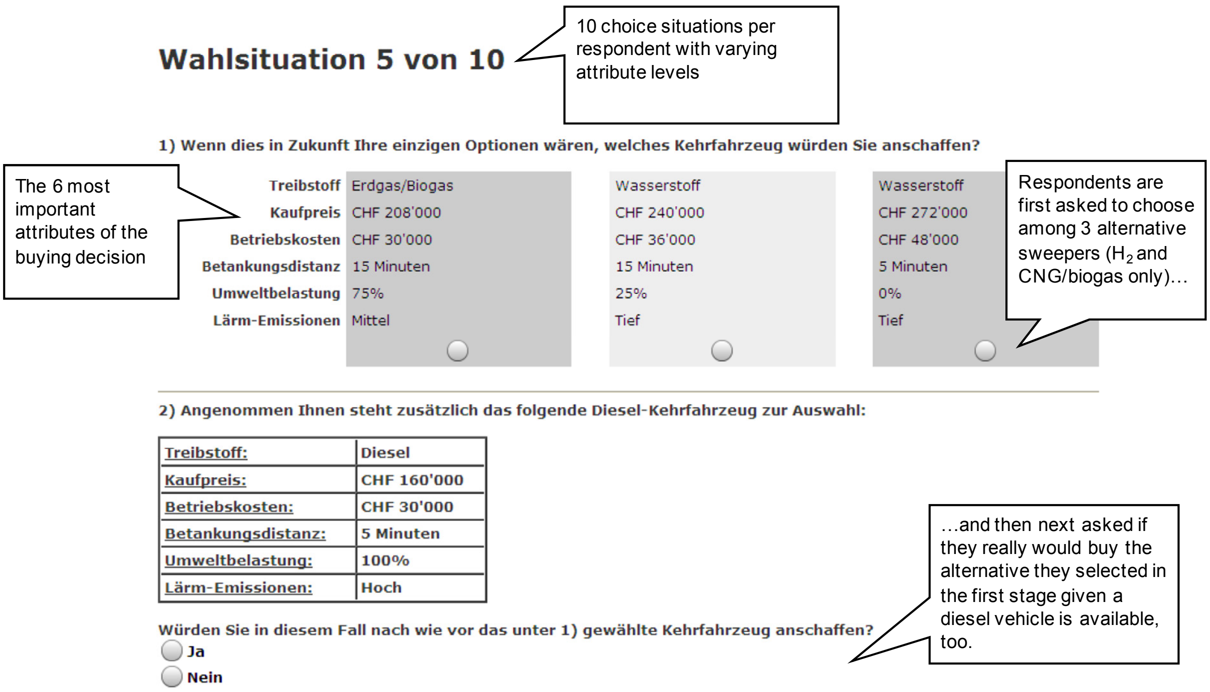

Figure 3: Sample Choice Situation.

Through expert interviews and a literature review, we identified the most relevant attributes for road-sweepers. The attributes include (1) fuel type, (2) purchase price, (3) running costs, (4) refuelling distance (i.e., the time it takes to drive the road-sweeper to the next refuelling station), (5) polluting emissions, and (6) noise emissions. In addition to these six attributes, respondents were told to assume that the street-sweepers are identical in all other aspects (e.g. cruising range and reliability).

4 First Results

By using Hierarchical Bayes estimation we determined customer preferences and the importance of product attributes in vehicle choice. This procedure makes it possible to simulate different market scenarios based on stated preferences and to answer strategic questions such as communication or pricing strategies. A first selection of scenarios will be presented at the conference. We also conducted “sensitivity analysis” for the attributes. For example, the relative price sensitivity (e.g. a 10% raise in price) can be used to generate relative demand curves.

One of the most frequently cited rationales for targeting fleets for the introduction of a new drive train technology is that they often refuel their vehicles at one location (on-site or central refuelling). Therefore it would be interesting to see whether the street-sweeper fleet’s refuelling practices could potentially mitigate the “chicken-or-egg” quandary of marketing fuel cell vehicles in the absence of a public refuelling station network. Furthermore we will present whether our results are consistent with the findings from previous studies which state a low level of public awareness and knowledge of hydrogen and its associated technologies.

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Brazilian Hybrid Electric Fuel Cell Bus

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Abstract

The first prototype of a hybrid electric fuel cell bus developed with Brazilian technology is unveiled. It is a 12 m urban-type, low-floor, air-conditioned bus that possesses three doors, air suspension, 29 seats and reversible wheelchair site. The bus body was built based on a double-deck type monoblock vehicle that is able to sustain important load on its roof. This allowed positioning of the type 3 hydrogen tanks and the low weight traction batteries on the roof of the vehicles without dynamic stabilization problems. A novel hybrid energy configuration was designed in such a way that the low-power (77 kWe) fuel cell works on steady-state operation mode, not responding directly to the traction motor load demand. The rate of kinetic energy regeneration upon breaking was optimized by the use of an electric hybrid system with predominance of batteries and also by utilizing supercapacitors. The electric-electronic devices and the security control softwares for the auxiliary and traction systems were developed in-house. The innovative hybrid-electric traction system configuration led to the possibility to decrease the fuel cell power, with positive impact on weight and system volume reduction, as well as to significantly decrease the hydrogen consumption.

1 Introduction

Several hydrogen fuel cell buses have been built and tested throughout the world up to the present. The most significant field trial was the European demonstration project CUTE – *Clean Urban Transport for Europe* [1]. The CUTE project involved the operation of 27 similar buses effectively transporting people in regular urban lines in ten different European cities within a two-year span period. This was followed by the operation of six more buses of the same kind associated to projects in Iceland and Australia and three additional ones in China. Other than the great amount of technical assessment it allowed on the fuel cell bus technology, these trials have also brought knowledge on the good public acceptance of this advanced and environmentally friendly urban transport option and on the accumulation of expertise on producing, distributing, storing and servicing high purity hydrogen for large scale energy purposes. However, several instructive drawbacks were also withdrawn from the analysis made. The powerful, heavy and costly fuel cells used imposed an important penalty on fuel consumption. The average hydrogen consumption in the CUTE project was equal to 24.6 kg H_2/100 km. Important technical features of the CUTE technology have contributed for this high hydrogen consumption. More recent energy accumulators have allowed the design of energy hybridized power trains that have shown to be an important factor for the bus fuel

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economy. Consequently, other hybrid fuel cell buses reached much better fuel economies than that of the CUTE project [2 (6), 3 (8)].

Although the conceptual work of a Brazilian urban fuel cell bus has started many years ago, back in 1999, in Coppe, a graduate centre of the Federal University of Rio de Janeiro, it was since the beginning idealized as an energy hybrid power train system, hardly achievable with that time's energy accumulators technology. These ideas matured in 2004 into the present development project that effectively started in 2005 with the concept of a 12m urban low-floor bus that should possess a low power fuel cell to work in steady-state condition, recharging a bank of traction batteries, which in turn should also be recharged by connection to the grid, in a plug-in bus version, and make use of an efficient regenerative breaking technology. The great majority of sub-systems and components composing the power train and auxiliary systems for this fuel cell bus were conceived, developed and fabricated in Brazil and is being unveiled herein for the first time. The objective of the present work is to demonstrate the actual feasibility of an innovative hydrogen fuel cell bus for urban use employing a stationary operation type low-power PEM fuel cell in a specially engineered hybrid plug-in power train.

2 Technical Features

The monoblock type low-floor bus chassis and body were fabricated in Brazil. It consists of an urban type 12 m air-conditioned bus with pneumatic suspension that possess three wide doors, the middle one with an wheel chair access ramp, that allows for 29 seated and 42 standing passengers, depicted in Figure 1.

Figure 1: Overall view of the bus before external graphic design was applied riding the standard road cycle chosen in the campus at the Federal University of Rio de Janeiro.

Figure 2 presents a schematic 3D view of the electro-mechanical equipments in the bus. Being a double-deck type bus, although not used that way, has facilitated the positioning of equipments on the bus ceiling, because it easily supported the weight of these equipments, keeping adequate dynamic stability. By describing the equipments located on the bus beginning from its fore top front to its rear top back onto the rear compartment until the chassis, one finds: 1) 160Ah, 3.2 VDC per element, ion-lithium traction battery bank and a homemade battery management device: hardware and software; 2) air-conditioning; 3) fuel cell system radiators; 4) four 7.2 kg H_2 capacity, type-3, 350 bar, hydrogen storage cylinders; 5) high and low pressure gases system, including tubing, valves, gauges and manifolds; 6) 77.2 kWe stationary operation PEM type fuel cell with balance of plant; 7) homemade electronic power system and main vehicular energy control device: hardware and software – UCPEV, standing for this meaning in Portuguese; 8) ultracapacitors and homemade ultracapacitors management device: hardware and software; 9) refuelling system; 10) traction inverter motor drive that operates in vector mode; 11) 143.5 kWe AC squirrel gage motor type with encoder; 12) electric powered hydraulic direction pump; 13) electric powered pneumatic air compressor; 14) 24 VDC auxiliary batteries.

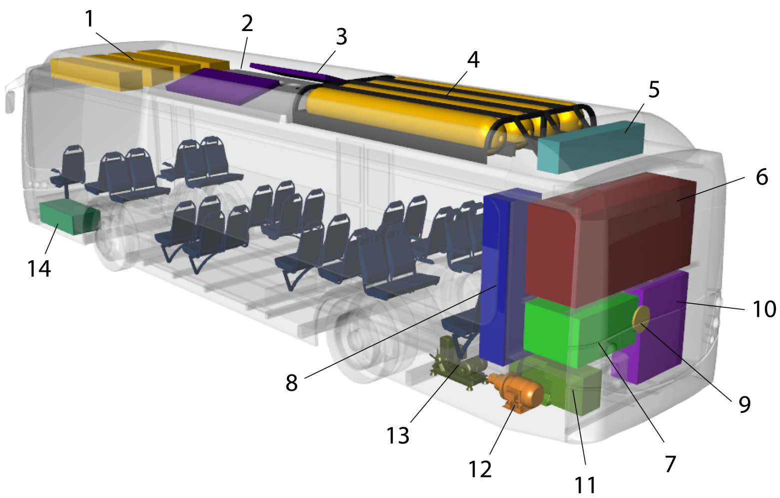

Figure 2: 3D schematic positioning of the electro-mechanical equipments in the bus. Each number stands for an equipment as detailed in the text.

Figure 3 presents a simplified electric block diagram for the bus power train and auxiliary systems. A centralized bus bar receives energy from different sources. These include: 1) the PEM fuel cell; 2) the traction battery bank; 3) the ultracapacitors; 4) the electric traction motor under regenerative breaking operation; and 5) the grid connection. Energy is consumed by: the electric traction motor and the auxiliary devices. The latter include: 1) the air conditioner; 2) the hydraulic pump; 3) the air compressor; 4) lamps and other small consuming devices. The microcontrolled UCPEV includes an efficient energy control algorithm that allows one to establish a specific control strategy for each particular route in order to optimize the energy consumption. It incorporates the system's intelligence and safety rules for operation. The UCPEV guarantees the steady-state operation of the low-power fuel cell on maximum efficiency conditions, situation that has been analyzed for hydrogen fuel cell buses in other situations [4]. As discussed before [5], a well engineered hybrid electric fuel cell bus such as that herein presented, may meet the requirements of low fabrication, operation and maintenance costs to facilitate the technology market introduction. Further details on the electro-electronic systems and on actual operation parametric analysis will be shown in the complete text.

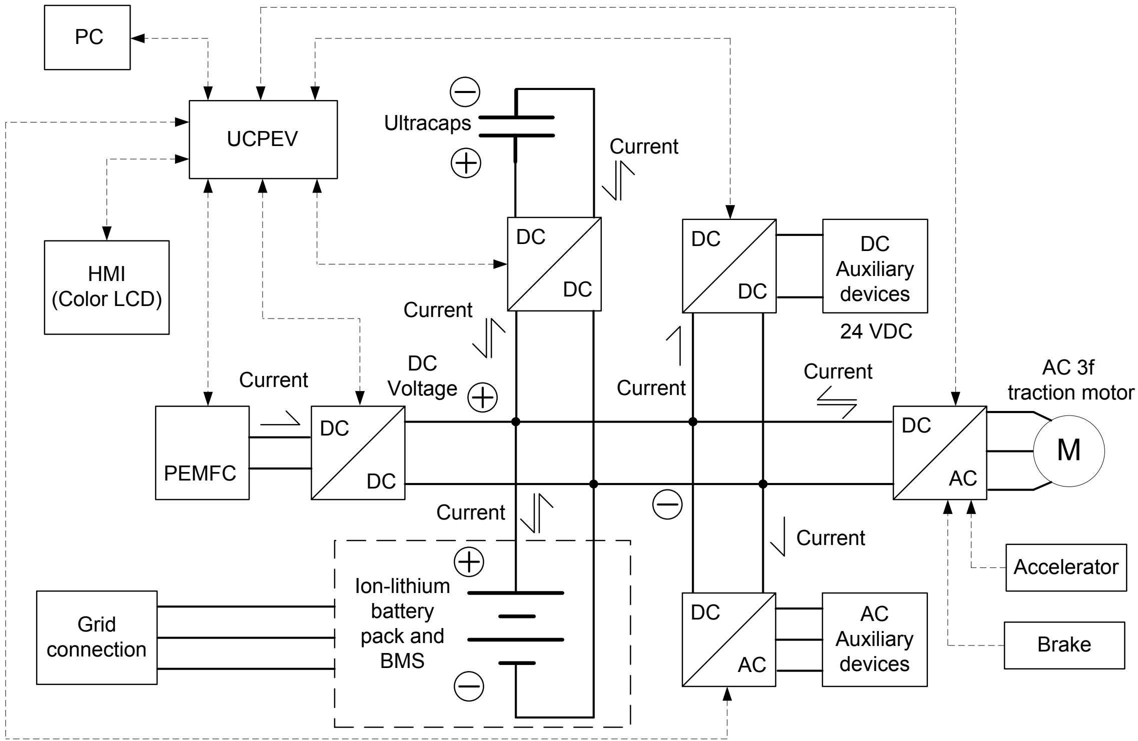

Figure 3: Simplified electric block diagram for the bus power train and auxiliary systems.

3 Conclusions

The present work unveils details on the pioneer hybrid electric hydrogen fuel cell bus that had most of its important technological devices and systems developed in Brazil. It consists of a plug-in type vehicle with ultracapacitors and predominance of batteries to achieve an efficient regenerative breaking system that altogether allowed the use of a low-power fuel cell that was made to work on steady-state operation mode, similarly to the stationary applications.

Acknowledgements

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Lessons Learned from Hydrogen Infrastructure Operation in the HyFLEET:CUTE Project

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1 Introduction

The main objective of the HyFLEET:CUTE project (January 2006 – December 2009) was to demonstrate hydrogen powered buses and their hydrogen infrastructures in everyday operation. 33 fuel cells buses and 14 buses with internal combustion engines ran in revenue service in ten cities on three continents (Amsterdam, Barcelona, Beijing, Berlin, Hamburg, London, Luxembourg, Madrid, Reykjavik and Perth / Western Australia).

This paper focuses on the experiences with on-site hydrogen infrastructure operation. Information on other project aspects can be found in an overall report [1]. Each infrastructure plant had a hydrogen refuelling station (350 bar rated pressure). The majority also comprised a unit for on-site generation of the fuel (water electrolysis, or steam reforming of liquefied petroleum gas or natural gas).

Figure 1 shows a generalised schematic of the HyFLEET:CUTE infrastructure facilities. The details of individual installations varied significantly.

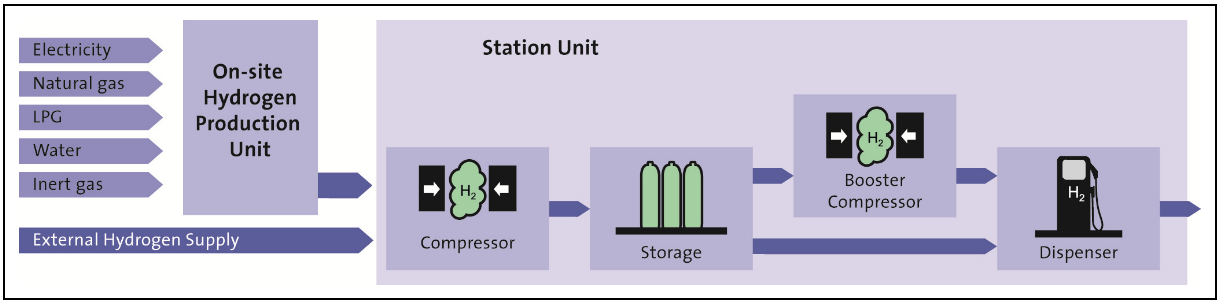

Figure 1: Generalised schematic of the HyFLEET:CUTE hydrogen infrastructures. Hydrogen was supplied by truck from external sources or generated on site from electrolysis of water, or by steam reforming of natural gas or liquefied petroleum gas (LPG). It was compressed, stored, and dispensed on demand to the buses. Dispensing required a pressure differential between the on-site storage and the vehicle tanks. In general, filling commenced using the pressure differential due to the empty bus tanks (decanting) and was completed with a booster compressor (booster mode). Some sites operated with decanting or booster mode only.

2 Performance Indicators

Qualitative and quantitative performance indicators were defined as part of the project's Assessment Framework. For a coherent analysis across all sites, the Production Unit and Station Unit as sketched in Figure 1 had to be treated individually. In particular, a meaningful comparison of facilities with and without on-site production of hydrogen only became possible this way. A similar set of indicators was first used in the CUTE project [2].

Quantitative indicators include:

- Availability of the Production Unit and of the Station Unit, respectively
- Distribution of downtime hours with respect to cause (such as maintenance, hydrogen supply, compressors and dispensing equipment)
- Specific energy demand of the Production Unit for on-site hydrogen generation including purification and drying
- Specific energy demand of the Station Unit for hydrogen, compression, storage and dispensing
- Efficiency of the entire on-site hydrogen supply chain
- Difference between hydrogen supplied (external delivery and/or on-site production) and hydrogen dispensed ("losses of hydrogen").

The scope of this paper is not to give a full account of all operating details of each of the sites but to provide an overview of findings and learnings. Girón [3] presented a thorough evaluation of the hydrogen refuelling installation in Madrid during the CUTE project.

3 Key Data

Most cities operated their three fuel cell buses and infrastructure for a one-year period as a continuation of their activities under the CUTE [4], ECTOS [5] and STEP [6] projects. A few of them extended their period of operation beyond the schedule of HyFLEET:CUTE voluntarily and at their own expenses. The Hamburg fleet with up to nine buses remained in service during the entire project. Berlin was the only site where a new hydrogen production and refuelling facility was built for HyFLEET:CUTE. It served a growing fleet of up to 14 buses with internal combustion engines from June 2006 plus two stationary fuel cells and vehicles outside the project (the latter with both liquid and gaseous hydrogen).

More than 344.000 kg of hydrogen were dispensed to the project buses between during over 13.960 fillings (January 2006 – November 2009). When also considering figures from CUTE, ECTOS and STEP, about 574.000 kg of the fuel were distributed to the vehicles from 2003 to end of 2009.

Under HyFLEET:CUTE, more than 170.000 kg of hydrogen were generated on site, mainly from water electrolysis. About 240.000 kg liquid and gaseous hydrogen were trucked in.

4 Example Performance Indicators: Availability of the Station Unit and Downtime Causes[1]

The average availability of the Station Units was 89,8% with the individual sites ranging between 61% and 99,6%. In fact, all Stations Units but one were operational for 80% of the time or more.

Calculation of this indicator was based on counting the time hours (unit not operational) and subtracting them from the total operating period on a "24 hours / 7 days per week" basis.

It is important to distinguish root causes for downtime. Ideally, downtime would be caused by (scheduled) maintenance.

Figure 2 shows that downtime across all sites was dominated by five factors that contributed more than 90% of all downtime hours. Problems with Production Units and compressors alone caused more than two thirds of all downtime. Maintenance contributed by less than 10%.

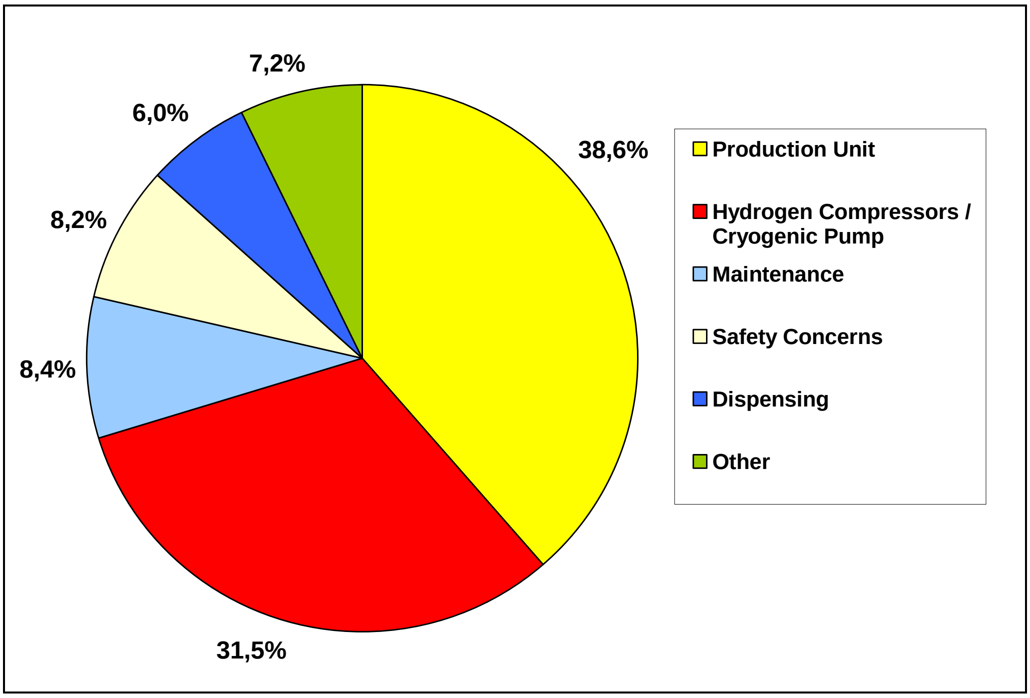

Figure 2: Normalised distribution of downtime hours of the Station Units with respect to cause.
As the operating period was different at the individual sites, downtime hours were normalised to one year. "Maintenance" stands for scheduled maintenance; "Safety Concerns" for periods when the station was technically OK but taken out of service due to safety concerns; all other categories stand for failure and repair of the components and their auxiliaries as stated.

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[1] Figures in this section are based on data between January 2006 and December 2008 when operation was planned to end at the last site (Berlin) according to the project schedule. Note that the Berlin partners continued their demonstration activities on a voluntary basis, similar to other HyFLEET:CUTE cities, as mentioned.

The issues with hydrogen supply affected bus operation (usually “no fuel”) but, from perspective of the Station Unit, were an external cause rather than being connected to technical difficulties with the Unit itself. Disregarding such “external problems” with hydrogen supply, the Station Units display an average availability of 93,8%, with each of them accomplishing of 89% or better.

“Hydrogen compressors”, including a cryogenic pump for liquid hydrogen in London, is the only category with contributions from all project sites. This is a matter of great concern since the compressors constitute the “heart” of the station units.

The dispensing equipment only caused 6% of all downtime and therefore less than maintenance. However, any matters related to these components deserve special attention since they constitute the “user interface”.

Comparison with the findings under the CUTE project reveals that similar types of problems prevailed. [2]

5 Lessons Learned

5.1 Production units

Electrolysers performed well overall. In particular, there were no problems with the core of the plant, i.e. the stack. The only major issue was corrosion in the lye loop of the Hamburg unit. Flexible operation is technically feasible. Energy consumption should be reduced in the future (stack and auxiliaries). As a rule of thumb, a well-maintained system can operate without difficulties.

The reformers failed to meet expectations. Severe problems with the core of the plant, the reformer tubes, were faced both in Berlin (feedstock: liquefied petroleum gas) and Madrid (natural gas). Process temperatures tended to exceed the allowed limits. In Madrid, auxiliaries caused significant downtime as well.

Start-stop cycles of reformers are energy and time consuming. Instead, the units were usually operated at part-load when the hydrogen storage was running full. Surplus hydrogen often had to be vented. Part-load operation reduced process efficiency. Flexible operation of the reformers therefore remains a big issue.

5.2 Station units

Availability of the Station Unit was most severely affected by on-site Production Units. Accordingly, arrangements for backup supplies by trailer delivery are vital.

The main internal factor reducing availability was hydrogen compressors, as mentioned. Redundancy would be beneficial but it is a cost issue.

5.3 Entire hydrogen supply chain

Sites with on-site electrolysis displayed an efficiency of the supply chain of about 50% (total end energy consumption divided by the energy content of the total amount of hydrogen dispensed).

Inaccuracies of hydrogen meters were proven or suspected at individual sites. This kind of unreliability also impeded quantifying losses of hydrogen due to (de-) pressurisation of pipes and hoses, purging, regeneration of driers, boil-off etc. These known mechanisms can sum up to significant amounts.

In HyFLEET:CUTE, hydrogen impurity (i.e. not according to specifications) was not a matter of great concern, unlike in CUTE.

6 Outlook

The challenges of the future include:

- Hydrogen compressors, the most critical component at present
- Durable dispensing equipment (nozzles, hoses, etc.) and hydrogen meters in particular
- Improved system integration, standardisation and simplification
- Increasing energy efficiency and reducing hydrogen losses
- Accounting for variable load patterns, intermittent and part-load operation

Modular design is required for scaling up hydrogen infrastructure facilities with growing fleets and increasing intensity of operation. Manufacturers need to advance on series development for infrastructure.

Acknowledgements

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5 Years of Experience with Ford Fuel Cell Vehicle Fleet Operations

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1 Introduction

Looking back the long road of electrification of vehicle (beginning with the first battery powered vehicles back in the days that outnumbered the ICE vehicles) the challenge remained unchanged: the energy to propel the vehicle has to be carried on board. We are still looking to find high density, light weight, affordable, safe forms of energy to place them in our vehicles. Since it surfaced to our minds that crude oil is not as abundant as we had thought, we are looking to find other sources of energy that we can use without emptying our stocks. Also, with the density of traffic specifically in the big cites augmenting, the need to reduce pollution from this badly needed form of transportation gained a bigger momentum and lead for example to the Californian Clean Air Act that demands a certain percentage of zero emission vehicles.

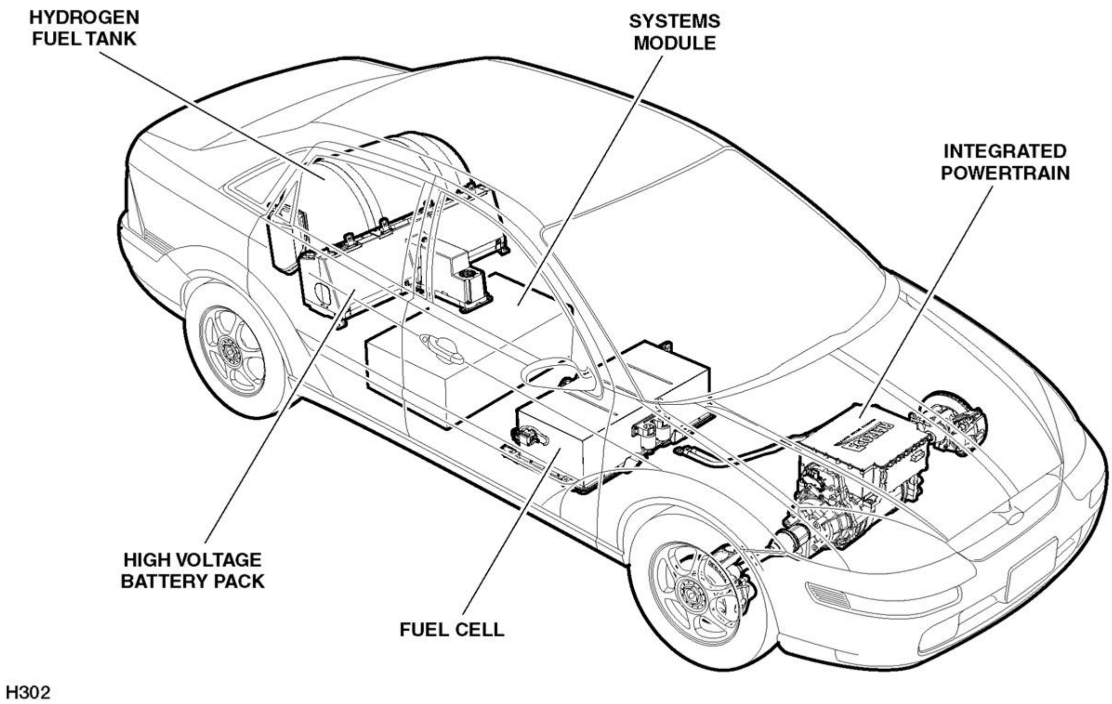

Figure 1: Main Module of the Ford Focus Fuel Cell.

Hydrogen in combination with a fuel cell onboard a vehicle was one possible way that promised to catch up on our conventional cars in terms of performance pretty soon. Ford has decided to team up with Daimler in 1998 to form an alliance and develop fuel cell and hydrogen powered vehicles that should not bear the taste of golf cart battery driven vehicles but regular, every customer standard cars. With hydrogen being well known, but not available at the pump, the OEMs had to join projects with energy supplying companies to solve the problem with providing fuel to the fleet. Fleet being here the entity of all H2-driven vehicles no matter which OEM labels the hood.

Thus, we are part of world wide vehicle demo projects (USA, Canada, Germany, and Iceland) nestled around the hydrogen infrastructure. We, the Ford Research Center Aachen, represent and operate the Ford Fuel Cell Vehicle (FCV) fleet in Germany. As partner in the Clean Energy Partnership in Berlin that was founded in 2002 we deployed 3 vehicles in customer hands in Berlin. In fall 2004 we celebrated the inauguration of the first public H2 fueling station, which operated through 2008. In spring 2005 the vehicles were handed over to our customers.

Since that time we gained a tremendous amount if customer insight, technical data, public events and feedback from technical and non-technical over business related and emotional statements. The most important findings could be characterized in the following.

2 Vehicle Technology

The initial phase of the demo project was planned for three years. All design and engineering was done to prove a three year life cycle of the Focus FCV. The uptime of the fleet was targeted at 85% but exceeded the expectations and averaged at about 92% of vehicle availability. The vehicles robustness showed to be better than anticipated leading to an extension of the fleet in customer hands though end of 2010 for the Berlin CEP. Other programs extended the vehicle use as well (Canada) or even stocked up like Iceland that actually received ten additional vehicles in January 2010 due to the fact that the DoE project in USA was terminated according to schedule. The US Department of Energy did decide not to extend the program due to the financial situation.

Ford wouldn't have opted for this proceeding without being sure to not create a financial burden to the stretched out budgets in nowadays. The cost for maintaining the fleet has been proved to be lower than anticipated.

3 Hydrogen Infrastructure

Given the fact that no hydrogen refueling infrastructure was available and that there was no fall back – standard refueling procedure, it became obvious even early in the project that one OEM by itself could not handle this approach. Pretty fast agreements on standards such as fueling receptacle and safety proceedings or fuel quality could be installed. Most of the hardware for example was modified from the technology that was used for natural gas (CNG) powered vehicles that also are the result of search for alternative fuels. This puts us in the position that even at the beginning of demo rallies around 2002 world wide the vast majority of all existing hydrogen powered vehicles could be flawlessly refueled on any given hydrogen station. The SAE standard J2600 was issued as early as October 2002 to cover this piece.

So now we can focus on making the refueling process even faster and more robust instead of making sure that a vehicle could be fueled at all.

Figure 2

4 Customers

We like to address the users of our vehicles as customers but also as development partners. Knowing that we placed an all new technology from the labs into real world, we tried to link our customers to their new vehicles technically and emotionally. Ford chose the approach to have down to earth vehicles, that means other than the decals the car looks, feels and handles just like an ordinary MJ 2004 US Focus. We at one part decided to do so to underline our commitment to deliver solid, affordable vehicles to the everyday customer without exaggerated technological display externally. If the technology was that different from the known, at least the vehicle should look familiar. It turned out that this was taken differently by the users of the vehicles: No one could tell that this was not an ordinary vehicle but an elaborate piece of the engineering department. After all, even if you are running an environmentally friendly vehicle, one should see what your ride is all about. At the beginning of the program we took larger efforts to make the technology – not only the vehicle handling – known and understood for our customers. Mostly our drivers have developed a relationship to "their" vehicle. We received positive feedback from the usage and customers that acted as multipliers in spreading the word about Ford's sustainable activities. It must be kept in mind that the majority of people have only driven one FCV by one supplier and cannot compare with the technology of other suppliers. The only reference to compare with is the regular internal combustion engine allowing for comparing with a vehicle technology that is in extensive usage since over 100 years. We will not forget the complaints we got during this project. Amongst fuel cell specific and non-fuel cell related topics, we learned that the customers were suffering from the very few H2 refueling stations that forced them to cross downtown Berlin from East to West during rush hour. We all can imagine how this affects mood – no matter what vehicle you are driving.

5 Public Education

One important part of the fleet operations was and is still to make the public and opinion leaders aware of the capabilities of the fuel cell technology. We participated in public events (60th Anniversary of North Rhine Westphalia, Open House at the Federal Ministry of Transport, Building and Urban Affairs (BMVBS), Night of Science Berlin etc.) or supported small events like projects on schools with show and tell of our vehicles. Another part was road demonstration with rallies, like the 2009 from Oslo to Stavanger for the opening of the Norwegian Hydrogen Highway. Being out and about with the FCVs it was not easy to spread the essence of the technology and why it is so important to look for an alternative to conventional cars. The public has quite some misconceptions when it comes to hydrogen (the Hindenburg, the Challenger, the Apollo program etc). The German translation of fuel cell is rather misleading and the bridge to a technical device that is generating electricity is not easily built. Only since a couple of years the subject of environmentally friendly technologies and alternative propulsion systems finds its way to the curriculum in our schools. Over the past 5 years we had more requests to go into middle schools and explain our vehicles as well as the job description of modern engineers.

6 Lessons Learned

So, what have we learned from all this? Why all the effort when now it seems that everyone is voluntarily jumping back to pure battery powered vehicles?

The answer might be as simple as Fuel Cell Vehicles are driven by an electric motor without having the fall back of an internal combustion engine. All components and accessory drives are electrical. Hybridization takes place between the usage of the fuel cell and the HV battery. Electrical safety has to be considered since we are dealing with voltages above 60 V DC.

Engineers are required to be thinking out of their well known box.

Energy providers see those vehicles not as a mono-directional sink for what they provide but rather as a bi-directional usage that they want to look into to be more efficient in the usage of our precious resources.

As for the fueling infrastructure where nothing substantial was available we used the existing work from CNG technology and modified it to suit the needs for the H2 infrastructure. Since nothing was pre-set there, achieving common standards (see SAE J2600) was relatively easy and lead to a common understanding of the hardware equipment of a fueling station. Surprisingly, all OEMs agreed on one solution pretty soon. For the recharging infrastructure for battery electric vehicles we have some more work to do.

We also discovered that besides the challenges to bring flawlessly operating BEV to the market, the public embraces this technology a lot more than they did with FCVs. Maybe this comes from the fact that everyone changed batteries at least once in their lifes on the flashlight – hardly anyone who handled hydrogen at all.

Ford still believes that the long term solution will be supported by hydrogen/fuel cells and that BEV will be around as well. We found a lot of synergies in both fields and engineers that worked on fuel cells bring a great knowledge to work on battery vehicle technologies as well.

Demonstration of a Fuel Cell Powered Boat

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A 1.2 kW fuel cell power system (Nexa by Ballard) was used to power a small boat equipped with a 600 W electric outboard motor (M26 E-Drive by Yamaha). A DC/DC converter/voltage regulator was used to match the voltage of the motor (12 V). Two 12 V 65 Ah batteries were incorporated in the system in parallel in order to provide 24 V required for the Nexa system start-up, but they also provided additional energy. Hydrogen was stored in 3 metal hydride bottles; each 2.6 liter bottle contained up to 600 standard litters of hydrogen at 10-14 bars. Figure 1 shows the configuration of the boat propulsion system.

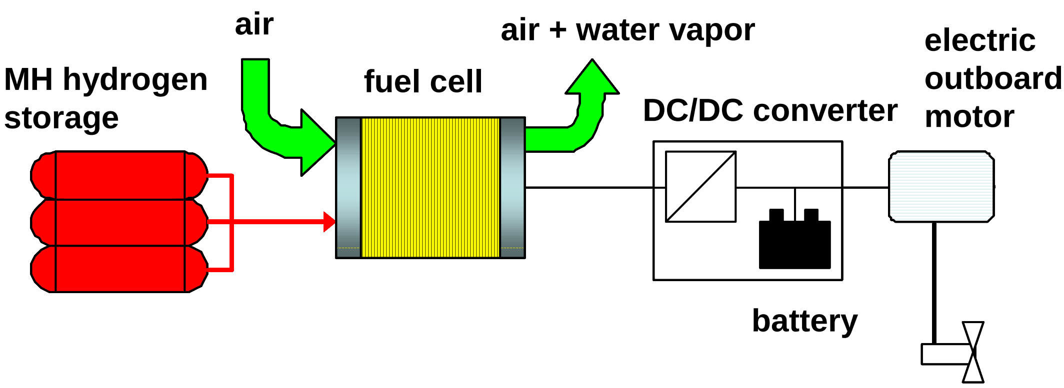

Figure 1: Configuration of the boat propulsion system.

This configuration was able to run the boat at the speed of 4 knots for more than 5 hours (3 hours of running time coming from stored hydrogen and 2 hours from the batteries). Figure 2 shows the boat with installed equipment under the prow compartment. The advantages of electric propulsion are reliable, clean and quiet operation, and excellent maneuvering capabilities at very low speeds. Fuel cell adds additional operability of the system essentially as a range extender. By separating power from energy it would be easy to further extend the range of the boat by simply adding additional bottles.

During operation the temperature of the metal hydride bottles dropped significantly below the ambient temperature, reducing the immediate availability of hydrogen. Additional tests were performed in the laboratory in order to quantify this phenomenon and to provide inputs for more optimized system design. The results of both the field test and the laboratory tests will be presented.

Figure 2: Completed fuel cell powered boat.

Small boats may be an interesting niche market for the fuel cell systems. Clean and quiet operation has its price some may be willing to pay. This is particularly appealing for use in national parks, but also in every isolated tourist destination as quietness and clean air are a part of the vacation purpose. In addition, hydrogen can easily be produced locally from water electrolysis, which may be additional selling point for use in remote areas where fuel supply is not always easy.

This project is a part of a wider initiative called the Hydrogen Islands Initiative, launched by the UNIDO-International Centre for Hydrogen Energy Technologies. Islands are ideal polygons for demonstration of hydrogen energy technologies and entire hydrogen economy at a manageable scale. Because of their remoteness and isolation, energy solutions for the islands differ from those on the mainland. The choice of conventional energies on the islands is often limited and their cost may be several times higher than on the mainland. At the same time, most islands do not have energy intense activities, have historically learned how to conserve energy, and most importantly have plenty of clean renewable energy available, such as solar, wind, geothermal, waves, tides, ocean current, and ocean thermal gradient. These sources may be used to generate electricity and hydrogen, which then can satisfy all the energy needs of the islands communities. There are hundreds of islands where hydrogen inclusive economy would be not only technically but also economically feasible, even today.

The Hydrogen Islands Initiative strives to establish clean hydrogen energy systems on the world islands in order to solve the existing energy problems and at the same time preserve their pristine environment, and in such manner provide energy basis for sustainable development. With hydrogen energy systems based on renewable energy sources, the worldwide islands will become energy self sufficient, and serve as the showcase for development of the global hydrogen energy system. This initiative practically creates an early market for hydrogen technologies (technologies for hydrogen production, storage and use) and their demonstration in real-life applications.

Fuel Cells in High Seas

Keno Leites, TKMS Blohm + Voss Nordseewerke GmbH, Germany

1 ThyssenKrupp Marine Systems

ThyssenKrupp Marine Systems (TKMS) is the first privately owned shipbuilding group in Europe. The main activities are related to submarines (also with fuel cells), navy vessels and Mega-Yachts. Further activities are related to components and repair/upgrade services.

With our submarine business we have developed the first ocean going commercial fuel cell application: the submarine classes 212A and 214. Their systems are based on pure hydrogen and oxygen supply.

2 Challenges in Ship Power

The shipping industry is today facing enormous challenges. Most noticeable is the rise of the fuel prices which affects consumer prices. While the prices have fallen dramatically after summer 2008, they have doubled since then. And they will rise further, at least due to the CO_2 surcharge.

Probably more present in the media is the relation of ship borne emissions to the global warming.

Even if a ship is the most efficient means of transport actually available, the absolute amount of emissions from ship engines is significantly high. The overall CO_2 emissions have a share of about 3% in the worldwide emissions. In a view from a ports perspective the share is quite higher.

Although SOx emissions are due to the coming regulations not so much in focus anymore, NOx emissions are of interest. Many ports and shipping regions have emission fees and even more will come up. The IMO has concluded the tier III limits [1], which can hardly be reached without secondary measures as semi-catalytic reduction. Further, particulate matter is under discussion [2]; filtering measures like in road traffic have already become a standard for large yachts and will go into merchant vessels as well. Finally noise and vibrations should not be forgotten. Consequently the authorities of several ports and favoured cruise destinations are considering prohibiting the use of harbour generator sets and to oblige the vessels to use shore based power.

An alternative to these shore based solutions would be to enhance the power conversion on board. Mainly two ways seem to be feasible nowadays:

1. Exhaust gas treatment [3]
2. Higher efficiency and advanced fuels

The second option leads directly to the proposed solution in this paper:

<u>A high temperature fuel cell with sulphur free or synthetic fuel.</u>

3 Forming the Lighthouse Initiative

Since this concept is interesting for different ship types, a so-called lighthouse project is initiated, which aims to bundle demonstration projects based on these issues for seagoing ships [4].

The lighthouse consists of a top project '*Toplaterne*' and a number of demonstration projects under this 'roof'. The whole lighthouse is government-funded from funds of the German 'national innovation programme for hydrogen and fuel cell technology' (NIP).

Partners of *Toplaterne* include, among others, a number of shipyards, classification societies, operators, equipment manufacturers and universities. These partners work together on questions like ecology and efficiency, economy and LCC and rules and standards.

Actually three demo-projects are applying for partnership in the lighthouse. The first one is the presented project called '***SchIBZ***', which is lead by TKMS.

4 Current Status

Today the diesel generator sets are surrounded by a number of secondary measures to achieve low exhaust gas and noise emissions.

The catalytic reduction of NOx requires very low sulphur fuel oil and ammonia [5], which is an additional chemical on board. Filter and catalyst need certain exhaust gas temperatures which will result in reheating. Finally all these components have to be maintained.

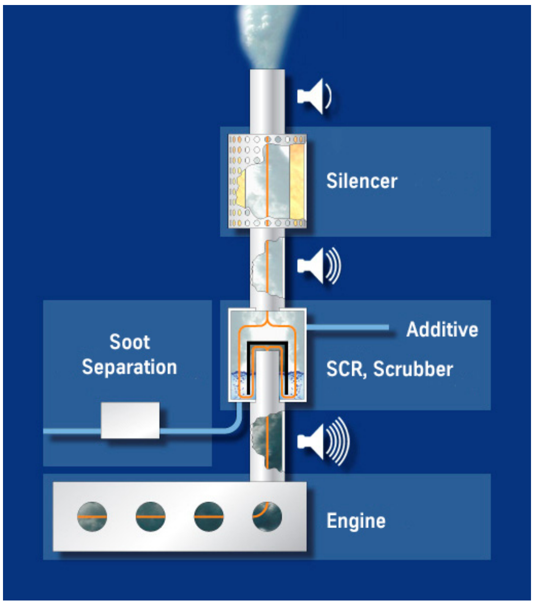

Figure 1: schematic of a sophisticated diesel generator set.

5 Choosing the Fuel

The marine industry is used to using oil as fuel. It is an easy to handle liquid with

- a high energy density,
- low fire risk,

- well proven system components,
- high efficiency when used in modern diesel engines.

Since the ecological influence of LNG is lower than that of higher hydro-carbons like diesel oil, many studies to use it are carried out. One big hurdle for the introduction onto ships is the storage with a high volumetric energy content [6].

From the above follows, that it is preferable to stay with diesel type fuel for the near future. Even better is synthetic fuel [7]. This fuel is produced using the Fischer-Tropsch-process. The fuels are called XtL, where X stands for Coal, Gas or Biomass-to-Liquid.

The above mentioned fuels have the advantage of fitting in existing logistics, do not need new or special safety measures and the personnel are used to handle such liquids.

The only additional effort needed is the installation of a completely separated piping system, to protect the sulphur free fuel from contamination by other fuels, if onboard.

6 Choosing the Fuel Cell

Fuel cells have in common, that they operate on gaseous fuels. The difference is that low temperature fuel cells like PEM only use and tolerate hydrogen, which has to be supplied in a very high purity. High temperature fuel cells tolerate CO_2 and generate electrical current from CH_4 and CO [8].

To utilize liquid fuels they have to be transformed into a gaseous state, this is called pre-reforming. In this process the liquid is under high temperature catalytically broken down to a gas mixture, which contains CH_4, H_2, CO and CO_2.

On vessels from around 80 m upwards space is an issue. Especially engine spaces in yachts are very tight, so the integration of such a fuel cell including the auxiliary components requires a major redesign. An intelligent modularisation of the components can ease the integration.

7 Energy Buffering

A high temperature fuel cell has a kind of “steady state dynamic”, which is in the range of 50% MCR in hours [9].

For this reason a fuel cell needs a supporting device, which compensates the load changes in the network until the fuel cell has followed. Depending on the power supply system set up, this may be an accompanying diesel generator set or an energy storage module like a battery.

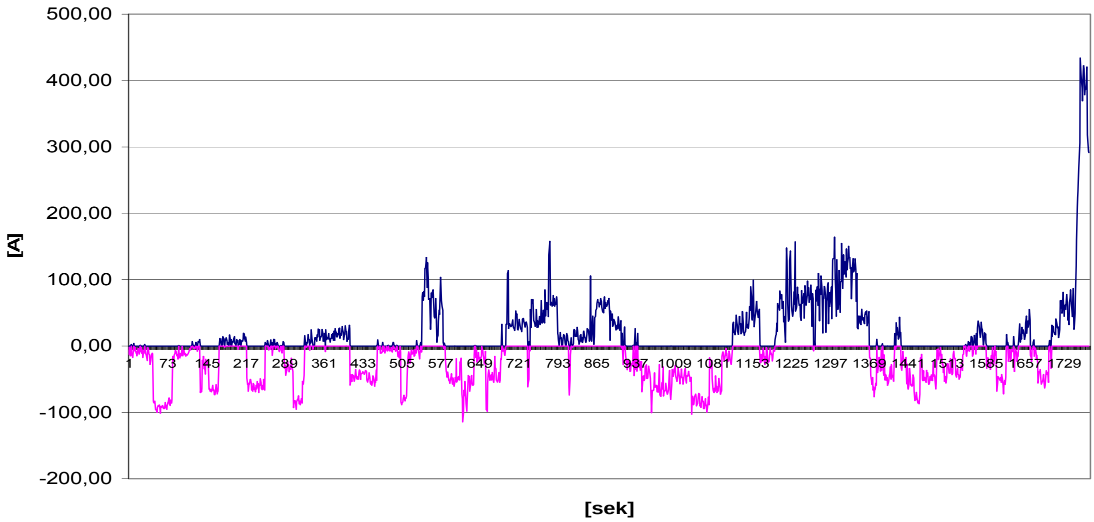

Figure 2: Typical power curve as deviation from the average.

The system suggested here shall be capable of operating in isle mode, without the aid of other combustion engines.

Very promising are the current improvements in the Li-Ion-technology. Depending on the material combination and sizing of active layers, a trade off between current and capacity can be made. With certain configurations a combined behaviour between battery and super cap can be gained. An important feature of Li-Ion batteries is that the lifetime increases over proportionally with a reduced depth of discharge (DOD).

This circumstance is fortunate because the battery cells must be sized to take several 100 kWh surplus energy, while the fuel cell is transferred to a different output level. In a steady state operation the battery cell has only to compensate smaller load changes [10]. This results in a low (DOD) and prolongs the lifetime drastically.

8 DC/AC Conversion

The board network of a ship is normally a 50 or 60 Hz system, while the fuel cell output is direct current.

To match this with the board network a specialised inverter will be used, which incorporates frequency control, voltage regulation and back-voltage prevention.

9 System Concept *SchIBZ*

The project ***SchIBZ*** is a development undertaking for the above indicated fuel cell system. The system is intended to be a marine demonstrator plant, as close to a commercial application as possible.

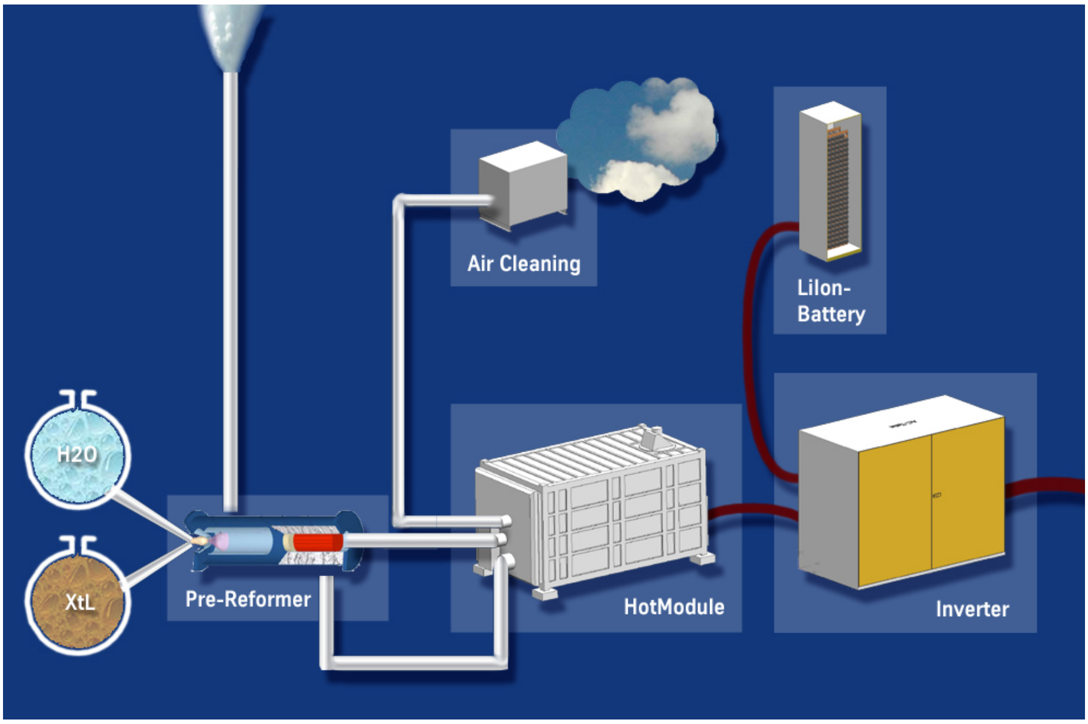

Figure 3: System concept of the fuel cell plant SchIBZ.

Core of the system is the MCFC from MTU Onsite Energy. The fuel cell is a revised and upgraded version from the well known HotModule. The most significant change is the new design of the stack, which is now self containing. This is important, since a ship is affected by forces in all three axes.

The fuel processing will be done by a pre-refomer from OWI Aachen. This unit cracks the supplied fuel and provides the fuel cell with CH_4, CO, CO_2 and H_2. A so-called steam reformer is chosen which does not need additional energy and can be thermally integrated with the fuel cell.

10 Partners

The project is carried out by a consortium of 8 partners.

Leader of the consortium is ThyssenKrupp Marine Systems (TKMS). The work package of TKMS is the ship integration, practically for the test installation as well as the theoretical investigation for newbuilds.

Supplier of the fuel cell is the aforementioned MTU Onsite Energy GmbH Fuel Cell Systems. The gas supply (pre-reformer etc.) is part of the work package of Oel-Waerme-Institut Aachen. They do also additional reforming tests with different fuels.

The general automation is developed by Imtech Marine Germany. This package includes remote control and monitoring and power management between fuel cell and battery.

The conformity with rules and regulations is supervised by Germanischer Lloyd. Their task is to control and consult design and manufacturing phase. The overall evaluation and analysis of the plant is carried out by the Helmut-Schmidt-University of the German Forces in Hamburg. They also develop a simulation system for automation purposes.

Figure 4: Demonstrator test vessel MS Cellus.

Finally, the vessel for the ship test belongs to the Reederei Braren. During the envisaged 11 months at sea the plant should experience every season and obtain many results for the development of a commercial version.

11 Challenges for Ship Bourne Applications

Even if we do see a ship not as a moving application like trucks or trains, it is a power plant in motion. This means, the equipment has to stand ongoing inclinations around two axes, accelerations and shocks along three axes and constant vibrations affecting all components.

Furthermore, the environment at sea and inside ships is challenging. The effects of temperature range, moisture and especially the salt-content of sea-air on the membranes are unknown.

MTU is working on a new marine design for the stack which will be tested in different applications.

12 Possible Application in Seagoing Vessels

The described system is best suitable for high-value seagoing vessels. Due to weight and size it is not very suitable for inland shipping, but for vessels operating a lot in coastal waters and with many harbour calls. Due to its characteristics it shall operate continuously, as a base load supply. The advantages in efficiency compensate for the higher fuel costs compared with MGO used in such operations. But even this will change in favour for the fuel cells with the upcoming IMO regulations on emissions and the emission trading.

According to first calculations more than half of the additional investment – compared with a state-of-the-art diesel generator – is compensated by the savings in fuel consumption. Including savings in maintenance and harbour emission fees the system is nearly cost neutral.

13 Time Frame

The project has started in June 2009 and runs for about 4 years. The superordinated *Toplaterne* runs 5 years, to have a phase for assessing the results of the demonstration projects [11].

14 Conclusions

The presented application of the fuel cell technology onboard sea-going ships shows a solution for the near term realisation of fuel cell based power generation.

The technologies and modules are today available, just the combination has to be developed. This is no basic research but advanced engineering.

Even the economies are in the range of a black “0”, so that it is the right time to start using fuel cells.

We expect the availability of commercial systems in short time after finishing the project.

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The Consumer’s Perspective on Hydrogen in Transportation – The Experiences of the World’s Third Largest Automobile Club with a Hydrogen Vehicle in Road Patrol Service

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Andrea Gärtner, Future Vehicle Technologies, ADAC, Germany
Frank Buchholz, Road Patrol Region East ADAC, Germany

ADAC is the worlds third largest Automobile Club. ADAC annually assists its 16.8 million members in approx. 3.9 million breakdowns. 1,700 road patrol vehicles are specifically equipped with parts and tools for breakdown assistance. At the “ADAC Technik Zentrum” – ADAC’s technical centre – in Landsberg near Munich, road patrols receive training on current and future vehicle technologies. Also, the ADAC Technik Zentrum is the European automobile clubs’ “European test centre”, developing a joint test programme of environmental, safety and consumer protection tests. The tests include various crash tests, durability and long-term driving tests for alternative fuels, environmental assessment based on well-to-wheel analysis, ADAC’s EcoTest and web-based market research analysis. In Berlin, ADAC has been running a GM/Opel road patrol vehicle driven by a hydrogen fuel cell since 2009. ADAC is interested in future consumer expectations on hydrogen cars and refuelling infrastructure, experiences with the GM/Opel hydrogen road patrol car and fuel-cell capabilities under real-life driving conditions, as well as well-to-wheel studies.

1 Consumer Expectations

Like electric vehicles, fuel-cell vehicles are powered by electric engines. But rather than carry the required electric power in a battery, they produce it right there in the fuel cell. Therefore we can transpose some of the results of a recent ADAC survey on battery electric vehicles to fuel-cell electric vehicles.

The results of the survey show that future car buyers are prepared to switch from fossil fuels to electric power or other alternative power-trains/fuels. But they are not prepared to accept makeshift solutions or any loss in comfort. Nor are they prepared to pay more.

First and foremost, the price must be right: Almost 40 % of the respondents are not prepared to spend more in terms of the total cost of ownership for a vehicle with an alternative power-train than they would for a comparable conventional car.

Furthermore, the vast majority are not prepared to compromise on range, top speed, refuelling and space. Consumer expectations like top speed, space and range are not a problem in fuel-cell electric vehicles, unlike in battery electric vehicles. Therefore battery electric vehicles may remain for niche use only, like city cars with limited range, but adequate fuelling infrastructure at power points. Therefore the niche of battery electric vehicles is defined by range limitations.

In contrast fuel-cell electric vehicles offer a large utilisation. But in order to facilitate their launch and ensure acceptance, we need to establish a wide-area network of hydrogen refuelling stations. However such a network would have to be built from scratch. Therefore the niche for fuel-cell electric vehicles is defined by infrastructure limitations.

In addition, some aspects come into plays which have thus far made the consumer reluctant. They include the question of the hydrogen production chain (coal, nuclear, renewable) and also the fact that the safe storage and transport of hydrogen in vehicles are quite energy-intensive. Therefore sustainable scenarios calculate a minimum share of 50 % renewable energy. These energy and cost scenario calculations show that hydrogen cost may result in 10 years in a fuel price of 1.10 - 1.60 € per litre petrol equivalent at the fuel pump, which may be reduced by further 15 % in long term (www.germanhy.de). If the German fuel taxes and added value taxes (VAT) for petrol are added to these hydrogen cost, it would result in 2.10 - 2.70 € per litre of petrol equivalent.

2 The Road Patrol Project

GM is currently having 100 HydroGen4 vehicles world-wide tested by customers. Ten are being used in Berlin under the Clean Energy Partnership (CEP). Opel made one of them available to the ADAC's Berlin road patrol. The vehicle is fully equipped with road patrol tools and spares. The test period runs from February 2009 to the end of 2010. The test is aimed at gathering experience with the fuel-cell drive under everyday conditions of operation and the logistics of hydrogen refuelling.

3 The Vehicle

The basis of the hydrogen car is a Chevrolet Equinox. The vehicles are fuelled with 4.2 kg of hydrogen (app. 16 litre petrol equivalent) stored in three 700-bar high-pressure hydrogen tanks made of a carbon fibre compound. In a fuel-cell stack made of 440 in-line polymer electrolyte membrane cells, hydrogen and oxygen are electro-chemically synthesised to water and, in the process, electrical and thermal energy are released. The system has a power output of 93 kW.

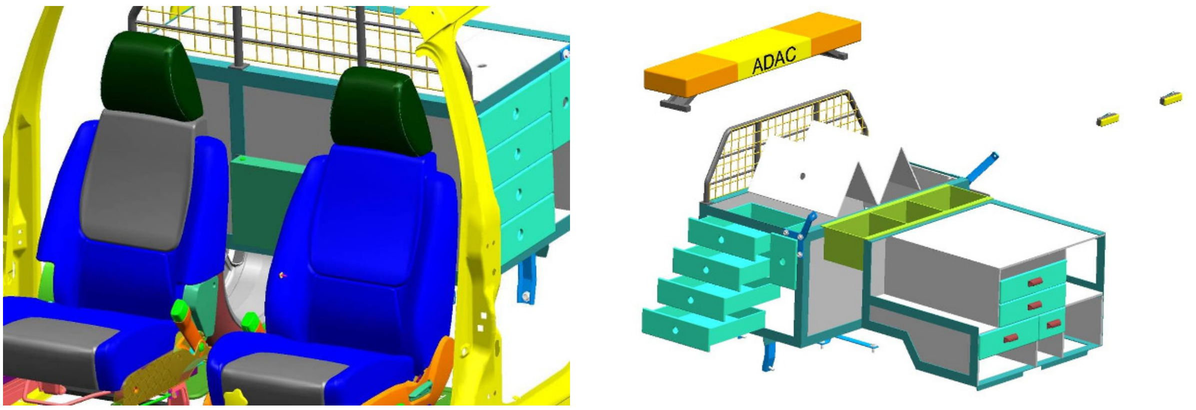

Figure 1: Components for HydroGen4 for Berlin road patrol.

A 73 kW three-phase synchronous motor with integrated power management and a planetary gearbox produces 320 Nm of torque and accelerates from 0 to 100 kph in 12 seconds. The vehicle's top speed is 160 kph. Only the original test vehicles have the effective range of 320 km. With the added weight of its equipment and the additional systems served by the power source (**Figure 1**), ADAC's road patrol vehicle only has a range of approx. 150 km.

4 ADAC Experiences

The hydrogen road patrol vehicle has clocked over 1,000 operating hours and run up approx. 15,000 km under standard road patrol conditions. For almost 60 % of the operating hours, the vehicle stood with the engine idling, since Opel/GM instructions require the system not to be powered off during breakdown assistance in order to ensure the power supply. Based on the available data, Opel/GM is now determining whether the system can be powered off at least during longer assistance stops (**Figure 2**).

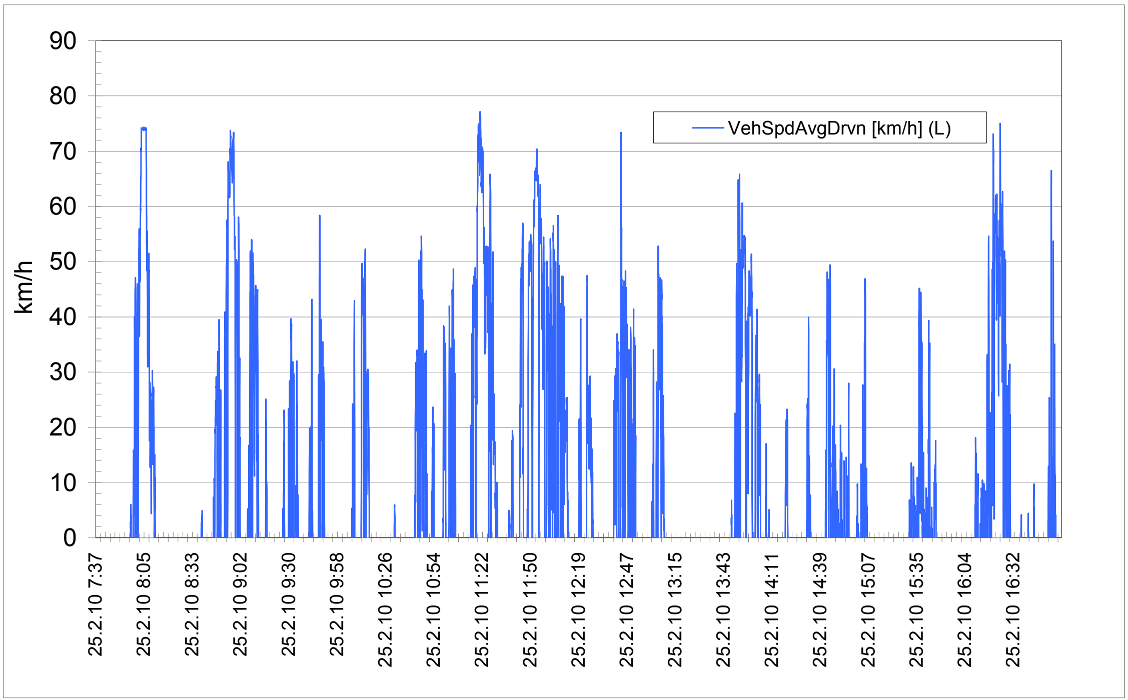

Figure 2: Driving conditions of Berlin road patrol.

The vehicle can be put to the same uses as any other road patrol vehicle, except for towing, since it is not equipped with either a tow hook or a tow lug allowing the attachment of a tow bar or rope.

The road patrols did not report any system failure. It seems to be working quite reliably under any conditions and temperatures – despite the higher demand on the system due to the additional weight and power equipment served. The vehicle carries three ADAC portable power stations. Two of them are used for jump-starting, one as an additional power source for the vehicle (flashlights, radio etc.). The power stations are powerful enough to jump-start larger vehicles. The special recharging devices developed for the power stations have so far proved efficient and adequate (**Figure 3**).

For refuelling, there is a fuel station with 700-bar technology at Berlin-Spandau. This is the first commercial fuel station world-wide equipped with an infrared vehicle-to-station data communication interface. The interface communicates the data relevant to the recharging process (such as temperature and pressure) as well as the recorded driving and operating cycle and fuel consumption data directly to Opel. With the technology developed for this station, refuelling does not take longer than conventional filling up. Two other fuel stations are not equipped with the 700-bar technology, which renders refuelling considerably longer.

Figure 3: Berlin road patrol HydroGen4.

Actually, the only problems are with the logistics of refuelling, which were also included in the scope of the test. The refuelling pumps are often out of service due to soft- or hardware problems. When this happens, the hydrogen road patrol vehicle takes an involuntary break since refuelling at other stations is too time-consuming to be practical for us.

During its over 1,000 hours of operation and approx. 15,000 km on the road, the fuel-cell vehicle was refuelled 172 times. On average, it runs 100 km on 2.4 kg of hydrogen (app. 8.8 litre petrol equivalent). Again, we need to consider that for almost 60 % of the time, the system was idling (during breakdown assistance stops). Looking at the driving cycles as such, the average hydrogen consumption per 100 km is only 1.3 kg (app. 4.8 litre petrol equivalent).

5 Conclusions

Together with GM, ADAC has proved, that fuel-cell electric vehicles can offer the same technology standard, as required from today's diesel and petrol cars. Fuel cell cars have significant benefits in areas, where the fuelling infrastructure is available. Even if in principle the feasibility for an introduction of fuel-cell technology in cars is proofed, open questions on cost of clean fuels, storage cost and vehicle cost must be answered, before steps for a market introduction are taken. If these questions on cost are answered satisfactory for consumers, there are no barriers for public acceptance of fuel- cell vehicles.

FORMULA ZERO: Development and Kart's Competition Driven by PEM Fuel Cell

Ismael Aso[*], **Joaquin Mora**, **Leire Romero**, **Pablo Marcuello**, Aragon Hydrogen Foundation, Spain

1 Introduction

Formula Zero (FZ) is a new category of racing for zero emission vehicles and hydrogen fuel cell (FC) that defends an ecological and fun future. The competition is an ideal platform for the development of new technologies and to attract the attention of the general public [1].

In a motor sport competition every team have to follow rules in order to ensure a fair competition. In the Formula Zero championship, there are many rules [2], for the different aspects of the race but here the most relevant technical ones are marked:

- **Vehicle general characteristics.** Fuel cell powered hybrid electric drive train, single seat, no roof, no suspension, four wheels, steering ensured by at least two wheels, propelled by at least two wheels. The maximum weight is 275kg without driver and the minimum 150Kg. If the driver weights less than 75kg, ballast must be added to the vehicle to rise 75Kg. Dimensions (Maximum): length 230cm, Width 150cm, Height 75cm, Wheelbase110cm min 160 cm max, ground clearance 35mm min.
- **Fuel cell.** Vehicles must be powered by one Hydrogenics HyPM HD 8 Fuel Cell Power Module. Exhaust water must be collected in a container on-board the vehicle.
- **Energy storage**. The collection of all components witch store energy recoverable to participate in the propulsion of the vehicle, except for the hydrogen cylinder provided by the organizer, is considered The Energy Storage System (ESS). The maximum usable energy storage capacity of the ESS is 250.00 Joules.
- **Propulsion and motors**. Only electric motors may be used. Propulsion of the vehicle must be made through the wheels. The vehicle must be fitted with a reverse mode.
- **Brakes**. A Hydraulic braking system (the primary braking system) operated by pedal is mandatory. The primary braking system must be a dual-circuit system, with a front and a rear circuit. Any kinetic energy recovery system may not be activated by any means other the brake and/or the accelerator pedal.
- **Electrical equipment**. The fuel cell has to be started without connecting an external energy source. Batteries or capacitors not included in EES must be fused to limit power output to 600W. Battery types other than those listed below are prohibited: Nickel-iron, Nickel-Zinc, Nickel-Metal -Hydride, Lithium-Ion and Lithium-Metal-polymer. Capacitors others than the following types are prohibited: Glycol Ether, Lactone, Amide, Aliphatic carboxylic acids, Ammonia based... Electrical potential of more than 120V DC or 71V AC RMS referred to system ground is prohibited.

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Electrical potential of more than 50V between system ground and the chassis or body of the vehicle is prohibited.

- **Hydrogen feed system**. The hydrogen feed system must be routed such that accumulation of hydrogen in enclosed or semi-enclosed areas is minimized in the event of a leak. Hydrogen cylinders other than those supplied by the organizers are prohibited. Those are 200 bar pressurized deposit. The manual shut-off valve must be accessible by the driver while seated in the cockpit.

1.1 How does the kart?

The complete system converts hydrogen energy into mechanical energy and thus gets the movement of wheels (fig. 1).

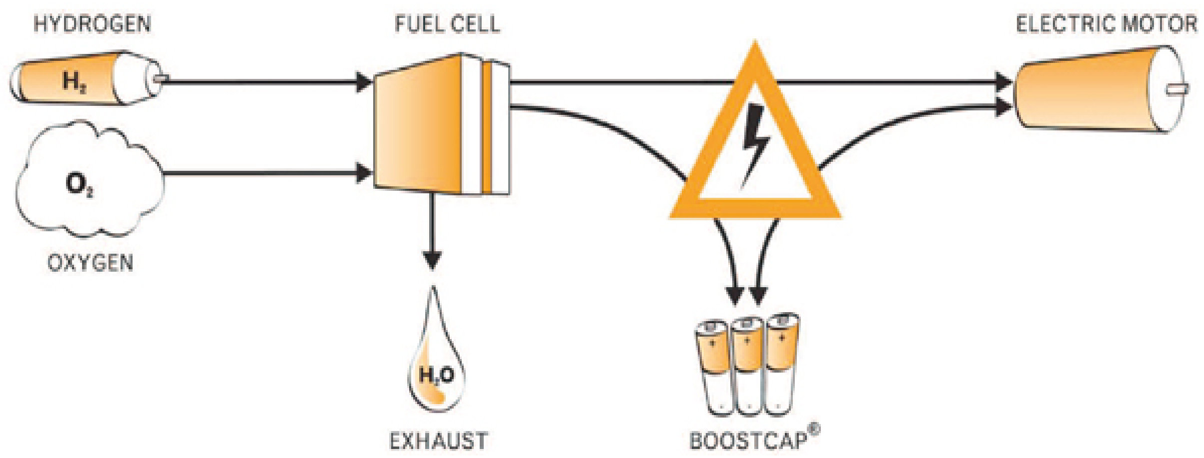

Figure 1: Basics.

The fuel cell converts hydrogen and oxygen into electricity and water and the management control system storage the electricity in capacitors or use it directly for propulsion. When the kart requires more power than the one from the fuel cell, energy from capacitors is added to this to get the peak power needed. Besides, electric motors act as brakes, to recover breaking energy in electrical energy way (fig. 2).

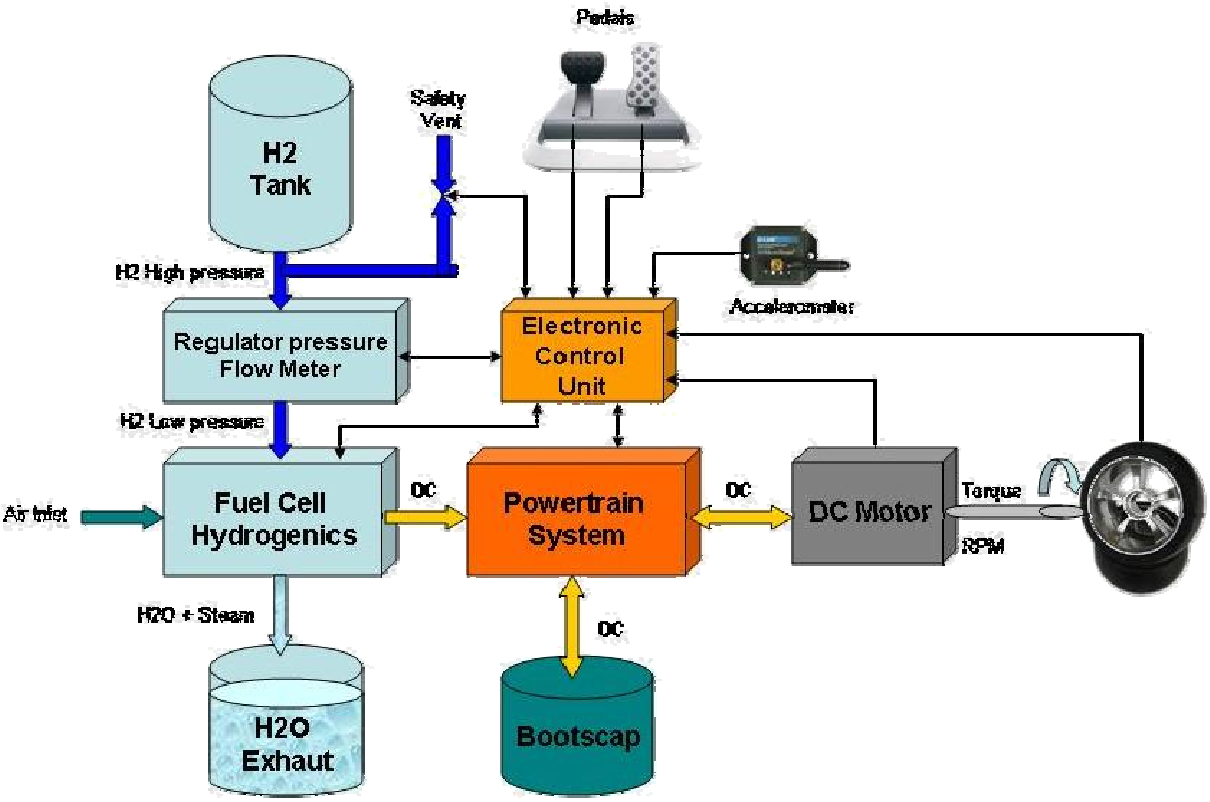

Figure 2: System diagram.

Meanwhile, water produced is discharged into the air, as the only waste. After 6 minutes on racing, it has been produced only 0.3 l of water.

Mainly are 3 systems which comprise the go- kart (fig. 3):

- **System of hydrogen:** H_2 gas cylinder, H_2 safety features fuel cell.
- **Electronic System:** main control, telemetry, data visualization on the steering wheel, capacitors, electric motors.
- **Mechanical System:** chassis, dual rear traction independent, distribution weight central steering wheel, brake.

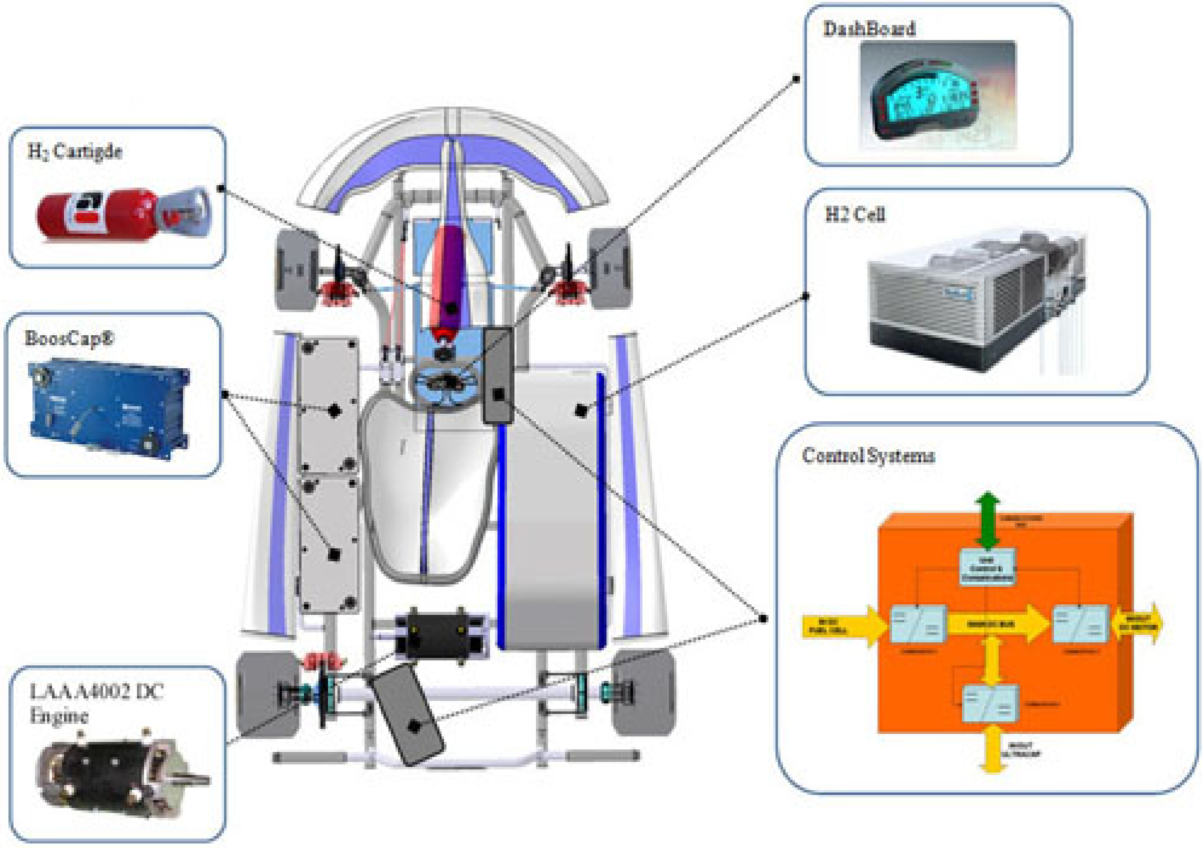

Figure 3: Kart systems.

1.2 Go-karts built

The first stage (fig. 4) was design and built a prototype kart with a stack of 1.2 kW from Ballard Systems.

Figure 4: First go-Kart.

See 1.2 kW prototype data sheet below:

- **Weight:** 150 kg (without driver)
- **Chassis:** Tubular steel special, stretched cold
- **Max.:** 750W, 2200W peaks at 12 seconds
- **Autonomy:** 20 min·bottle-1
- **Speed:** 90 kmh-1

A second stage was to develop 8 kW fuel cell kart with Hydrogenics technology (fig. 5).

Figure 5: Second go-Kart.

See 8 kW prototype data sheet below:

- **Weight**: 250 kg (without driver)
- **From 0 km/h to 100 km/h:** in 4.3 seconds
- **Fuel cell:** Hydrogenics HyPM 8, 8.5 kW
- **Power rating:** 26 kW until 45 kW peaks in 20 seconds
- **Autonomy:** 40 min·bottle-1
- **Speed:** 150 km/h

2 Development

The aims of this project were to development electronics and hydrogen system, first step separately and second step together.

First step: experiments.

- Ensure that the component are working properly
- Characterize the way of working of every component. To get a better understanding and accuracy of its.
- Find the stability limit working points for each component.

Second step: test.

- Different configurations to observe how all the components interact together.

Third step: verify reality with simulations.

2.1 Hydrogen system

The system consists in a hydrogen storage and fuel cell. In it, hydrogen is storage in a cylinder in the form of hydrogen gas to 20 MPa with pressure reduction integrated. Hydrogen system is supported by filters antiparticle, check valves, relief valves, hydrogen sensors and actuators to cut off the supply of hydrogen when needed.

The Fuel Cell used in the system is a HyPM HD 8 from Hydrogenics manufacturer.

There is not possibility of using another one because of the race rules.

It is a low temperature Polymer Electrolyte Membrane Fuel cell with a power of 8.5kW. This power is supplied between 49 and 79 Volts DC (fig. 6).

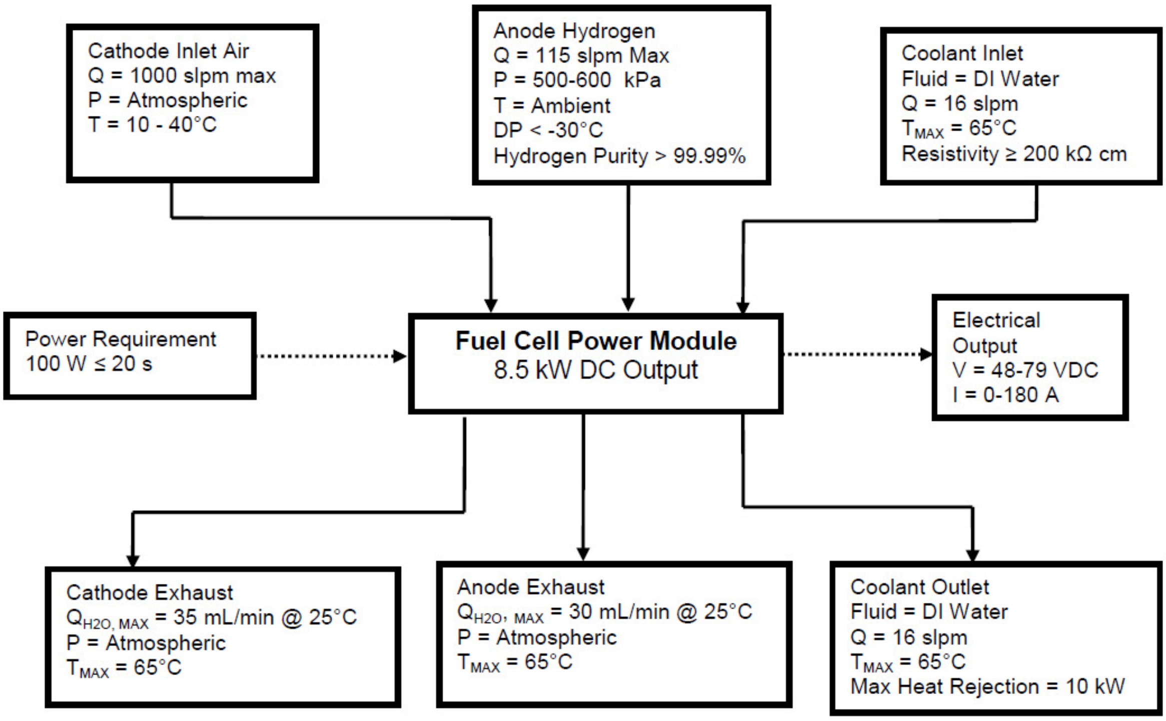

Figure 6: HyPM Technical data.

The Fuel cell is characterized by the manufacturer in the data sheet. But it is necessary to know the real limits of the manufactures control system, because the fuel cell is forced to the limit during the race. For these reasons characterizing experiments are done. The main objectives of the experiment are:

- Check the correct operation of the fuel cell
- Know the fuel cell real polarization curve
- Find the fuel cell operation limits.
- Verify how fast the fuel cell dynamic is.

In the first part of the experiment, the fuel cell is directly connected to an Electronic Load. This is a variable load controlled with a laptop. It can simulate current and impedance variable loads. For this experiment a current versus time load is implemented in. It has to be low rate ramp to ensure that the fuel cell is always working in steady state. At the same time the electronic load is monitoring in the laptop the voltage and current measurements each 0.1 seconds. This way we obtain the polarization curve (fig. 7).

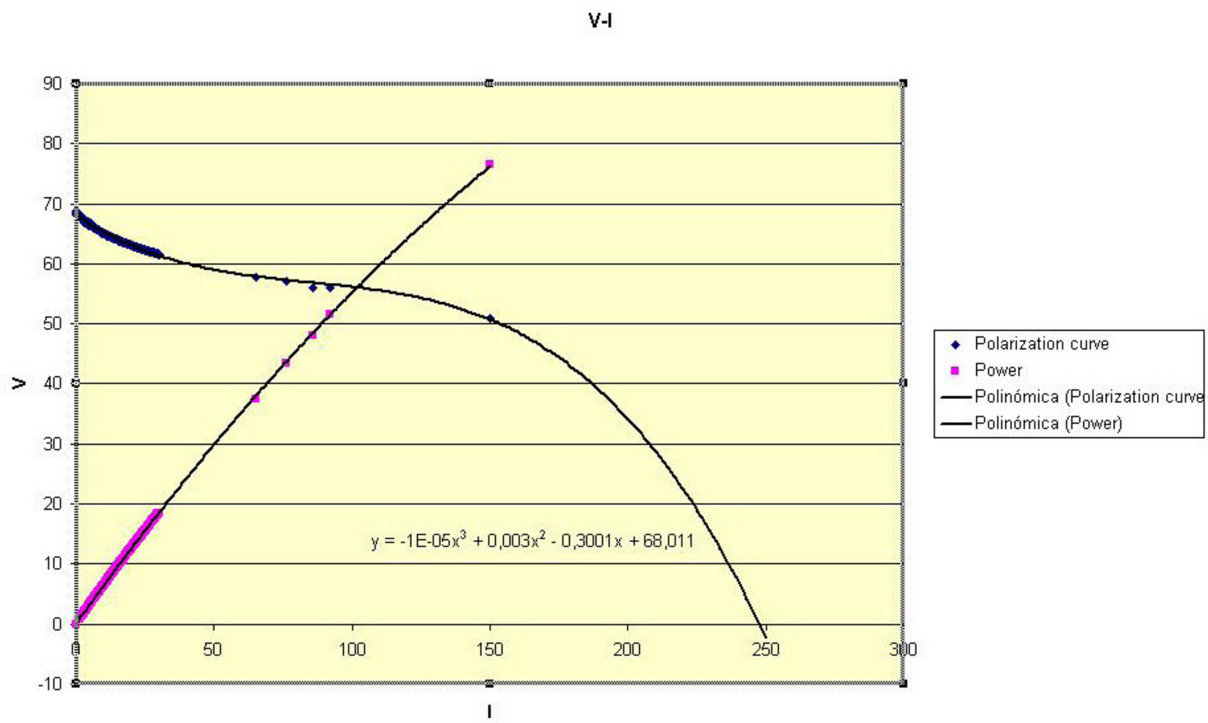

Figure 7: HyPM polarization curve.

The polarization curve is:

$$V = -10^{-5} \cdot I^3 + 0.003 \cdot I^2 + 0.3001 \cdot I + 68.011$$

The aim of the second experiment is to study the dynamic limits of the fuel cell.

The fuel cell is tested with different current ramps rates. The maximum current rate supported is assumed to be the maximum fuel cell rate. First step is to apply to the FC the maximum step allowed by the electronic load used before. Next graph shows the FC behavior with 30A (fig. 8).

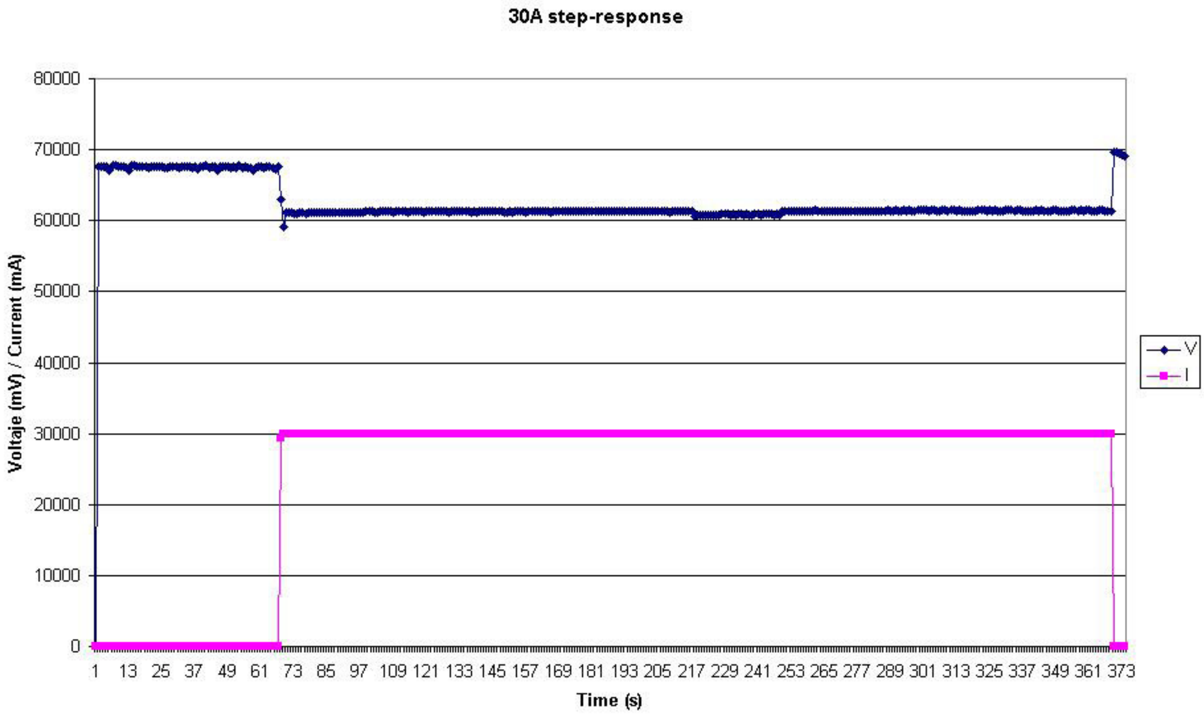

Figure 8: HyPM behavior with 30A.

2.2 Electric system

The electric system is composed by DC-DC converter, capacitors, a regulator for each electric motor and a central control unit.

The first part of the power system is a single DC / DC converters with a switching technology, which seeks the maximum energy from the fuel cell as long as possible to be supplied to the wheels or to be stored at the storage system.

2.2.1 Capacitors

The race rules limits the energy that can be stored in batteries and super capacitors. As the target in this car is to increase power and reduce the weight, supercapacitors are the best solution. The use of Maxwell capacitors was decided because those are one of the most power full capacitors in the market and its technology is accepted by the race rules. The energy that can be stored on is limited to 250.00 Joules. Each capacitor has a capacity of 3000 Farads and it can support 2,7volts. The number of capacitor was calculated not to store more energy than the maximum allowed. To get the voltage necessary for the motors the capacitors was connected in parallel (equ. 1).

$$\frac{1}{C_{tot}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \cdots$$

Equation 1

Where C_{tot} is the total capacitance of all the capacitor´s connection and C_i is the capacitance of each capacitor. The energy stored is calculated in the equation 2.

$$E = \frac{1}{2}CV^2$$

Equation 2

To install 30 capacitors and operate it at 72 volts was decided, so the maximum energy stored is 259 200 Joules. But the capacitance will be decreasing with use so forthe race the rules will be followed. The maximum voltage allowed by the capacitorsis 81 volts so it is a safe system because the operating voltage is far from the limits.

An ideal capacitor is connected to a parallel resistance that represents the auto discharge of the capacitor. It is also connected to a series resistance that represents the instantaneous decrease in the voltage when a current is demanded to the capacitors.

Two experiments are done to determine the value of each resistance.

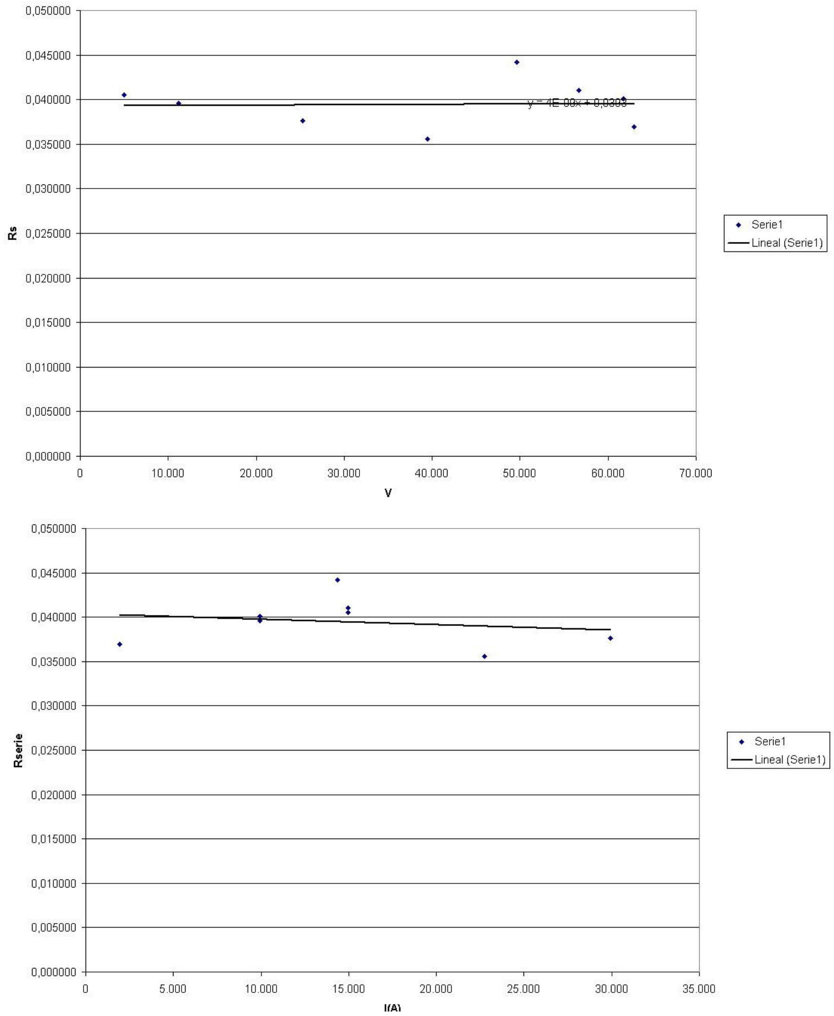

Figure 9: Capacitor series resistance.

The real capacitors are connected to the electronic variable load. The load generates different steps of current demand from zero to different values of current. Measuring the voltage difference before and after the step and knowing the current demanded the instantaneous resistance can be measured (fig.9).

As a conclusion the series resistance of the capacitor is assumed as constant every situation and equal to 0'04 ohms. The measure of the parallel resistance is done by discharging the capacitor alone. The experiment consists on charging the capacitor to a voltage, leave it alone and measure the voltage from time to time. Applying the RC discharge formula [3] and approximation of the parallel resistance can be obtained (equ. 3).

$$\frac{t}{R_p} = ln(V_0) - ln(V_c)$$

Equation 3

Where V_0 is the initial voltage, V_c is the instantaneous voltage t is the time in second from V_0 to V_c and R_p the parallel resistance.

The resistance obtained variates a lot depending of which point of the discharge is took. But it is always a big value greater than 1000 ohms.

This resistance is not really important in a motor sport go-kart because the time of discharge is quite bigger compared with the race times (3-5 min approximately). Therefore a infinite parallel resistance can be assumed

2.2.2 Motors and Controllers

The motor is a permanent magnet DC machine, because of the high power weight ratio of permanent magnet machines. In every mobile application the weight is a significant factor, as less weight of the car as less energy needed to accelerate the car. The motors (in case of full power demand) have to transmit to the car the power from the fuel cell and the capacitor together:

- The maximum peak power of the fuel cell is 8,5 kW.
- The capacitors can supply until 3500 amperes in a peak. But then the capacitors are discharged in less than one second. Let's assume that at least 15 seconds of capacitor power is needed. If the capacitors are fully discharged in 15 seconds it gives a power of 18kW.

So the maximum power demanded by the motors has to be 26,5kW. The car has two motors, one for each rear wheel. Each motor has a nominal power of 7,22 kW but it's can be operated at twice its power for a period no longer than 10 minutes.

As the formula zero races are less than 10 minutes it can be assumed that each motor has 14,44kW nominal power. Therefore the dispensable mechanical power in the wheels is 28,88kW.

2.2.3 DC/DC converter (Step Up)

For the voltage control of the capacitors an DC/DC converter connected to the fuel cell is necessary. It has two deferent functions:

- Control the voltage on the capacitor terminals. To control the capacitor it supply or store energy when needed.
- Ensure that the current from the fuel cell is lower than it maximum. So the fuel cell doesn´t stops and works in a properly working point.

An ideal voltage control has to allow the maximum variation in the voltage, so most of the energy stored in the capacitors is used. The capacitor voltages are limited by the motor controller; it can admit an input voltage from 25 volts to 96V. The optimal device for this task is a step up and down so the output voltage can be lower and greater than the fuel cell one (fuel cell voltage 49-79V).

The step up is tested to ensure that all the internal devices are working properly and its limits.

First it is tested without current limitation, to just simply check how it controls the output voltage. The reference (signal that controls the output voltage) is decreased until the output voltage is not decreasing any more. Then the maximum voltage difference between input and output is get. As it is a step up, it is suppose that the output voltage is always greater than the input. But in the reality it allows to decrease the voltage a bit from the input that is the value obtained in this experiment. On the table 1 the input voltage is 35 but the outlet voltage can be decreased until 34,3.

Table 1

Working Point	Vref	Vbat	Iin	Vout	Iout
1	-4,76	34	33,5	70	15
2	-3,42	34,86	23,6	50	15
3	-2,45	35	17,1	36	15
4	-2,38	35	16,7	35,1	15
5	-1,62	35	16,2	34,3	15

The second experiment is setup to check the way of working of the current limitation.

The firs fact checked is that the current limitation is lost if the step up has less voltage at output than at input. In the real car it can happens if the capacitors are too much discharged. That is a situation that have to be avoided, because in this case the FC demand is not controlled, therefore there is risk of fuel cell stop.

For the next part of the experiment the current demand is fixed to 9A and the input current limitation set up to 13A. Then reference is increased until the output voltage is not increasing any more. It is the upper limit, where the input current is in the limit, so the output voltage can´t increase due to a energy balance. The input energy is in the maximum allowed so the output energy (voltage) can´t increase.

Then the reference is decreases until the voltage is in the minimum, like in the first part of the experiment. This part of the experiment is done to check the voltage range with current limitation and how it affects to the lower voltage limit (table 2).

Table 2

Working point	Ref (Lim, current)	Vref (Voltage)	Vbat	Iin	Vout	Iout (A)
6	56ohm (max Vout)	-3	34,95	13	44,2	9
7	56ohm	-2,72	35,06	12	40	9
8	56ohm	-2,59	35,03	11,3	38	9
9	56ohm	-2,45	35,05	10,7	36	9
10	56ohm	-2,38	35,05	10,5	35	9
11	56ohm (min Vout)	-2	35,06	10,2	34,2	9

2.3 Electronic system

The fuel cell status is sent via CAN bus so it can be monitored. The same CAN bus is used to receive orders (switch on, switch of …). It also gives the Current Draw Allowed (CDA) [4] that indicates the maximum current that the fuel cell can supply in the next time step. If the current demand is lower than the CDA the manufacture ensure that the fuel cell is working properly.

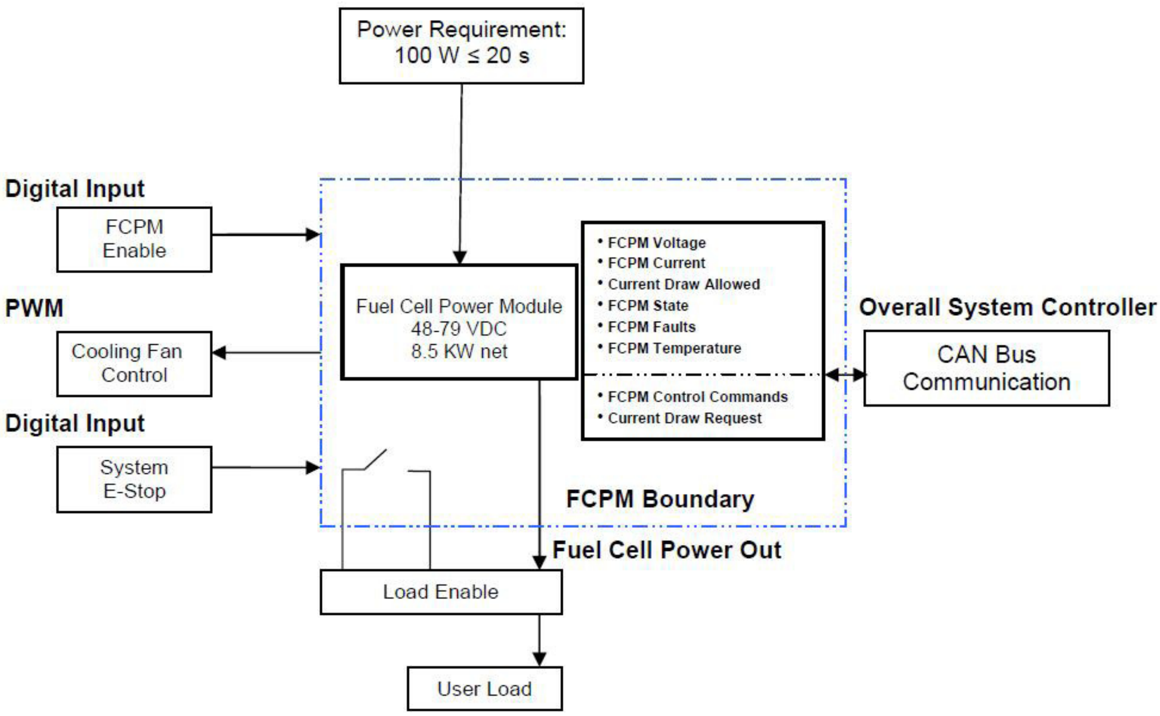

Figure 10: HyPM communication.

The kart system also has a telemetry system. This system send (in real-time) data from every parts of kart, collected in data acquisition system based on an Arduino microchip, to a external computer, in this allow to study the behavior of the kart and all its subsystems for further development of improvements (fig. 11).

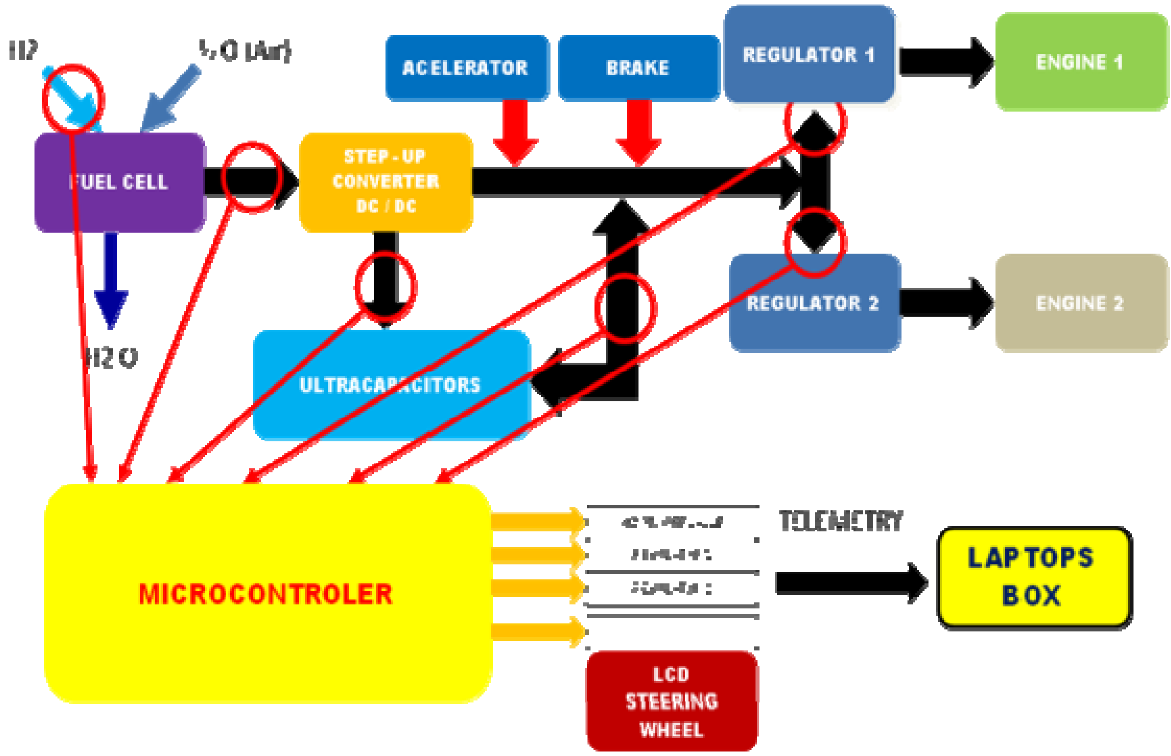

Figure 11: Electronic system.

2.4 Safety system

The first priority in every car has to be the security. As security criteria the fuel cell switch-off if something goes wrong. Because of this, a life line was designed. It is a single 12VDC wire that ends in the fuel cell, it switches of if this life line circuit is open (fig. 12). Also the super capacitors are disconnected from the system with the same signal. There are deferent security devices that open this circuit in case of danger:

- Crash sensor: It measures the acceleration of the car, if it is greater than a crash value (fixed) it opens the life line.
- Driver out sensor: It detect if there is driver or not using a mechanical device. If the driver isn´t in the car, this sensor opens the drive line. In case of crash, if the driver jump out of the car the life line is also opened.
- ON switch: The pilot has to push this button to switch on the car.
- Emergency stop switch pilot (S1/A): In case of emergency the pilot can pulse this button to open the life line.
- Emergency stop switch team (S1/B): In case of emergency the team can pulse this button to open the life line.

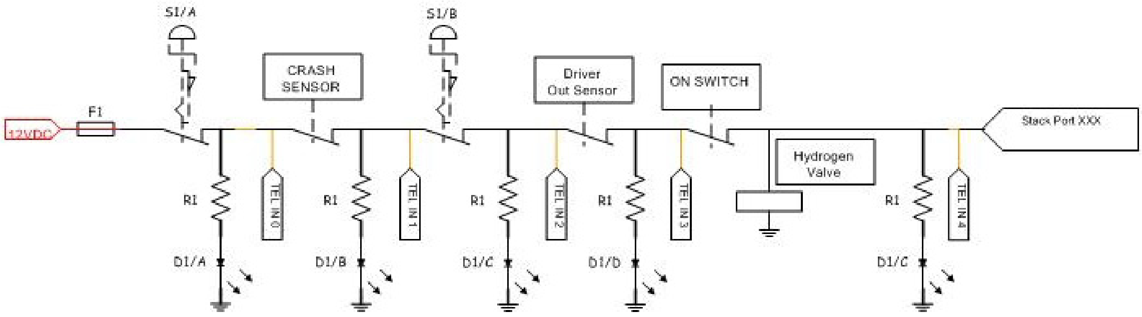

Figure 12: Life line.

When current is passing through the life line is also holding open a hydrogen solenoid valve. If one of the security system is activated and it opens the life line, the fuel cell stops and the hydrogen supply is disabled.

2.5 Connection

Once all the devices are tested alone. Is time to see how is the way of working all together. The fuel cell connected to the step up input, the capacitors and motor are in parallel at the step up output.

In that configuration the step up is set up to limits the current to 50 A at the start of the experiment, it variates to 160 A in the middle of the experiment. The reference set the output voltage at 70 Volts. The motors are accelerated in order to generate a demand higher than the step-up maximum power (limits by the input 150A).

The graphical result of the experiment can be seen in the figure 13. All the currents and voltages are monitored with current (lend effect) and voltage sensors connected to a data acquisition system.

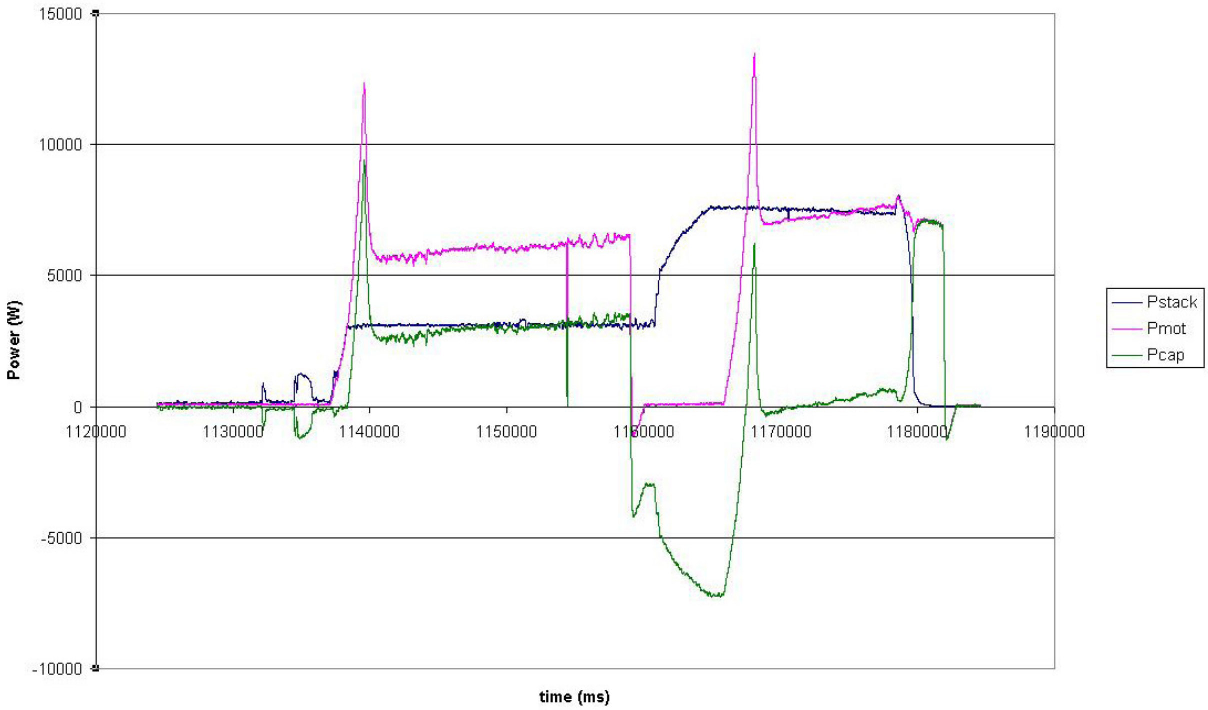

Figure 13: Power train behavior.

3 Results

The devices have been checked and all of them are working properly. The way of working of each device is obtained. The fuel cell has been approximated by a third order polynomial, because this is the polynomial order that it's better the polarization curve. The maximum current ramp allowed by the fuel cell is 150A in 0,5 seconds. The capacitor parallel resistance is considered infinite, because the auto discharge time is quite long in relation to race time (in a order of hours and the races are always less than 5 minutes). The step up is the key of the system, depending how is managed the control of the current limitation and voltage reference the system acts in a different way.

The current have to be limited always to ensure that the system can supports any kind of current demanded. Depending of the current limit fixed in the step up and the demand the capacitors supply or store energy. So by the step up the capacitors storage can be controlled. The voltage references fix the maximum voltage value that the capacitor can achieve.

The system way of acting is:

- The step up fixes the limit of fuel cell current.
- The capacitors supply the power difference between fuel cell current and demand.
- If the load is lower than FC production the capacitor is charged until the maximum voltage (limited by voltage reference signal).
- If the load is higher than the FC production the capacitor is discharged.

- When the capacitors voltage becomes lower than the FC voltage the system became unstable because of the step up voltage cross. This voltage cross fix the minimum useful voltage of the capacitors.
- The CDA (Current Draw Allowed) is the value of demand that the fuel cell can supply every instant. The fuel cell communicates it via a BUS CAN wire.
- This value of CDA is used in the circuit test to control the current limit of the step-up. By this way the properly working of the fuel cell is ensured, the fuel cell demand in never higher than CDA. The problem is that these CDA can´t be modeled, because is unknown how the fuel cell calculate this value.

4 Conclusions

A Formula Zero car has been designed, simulated and circuit tested. The car is working properly and it follows all the FZ organization rules. All the car devices have been tested.

By the experiments the way of working of all the car elements is known. The fuel cell is completely characterized (dynamic and static working points). The values of the parallel and series resistance of the capacitors are obtained. Also the step-up control limits are now known. The car was working properly in the circuit test. The voltages and currents are behaving as it was planned in the design. This car is a step forward in comparison to the previous car version. Comparing this car with the time results of the last race, our car is the fastest one.

The reason of the configuration selected is simply, it is the faster one. The electrical part of the simulation is really close to the reality because the blocks came directly from the experiments. But the load part is just estimation. So the controllers have to be checked in the real car to be sure that the control is the better one.

Choosing between a system with step up or not, is a trivial decision. As far as the demand supported is quite lower in the system without step up. The capacitor is worse controlled in this case. Also in this configuration the fuel cell is not limited so there is the risk of fuel cell stops.

In this project the feasibility of build a hydrogen motor sport vehicle is demonstrated. The next challenge is to get good results in the next Formula Zero championship. To get this target a good car set up for the concrete circuit have to be done. The correct controller for one race could not be the best one for other races.

Also the knowledge generated at this project will be applied into future projects at Foundation for the Development of New Technologies Hydrogen in Aragon [5].

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TA Transportation Applications

Electrification in Transportation Systems

Arndt Freialdenhoven and Henning Wallentowitz

Abstract

Environmental questions and shortcomings in hydro carbon resources are the driving forces for the electrification in transportation systems. The report describes these starting points of the discussion and studies the design of batteryelectric and fuel-cell powered cars. They are both using electricity for driving. The questions regarding the energy sources (batteries, fuel-cells) are discussed, the new requirements for these electric operated cars are described. The requirements are touching the whole car and especially the aggregates like steering, braking, heating, etc. As a consequence changes in industrial structures will happen. This finally opens the discussion about large scale changes in conventional car companies and the chances for "new-comers". Co-operations seem to be an adequate solution for the future business.

Fuel Cell and Battery Electric Vehicles Compared

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Detailed computer simulations comparing various alternative vehicles illustrate that society must move toward all-electric vehicles to achieve our goals of an 80% reduction in greenhouse gas emissions, substantial reductions in petroleum consumption and near-zero urban air pollution. Biofuels, hybrid electric vehicles and plug-in hybrids that still rely on the internal combustion engine for some motive power will help to reduce environmental and energy security burdens, but we must eventually eliminate most internal combustion engines to fully achieve our societal goals.

We have two primary choices to power all-electric vehicles: hydrogen-powered fuel cells and batteries or other energy storage devices such as ultra-capacitors. This paper compares the major attributes of fuel cells and batteries for full function passenger vehicles, including on-board vehicle mass (Figure 1); on-board energy storage volume (Figure 2); greenhouse gas emissions; electric vehicle mass production incremental costs compared to conventional cars; fuel costs per kilometer; life-cycle costs; well-to-wheels energy efficiency using natural gas, biomass and wind turbines as the energy source; fueling times and infrastructure costs to support these two options. We conclude that the hydrogen-powered fuel cell electric vehicle is superior to the battery electric vehicle for most of these major attributes if consumers demand vehicles with more than 150 to 200 km range.

Consider the weight of an electric vehicle. As shown in Figure 1, the weight of a battery EV (BEV) grows rapidly with increased vehicle range. For each additional km of range required, more batteries must be added. But each kg of battery weight also requires extra vehicle structure to support that weight. In addition, each kg added requires a slightly larger motor to provide adequate vehicle acceleration. And the braking system must be larger to stop the vehicle. This non-linear feedback process is called „Weight-compounding," or „mass-compounding."... the vehicle mass grows more than linearly to achieve greater range. For example, to achieve the 480 km range demanded by most US drivers, a FCEV would have a mass of approximately 1280 kg, while a BEV would have 1.72 times more mass at 2196 kg, assuming an advanced lithium-ion battery with a useful specific energy of 150 Wh/kg. But achieving 150 Wh/kg will require significant improvements over current Li-ion technology. For example, the new Chevy Volt PHEV with 40 miles all-electric range reportdly has a 181-kg battery with a nameplate energy of 16 kWh. But only half of this energy can actually be used, so the useful specific energy is 0.44 Wh/kg which is 3,400 times lower than the specific energy used in our models. Similarly, according to the literature, the Audi „e-tron" 471-kg battery pack has a nameplate energy rating of 53 kWh, of which 80% can be used to propel the car, resulting in a useful specific energy of 0.0899 kWh/kg, or 1,700 less than that used in our computer model. Finally, the US Department of Energy estimates that the current useful specific energy of Li-ion batteriy systems is approximately 0.025 kWh/kg, which requires a 3.5 times improvement to reach the 150 Wh/kg used in our model. Therefore our model assumes significant future improvements in Li-ion battery system performance.

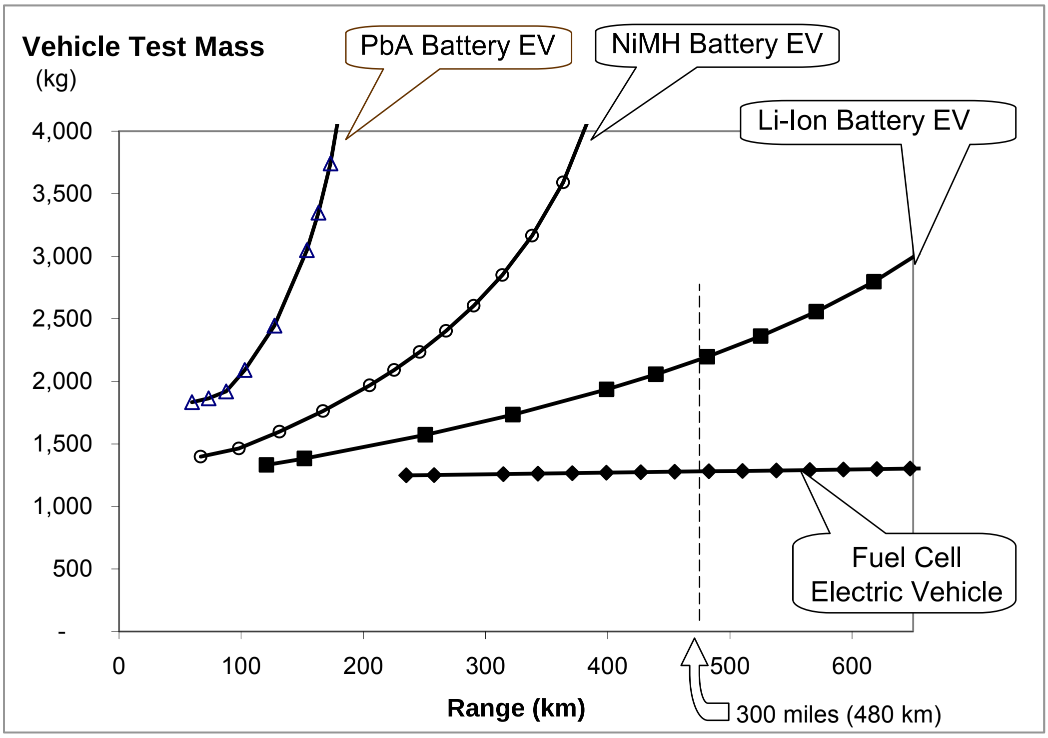

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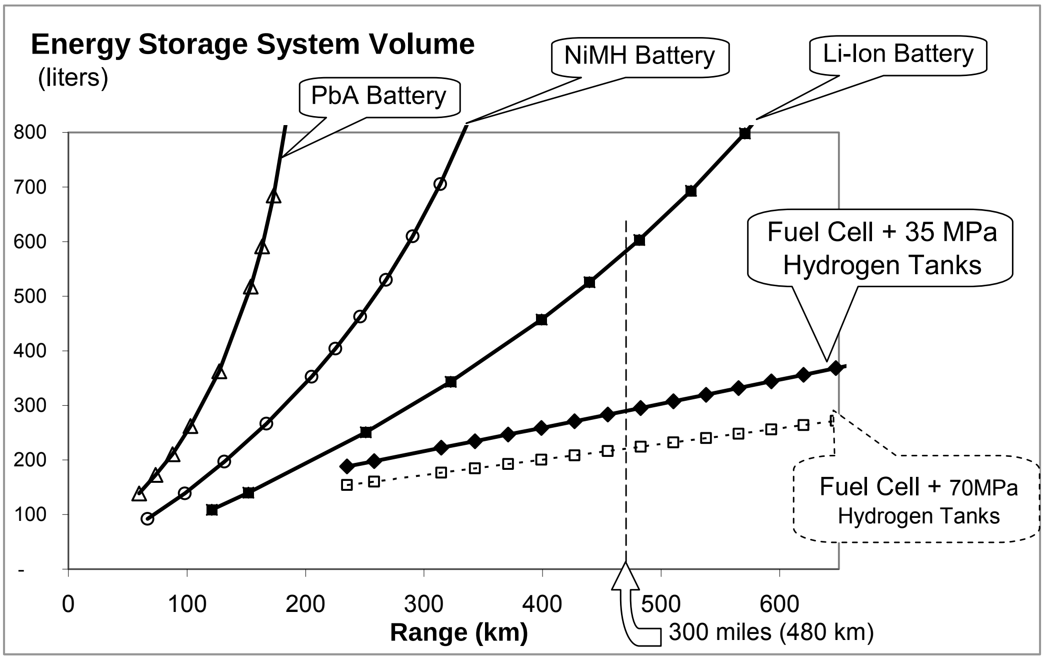
Figure 1: Estimated vehicle test mass for battery EVs with three different battery technologies compared to a hydrogen-powered fuel cell electric vehicle as a function of vehicle range.

Everyone knows that batteries are heavy. Many do not realize that batteries also take up lots of space. Commentators criticize the space required to store hydrogen in high pressure tanks. But advanced Li-ion batteries have approximately the same energy density (200 Wh/liter) as a 300-bar (35 Mpa) compressed hydrogen tank plus fuel cell system. However, since the BEV weighs more than a FCEV for a given range greater than 60 km, it will need more stored energy to meet the vehicle range and acceleration specifications (we require a zero to 37.3 km/hour (60 mph) acceleration in 10 seconds for all vehicles in this study.) Thus the space occupied by the battery bank is larger than the space required for the 300-bar compressed hydrogen tank and fuel cell system for Evs with more than 200 km range as shown in Figure 2.



BPEV mass, vol, cost vs range.XLS; 'Compound' AF114 3/9 /2010

Figure 2: Estimated storage volume required for batteries and for hydrogen tanks plus the fuel cell system as a function of vehicle range

The Electrification of the Automobile – Technical and Economical Challenges

Arwed Niestroj, **Christian Mohrdieck**, Daimler AG, Germany

1 Summary

Sustainable drive systems and innovative safety technologies are the mainstays of Daimler's vision of mobility for the future. Vehicles with hydrogen-powered fuel cells and battery powered drive trains provide ideal conditions for environmentally friendly mobility that saves natural resources.

Already several years ago Daimler launched a vehicle fleet of 100 smart electric drive that are operated by customers in London Metropolitan area. Key enabler for this powertrain technology is the high voltage battery. The customer feedbacks of the smart electric drive vehicles well prove that battery electric vehicles are a successful answer to zero emission mobility in urban areas.

As the pioneer of the fuel cell technology, Daimler already presented the first vehicle with this highly efficient and environment-friendly drive concept in 1994. With more than 100 test vehicles that have altogether covered more than four million kilometres, Daimler has the most experience in fuel cell vehicles worldwide – from compact A-Class passenger cars to Sprinter vans and large Citaro fuel cell buses.

The Mercedes-Benz B-Class F-CELL is the first series-produced vehicles with a zero-emission fuel-cell drive. Small-series production of the passenger car has started in late 2009. A new generation of fuel-cell drive is used to power this innovative vehicle. The fuel cell system is much more compact while at the same time offers higher performance. It is also completely suitable for everyday use.

The fuel cell system used in the Mercedes-Benz B-Class F-CELL is also demonstrating its suitability for heavy-duty operation in commercial vehicles. By means of combining two B-Class systems with an energy storage unit, a highly powerful aggregate is created for application in the new FuelCELL-Hybrid bus.

2 Battery Drive

With Daimler's thorough analysis and long time experience in battery electric vehicles it was decided some years ago to focus resources on the most important technology - the high voltage battery. In order to ensure a successful battery development for vehicle usage as well as necessary reliability, production knowhow and cost levels joint ventures with competent partners have been established. Due to the exceptional demand of power and energy content of batteries for automotive vehicles – in comparison to consumer battery cells e.g. of computers – the path to Li Ion based battery cells was clear. As of today's knowledge the Li Ion batteries will be able to provide enough energy content for urban city driving in suitable urban vehicles.

3 Fuel Cell Vehicles vs. Battery Electric Vehicles

Electric vehicles with a fuel cell powertrain compared to a battery electric powertrain benefit from 2 key advantages: high driving range and short refuelling times. The well-to-wheel balance shows that BEV would be the optimum solution only if driving range and recharging times were suitable for everyday customer operation in all types of passenger cars. Today BEV can ensure customer satisfaction mainly in an urban mobility environment.

4 The B-Class F-CELL

4.1 General achievements

Compared to the A-Class F-CELL a refined, more compact and efficient system is used in the B-Class F-CELL. The electric motor has a maximum output of 100 kW. This means that the B-Class F-CELL offers high driving performance standards that surpass those of a standard two-litre gasoline engine. At the same time, the zero-emission fuel-cell drive in this family-friendly compact vehicle consumes just about 2.9 litres of diesel equivalent per 100 kilometres.

Daimler has made huge progress in terms of size, power, fuel consumption and range of the fuel cell drive train. Also, the reliability of the vehicle has been improved. The B-Class F-CELL has undergone the same quality-ensuring processes applied to all Daimler vehicles.

Figure 1: Two generations of fuel cell vehicles.

The B-Class will have a stack lifetime of more than 2000 hours. This clearly distinguishes the car from prototypes and shows Daimler's commitment to commercialize fuel cell vehicles. In just a few years the fuel cell drive train will reach the lifetime of conventional Internal Combustion Engines (ICE).

Another focus has been the packaging of the fuel cell drive train into the compact body of the Mercedes-Benz B-Class. This could be accomplished without any restrictions in regard to passenger and luggage space. The outer body shell remains completely unaltered from a conventional B-Class vehicle. In order to save costs and benefit from synergies, identical parts from other series-produced vehicles are used.

Altogether, the B-Class F-CELL is well-suited to demonstrate full customer acceptance and shows that advanced fuel cell technology is now ready for everyday use.

4.2 Technical data

The power of the electric motor will be 100 kW. These 100 kW are comprised of the effective outputs of the fuel cell and the battery. In addition, maximum torque has been increased from 210 Nm to impressive 290 Nm. Also, a better power-to-weight ratio could be realized.

Table 1: Technical data B-Class F-CELL.

B-Class F-CELL	
Power	
Effective power fuel cell	80 kW
Effective power electric motor	100 kW
Maximum torque	290 Nm
Accumulator/Consumption	
Capacity accumulator	1.4 kWh
Hydrogen pressure	700 bar
Range (NEDC)	approx. 400 km
Consumption (adjusted)	2.9 l diesel equivalent/100km
CO_2-emissions	0 g/ km
Driving Performance	
Acceleration 0-100 km/h	11.4 sec
Top speed	170 km/h

According to NEDC cycle testing, the B-Class F-CELL will consume only 2.9 litres of diesel equivalent per 100 kilometres. The range will be extended to approximately 400 km due to enhanced hydrogen tank storage capacity with 700 bar technology. At modern hydrogen fuelling stations it can be completely refilled within less than 3 minutes.

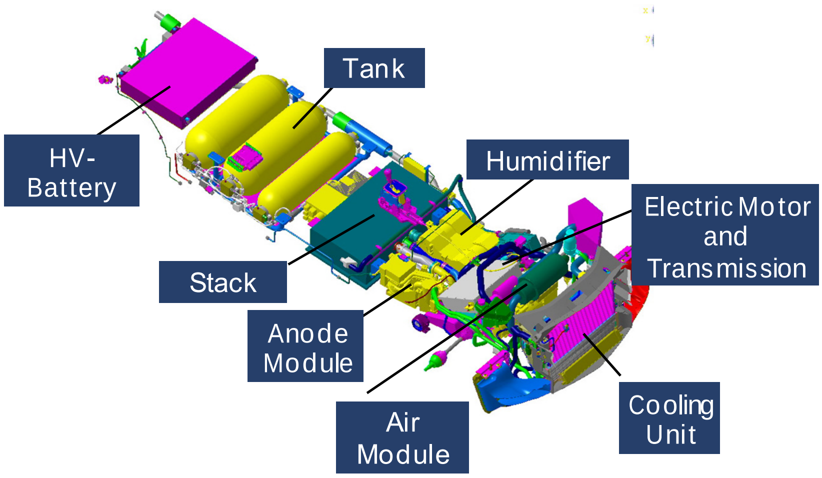


Figure 2: Drive train B-Class F-CELL.

4.3 Fuel cell stack and system

Fuel cell stacks have made significant progress within the last 5 years regarding weight and volume due to improved stack engineering and new materials. Thus, the stack powering the B-Class F-CELL is now 40% smaller and at the same time 30% more powerful than its predecessor in the A-Class F-CELL.

However, the fuel cell itself is just one part of the system. The entire fuel cell system is integrated in the sandwich-floor of the B-Class F-CELL so that the available passenger and luggage space is not affected.

The system-box-concept of the A-Class F-CELL has been abandoned for a system-module-concept. The module concept of the B-Class F-CELL allows for more packaging flexibility and better maintainability.

Figure 3: Cross-sectional model with stack.

4.4 Cold start ability

The B-Class F-CELL will be able to start without problems at temperatures above minus 25°C. Previously, cold start ability has always been a challenge. Now having switched to a passive humidifier system, based on gas-to-gas membrane humidification, the B-Class F-CELL is well suited for colder regions, too. This has been recently confirmed by winter testing in Sweden. In addition, the complexity of the system and the number of components could be reduced.

4.5 Battery

To improve the overall efficiency of the car, Daimler uses a lithium-ion battery instead of the nickel-metal-hydride (NiMH) battery employed in the A-Class F-CELL for (fuel cell) full hybrid operation. This leads to an improved overall efficiency and provides for more power at low temperatures. In addition, the power density could be increased.

Daimler was the first car manufacturer to adapt lithium-ion batteries, previously mainly used for consumer electronics, to automotive requirements. A decisive element in this process was the integration of the battery into the air conditioner cooling circuit of the car. Thus, the accumulator can permanently operate at temperatures between 15°C and 35°C which are best suited for a long lifetime and optimum performance.

4.6 Electric drive train

The B-Class F-CELL is equipped with a permanent magnet motor, in contrast to the A-Class F-CELL's asynchronous (AC induction) motor. Daimler has made this change in order to realize higher efficiency, more power and torque.

For the new B-Class F-CELL a compound-planetary transmission with bevel gear differential will be employed.

4.7 Cooling system

Wherever possible, identical parts from other vehicles are used for the cooling system of the B-Class F-CELL. This strategy assures high quality at reasonable costs. Other improvements are the reduction of weight and an overall simplification of the cooling system. To make the cooling system more compact, a minimized ultra pure water loop is used.

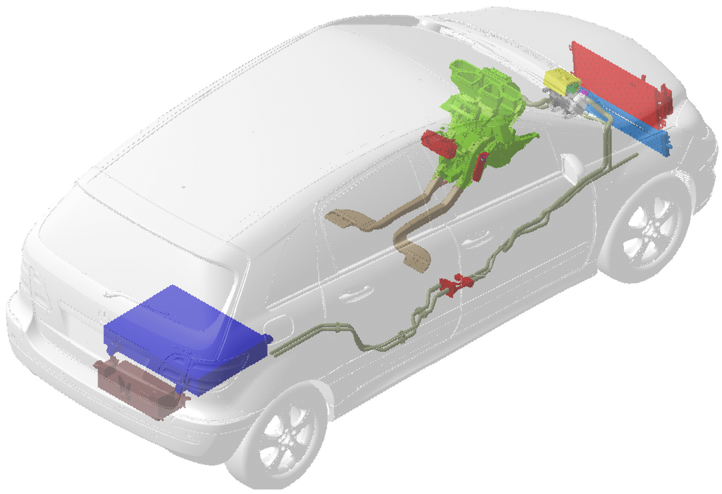


Figure 4: Cooling system.

5 The Mercedes-Benz Citaro FuelCELL-Hybrid Bus

5.1 General achievements

This year Daimler is presenting its new Mercedes-Benz Citaro FuelCELL–Hybrid. It is powered by two B-Class fuel cell systems. In contrast to the previous Citaro fuel cell bus, the new Citaro FuelCELL-Hybrid bus is also equipped with a HV-lithium-ion battery. This, together with other efficiency-enhancing measures, helps to realize significantly lower consumption and higher reliability.

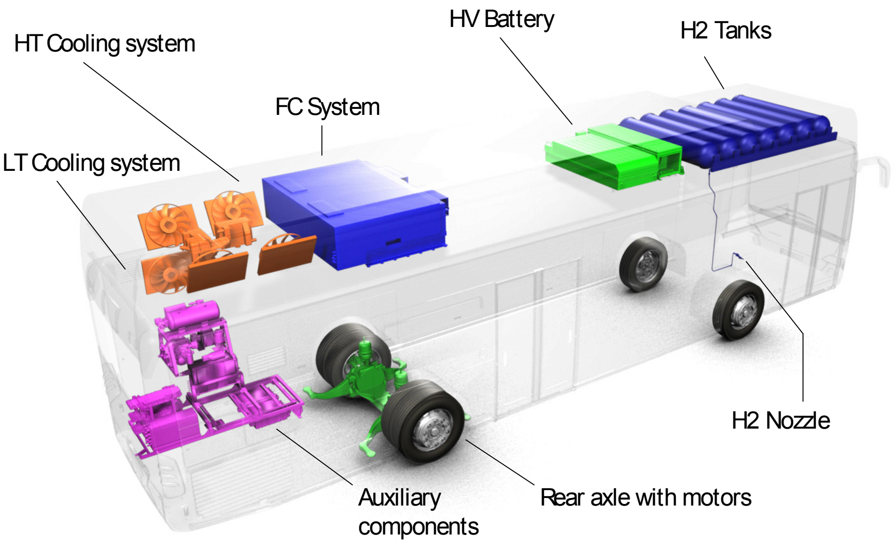


Figure 5: Citaro FuelCELL-Hybrid.

5.2 Technical data

Fuel consumption could be reduced from 20-24 kg of hydrogen per 100 km to only 10-14 kg hydrogen per 100 km. Also, the reliability of the next generation fuel cell bus could be further increased compared to the previous generation.

Table 2: Technical data Citaro FuelCELL-Hybrid.

Citaro FuelCELL-Hybrid	
Power	
Power fuel cell system	120 kW
Drive power	160 kW
Accumulator/Consumption	
Capacity accumulator	26.9 kWh
Power accumulator	180 kW
Hydrogen pressure	350 bar
Range	> 250 km (planned)
Consumption	10-14 kg hydrogen per 100 km
CO_2-emissions	0 g/ km

5.3 Fuel cell stack and system

In order to gain synergies with the passenger car program the next bus generation will use two B-Class F-CELL fuel cell systems. Thus, the Citaro FuelCELL-Hybrid is able to benefit from advancements made in the development process of the new B-Class F-CELL. These include cold start capability, a higher power density and the modular concept.

The Citaro FuelCELL-Hybrid marks a significant step forward in terms of fuel cell technology. The durability of fuel cell stacks could be increased. Evobus, the Daimler subsidiary producing the Citaro, now expects a warranty of 12,000 hours or six years.

The weight of the fuel cell system could be reduced from 1040 kg (without air supply) to only 688 kg (including air supply).

6 Commercialization of Fuel Cell Vehicles

Daimler is convinced that fuel cell vehicles will be the best long-term solution when it comes to commercializing a zero-emission vehicle technology that will be competitive with conventional vehicles in every respect.

The lead application in the development of fuel cell vehicles at Daimler are passenger cars. The fuel cell technology for vans and buses is derived from the passenger car technology.

To commercialize fuel cell vehicles Daimler has identified 5 steps along the way towards mass production:

The first step has been the technology demonstration with the A-Class F-CELL fleet. The B-Class F-CELL, being the second step, will meet customer requirements and thus gain customer acceptance. The aim of the following 3rd generation will be to reduce component costs.

In the 4th generation, costs will be reduced even further and fuel cell vehicles will be publicly available in larger quantities. The drastic reduction of costs paves the way for the fifth step. This will be the mass production of fuel cell vehicles within the next decade.

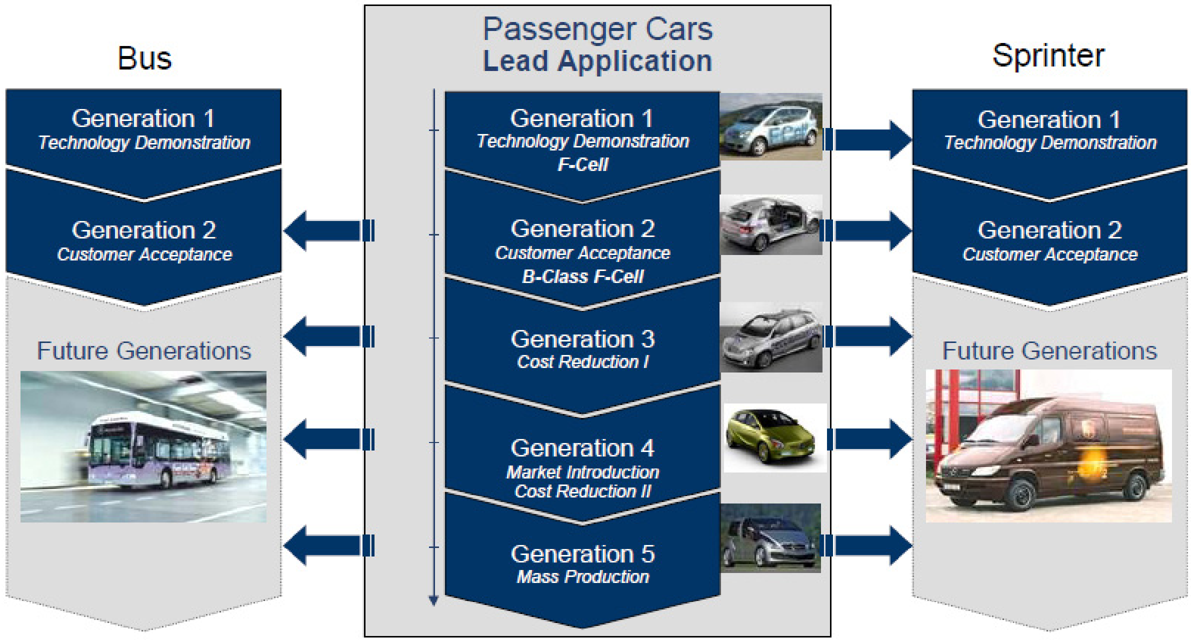


Figure 7: Daimler's Fuel Cell Commercialization Roadmap.

However, the demonstration project hydrogen fuelling infrastructure is not sufficient for the envisaged commercialization roadmap. For full customer acceptance an area-wide and convenient hydrogen filling station network is necessary.

In cooperation with a partner company Daimler has analyzed a possible network of 1,000 hydrogen fuelling stations for Germany. This is not comparable to the existing gasoline fuelling stations infrastructure, but would be sufficient. A network of this density would require an investment of 1.5 to 2 billion Euros. This, however, is not prohibitive but cannot be shouldered by one company alone.

7 Conclusion

Within the last years, Daimler has made significant progress with fuel cell technology. Advanced fuel cell vehicles like the Mercedes-Benz B-Class F-CELL are coming close to mass market readiness. Daimler is determined to commercialize this promising technology. Yet, Daimler and other OEMs cannot succeed without the assistance and cooperation of societal, governmental and economic actors.

Comparison between Electricity and Hydrogen as CO_2-Free Secondary Energy Carriers

Alfred Stulgies, **Frank-Detlef Drake**, RWE AG, Germany

Executive Summary

As future CO_2 -free final energy carriers, electricity and hydrogen have recently been in the focus of often polarising discussions. This study compares the two above-mentioned energy carriers. Based on a comprehensive analysis of well-to-wheel process chains, it turns out, that in the short- and medium term, the application of electricity in vehicles with battery drive reveals considerable advantages over vehicles with hydrogen drive when comparing energy efficiency, greenhouse gas emissions and total cost of ownership. The fact that until today the cruising range of battery-electric vehicles is still quite low and at the same time their charging time is quite long makes these vehicles in some cases less comfortable or applicable - especially for long distance driving. However, small town cars and certain user groups (especially commuters) are even today not adversely affected by low cruising ranges of these vehicles. In view of further progress in battery development, Plug-in Hybrid Electric Vehicles (PHEV) offer all benefits of an electric drive without any loss of comfort and thus represent an (intermediate) solution already today.

1 Introduction

In order to achieve a drastic cut in CO_2 -emission according to the specifications of the IPCC (Intergovernmental Panel on Climate Change) it is required to improve efficiency in all sectors and to decrease CO_2-levels from electricity generation; however, these means alone do not suffice. In view of the fact that currently more than 30 % of German global emissions are generated locally by the transportation sector, residential heating and small consumers, it is essential to abandon oil and gas in favour of potentially CO_2-free final energy carriers in order to meet climate targets in the long run. Two end energy carriers are suitable and under consideration to meet these objectives: electricity and hydrogen.

By means of selected examples of use, we would like to show the advantages and disadvantages of an increased use of electricity and hydrogen in the mobility-sector. The assessment is based on a system-oriented approach and considers its upstream processes as well as cost, climate-protection and practical aspects. The statements, further considerations and assessments in this study are based on the results of the correspondent study [1] conducted by the Fraunhofer-Institute for Systems and Innovation Research in cooperation with the Ludwig-Bölkow Systemtechnik GmbH on behalf of RWE.

2 Scope of Research and Assumptions

In order to ensure a sensible comparison between electricity and hydrogen, we only compare process chains with the same primary energy carrier (e. g. natural gas) and for similar applications - under consideration of equal means and routes of transport. Our study deals with small town cars, compact medium-sized vehicles, delivery vehicles, city busses and -

exemplary - passenger boats for inland waterways, but also Plug-in Hybrid Electric Vehicles (PHEV). The above-mentioned fields of application are compared to conventional applications using fossil fuels.

Our study is based on two time frames:

2015 – Market launch of the new technologies: We assume that hydrogen and electricity are produced at today's state of technology. The partly nationwide hydrogen supply is realised via on-site electrolysers and steam methane reforming (SMR) at gas stations, all systems operating at rated capacity. It is furthermore assumed that by 2015 approximately the first 20,000 vehicles with electric- and hydrogen-drive have been launched on the market.

2030 – The new technologies have been established: The new electricity- and hydrogen-based technologies have been established on the market and a hydrogen grid is available. Hydrogen is produced at central plants, often with Carbon Capture & Storage (CCS). Compared to 2015, the German Electricity Mix has reduced its CO_2 -emission by almost 50 % (427 g/kWh_{el} → 233 g/kWh_{el}). We furthermore assume that by this time all vehicles are in commercial mass-production (> 500,000 vehicles per year).

Natural gas, lignite, wind and the German electricity mix are analyzed as sources to provide electricity and hydrogen, while steam methane reforming, lignite gasification and electrolysis are considered as means to generate hydrogen. We start our comparison of the process chains with the exploitation and production of the primary energy carrier, followed by its conversion into electricity or hydrogen and proceed with its transport and consumption (Well-to-Wheel; WtW). The following evaluation criteria are employed: energy-efficiency, greenhouse gas emissions, fuel costs and total cost of ownership as well as quality-related parameters (infrastructure, handling, cruising range and charging/refuelling times). The required power consumption and emission to build the factories and vehicles are not considered in this study. As a rule, cost are usually calculated without taxes and levies in order to ensure comparability while a sensitivity analysis shows the effect of today's fuel taxes. The required primary energy input and GHG-/pollutant emissions are calculated using the methods of international (IEA, Eurostat, ECE, Concawe) and German (AG Energie-bilanzen = German Working Group on Energy Balances) organisations.

3 Comprehensive Results from Process Chain Analysis

On the basis of the above-mentioned approach, we can firstly draw some general conclusions when comparing electricity and hydrogen. For the medium-sized compact class with a VW Golf as reference vehicle we assume the following: cruising range of Battery Electric Vehicle (BEV) = 150 km, Fuel Cell Electric Vehicle (FCEV) = 500 km, annual number of kilometres travelled = 14,200 km.

3.1 Energy efficiency

Starting with the same primary energy carrier and similar vehicle, electricity production requires less energy than hydrogen throughout the whole process chain (see figure 1). This is obviously the consequence of energy losses resulting from the electrolysis of water, as the secondary energy carrier has to be converted twice (electricity via electrolysis → hydrogen → hydrogen via fuel cell → electricity). For all processes the energy consumption of the H_2 -

chain depends on the prevailing application (H_2 -storage with 70 MPa). For H_2 production paths that are not based on electrolysis the energy consumption with on-site SMR will be approx. 20 - 55 % (by 2015) and with central SMR + pipeline or lignite gasification about 7 - 12 % higher than for the direct electricity chain.

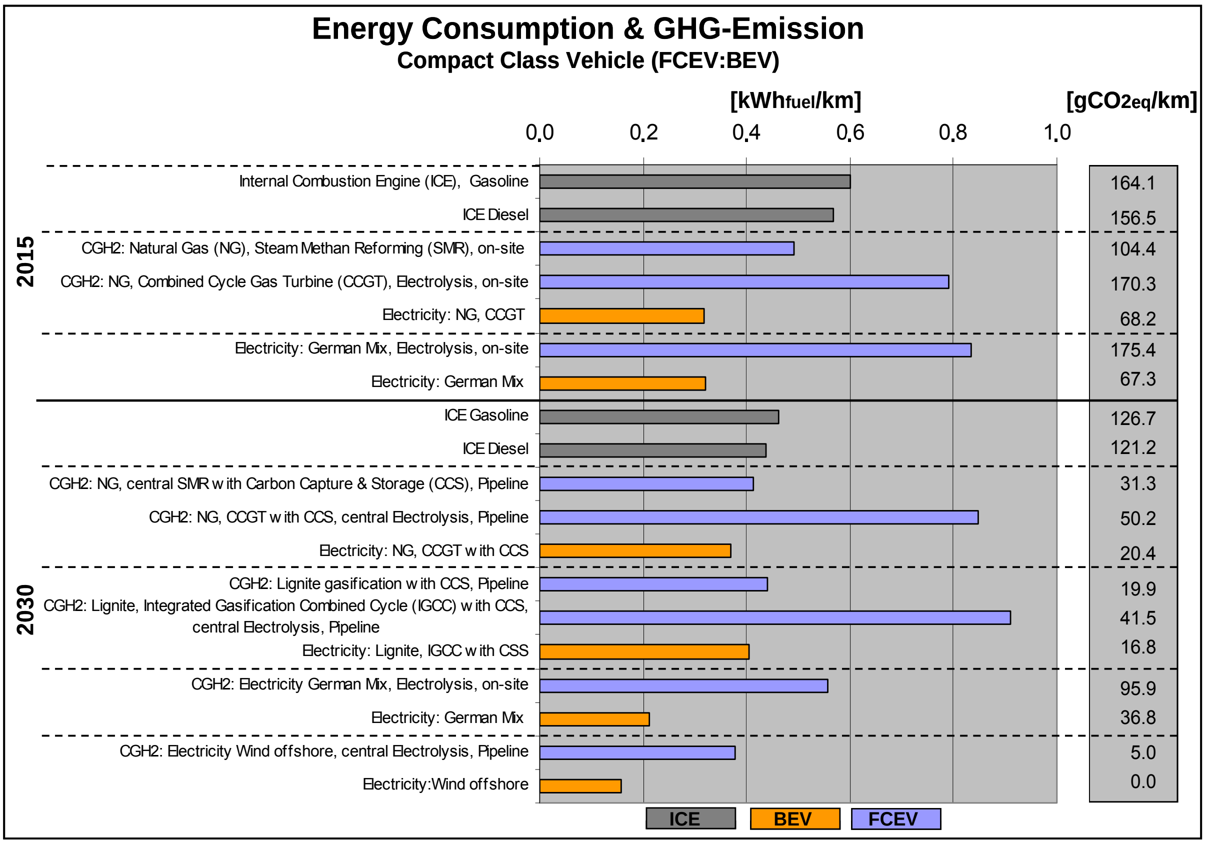


Figure 1: Energy consumption and GHG-emissions for different production pathways but identical vehicles.

3.2 Greenhouse gas emissions

Thanks to its high efficiency, the electricity path requires less fossil primary energy and thus CO_2-emissions are considerably reduced (compare figure 1).

The Well-to-Wheel comparison, based on natural gas as primary energy carrier, reveals that a compact-class BEV with electricity from a gas and steam plant emits 68/20 g_{CO2eq}/km (without/with CCS), while a FCEV with H_2 from steam methane reforming emits 104/31 g_{COeq}/km (without/with CCS) – which is about 50 % more. A FCEV with H_2 from electrolysis (German electricity mix and electricity from a gas and steam plant in 2015) emits even more GHG than a vehicle with diesel- or gasoline-engine (ICE). Due to the continuous reduction of CO_2-levels, the German electricity mix will contain distinctively less CO_2 in 2030 than in 2015 and will thus also have a corresponding effect on the H_2 electrolysis path (175 g/km → 96 g/km). The CO_2eq emission of the corresponding electricity path for a BEV will go down from 67 g/km (in 2015) to 37 g/km. This value corresponds to approx. 30 % of the GHG-emission of a comparable combustion engine in 2030. Also FCEVs will emit less GHG than conventional vehicles by 2030.

3.3 Energy costs

Due to their high efficiency, BEVs will result in lower fuel costs per 100 km than diesel-/gasoline-and H_2-vehicles by 2015 - no matter if taxes and levies are considered or not (figure 2).

3.4 Total cost of ownership

Figure 3 shows the total cost for the operation of comparable compact class vehicles with diesel-/gasoline-, hydrogen- and electric drives. For 2015 we expect that expenses (incl. taxes) for BEVs will be 10 - 12 % above those for conventional vehicles, while the expenses for FCEVs will even be 35 - 50 % higher. With respect to the uncertainty resulting from the long forecast period (based on today's taxes and levies) the costs for FCEVs are still above (5 - 16 %) the expenses for a vehicle with diesel engine. A BEV will cost approx. 10 % less than a vehicle with diesel engine.

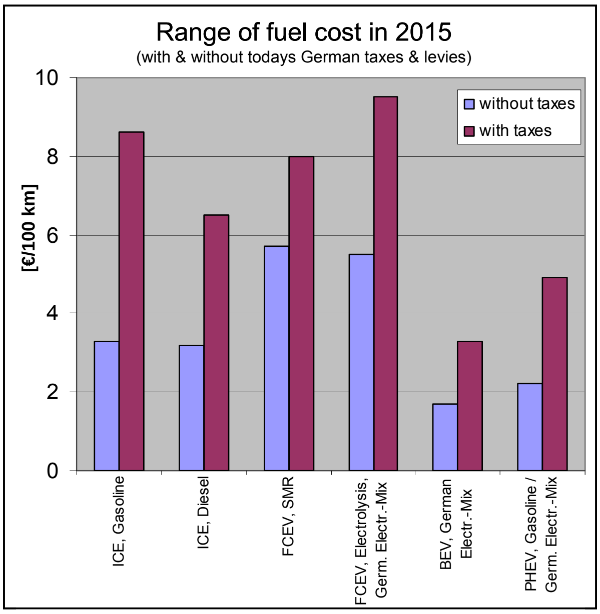


Figure 2: Range of fuel cost.

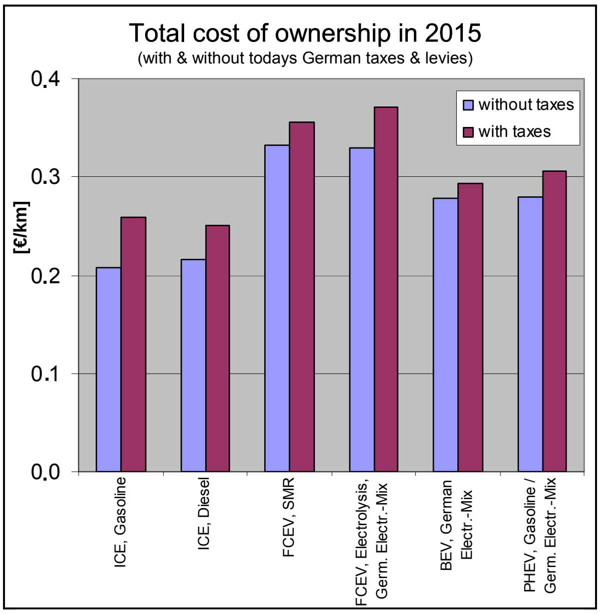


Figure 3: Total costs of ownership.

3.5 Infrastructure

There is a nationwide power grid and the gradual development of the charging infrastructure for BEVs (especially in the private and semi-public sector) may be realised at much lower costs than a complete new H_2-supply infrastructure – which would be required. The initial sharp increase in expenses, entailed by the development of a hydrogen infrastructure, will go down as soon as a nationwide infrastructure is available.

3.6 Handling

Every user knows how to handle electricity, whereas the broad public is not yet experienced in dealing with hydrogen as energy carrier.

In contrast to the above-mentioned benefits of electricity towards hydrogen, electricity still shows the following disadvantages in the mobility sector.

3.7 Cruising range

Today the cruising range of a BEV with a suitable battery size amounts to less than 200 km and is thus still lower than the range of a FCEV (> 400 km). However, we expect battery capacities – and thus cruising ranges – to improve further within the next few years.

3.8 Charging time/fuelling time

Today, the charging time of BEVs is considerably longer (> ½ h) than the fuelling time of vehicles with gasoline-/diesel engine (< 3 min.) or FCEVs (< 5 min.). However, they may easily be charged at any power outlet – no matter if at home or at work – while the vehicle is parked.

3.9 Interim conclusions

Due to their long charging time and the resulting loss of time and comfort in long-distance traffic, we would estimate that initially BEVs will rather be used for short distances or by commuters than in long-distance traffic (larger passenger cars, delivery vehicles, busses etc.). We assume that FCEVs have an advantage towards BEVs in the long-distance sector; but we do not yet know whether further progress in battery development could compensate this benefit. However, with Plug-in Hybrid Electric Vehicles (PHEV) we already today offer vehicles with a combined drive (battery and a small but efficient combustion engine) providing most of the above-mentioned advantages of a BEV without any loss of comfort.

Thus PHEVs may build a bridge in the long-distance segment to future quick-charging BEVs and FCEVs.

4 Further Fields of Application

4.1 Delivery vehicles

This study considers delivery vehicles with an admissible overall weight between three and five tons that are mainly used in urban delivery traffic. Our calculations (according to the above-mentioned pattern) use the example of a Mercedes Benz "Sprinter 316 or 316 CDI".

Like passenger cars also light duty vehicles (LDV) benefit more from electricity than from hydrogen with regard to energy efficiency, GHG-emission and expenses. Due to their characteristic field of application, the short cruising range still is an important disadvantage in this sector. However, battery replacement concepts, PHEVs or quick-charging batteries might solve this problem and should therefore be part of further research.

4.2 Busses

We have taken the Daimler “Citaro” as an example for our research in the bus-sector.

In this vehicle category, FC-buses (Citaro FuelCELL-Hybrid) already exist but no comparable model with battery electric drive. We have therefore calculated the current consumption for a fictive BE-bus with the aid of literature data from a trolley bus. Also in the bus-sector, electricity is more favourable than hydrogen with regard to energy efficiency, GHG-emissions and expenses. However, if the bus only runs on electricity, a battery of around 6 tons (state of technology in 2015) would be required to cover the distance of up to 250 km a bus travels per day. Compared to busses with a conventional drive, today’s FC-busses weigh around 2 tons more. Innovative approaches to reduce the battery weight - such as battery replacement concepts at turning points, inductive charging at bus stops or special PHEV-solutions are available but require more detailed research. A final analysis will have to show if and under what (e. g. regulatory) conditions the above-mentioned BE- and FC-bus concepts meet the requirements for an economical application in local public transport.

4.3 Passenger boats

Till December 2009 the passenger boat “Alsterwasser” operated in Hamburg was the only ship of this category with a hydrogen fuel cell drive throughout the world. Also a passenger boat with electric drive ("Alstersonne”) has been developed, which may however not be compared to the "Altsterwasser" with regard to design, weight and engine output. On the basis of a model calculation, comparing the consumption of a diesel-electric drive with a FC-drive, we learn that also in this sector electricity looks like the better choice: The energy consumption of an electric drive (German electricity mix) would be 34 % lower and the GHG-emissions would even be 50 % lower compared to a diesel-electric drive (in 2015). Like for commuter-BEVs, battery-electric drives would be suitable for short-distance passenger boats whereas FC-drives would be a good choice for larger long-distance transport ships.

5 Conclusion

With regard to the applied criteria (energy efficiency, GHG-emission and expenses), electricity as a rule reveals considerable advantages over hydrogen. Still, batteries have a lower energy storage density than hydrogen does so that today’s BEVs offer lower cruising ranges than FCEVs. Also the prolonged charging time of BEVs compared to FCEVs might have a negative effect on user comfort – which may, however, be reduced or even compensated by a future development of battery storage and fast-charging technology. Due to the above-mentioned advantages of electricity, it is likely that battery-electric cars will rather be applied in the short-distance segment where vehicles are only rarely used for trips of more than 100 to 200 km – and thus normally charged at home or at work. On the other hand, the FC-drive is presently ahead of the game for user groups or market segments where distances beyond 200 km are travelled. However, PHEVs with their battery (suitable battery size for standard distances) and small, economical combustion engine, provide already today all benefits of a BEV and the same user comfort (cruising range, charging/ refuelling time) as conventional cars.

Commercial vehicles are bigger and heavier than passenger cars, and, as a rule, drive long distances, cope with high payloads and remain in use for a sustained period of time. As long as the respective expenses for such projects are competitive with regard to FC- and hydrogen applications, battery-electric vehicles may still be applied in commercial vehicles, as (combined-) solutions like battery-change systems, inductive charging at bus stops (for busses) and PHEVs may help to meet the above-mentioned requirements. Vehicles with hydrogen drive will also in the long run be suitable for areas where combustion engines (gasoline and gas) are not allowed and where no power grid connection is available.

Abbreviations

BE	Battery Electric
BEV	Battery Electric Vehicle
CGH_2	Compressed Gaseous Hydrogen
CCS	Carbon Capture & Storage
DoD	Depth of Discharge
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
LDV	Light Duty Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
SMR	Steam Methane Reforming

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Hydrogen and/ or Battery Electric Vehicles – Where Will Development Go To?

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1 Background

The private transport sector is worldwide primarily based on the use of fossil fuels. Utilisation of these fuels causes a lot of emissions, including the greenhouse gas CO_2 and pollutants like particulate matter, nitrogen oxide, hydrocarbons etc. As a result of the emission of greenhouse gases the impacts of climate change are intensified. The other pollutants have various negative impacts on human health, flora and fauna. In 2005 the whole transport sector emitted over 6.3 Gt of CO_2, which is equivalent to 23 percent of the total global energy-related CO_2-emissions [1]. Light duty vehicles caused over 2.7 Gt of CO_2-emissions [2]; therefore they were responsible for around 10 percent of global energy-related CO_2-emissions. Like in other CO_2-emitting sectors a reduction of emissions is necessary for limitation of global warming. The worldwide increasing number of cars and thereby driven distances makes the challenge to lower emissions in this sector to a huge technical and political challenge.

In consequence of the growing consumption of fossil fuels, car drivers were faced with increasing fuel costs during the last years. As an effect of this and due to an increased environmental sensibility in general and especially on account of the climate change discussion, alternative fuels and drive concepts became much more important in the public interest.

Beside others the before mentioned factors led to changes of the whole road transportation system. Indicators for this development are the increasing use of biofuels and hybrid cars as well as an even smaller but also growing number of battery electric and fuel cell vehicles. In the future technological changes will be even more far-reaching.

2 Introduction and Research Question

Actual many kinds of alternative powertrains are in development, which will have stakes on the market for private used cars in the next years. Departing from this middle-term perspective, long-term strategies of automobile manufacturers (produced cars after 2020/2030) are primarily focused on only two of them: Fuel cell vehicles as a kind of hydrogen cars and battery electric vehicles.

By now there is a large disagreement in the political and public discussion, if both technologies will coexist in the future, or if only one will remain in the end.

This poster presentation deals with this subject and it tries to reach clarification in these discussions, by pointing out:

- The central factors of influence on the private transport market
- The main differences between battery electric and fuel cell vehicles

In this context the market introduction of fuel cell and battery electric vehicles is analysed in a comparative way.

In focus of the analysis is the car buyers' point of view (customer perspective). The main questions out of this perspective are: What are the expectations and requirements of the car buyer? And: Can the different car types meet these requirements in the future?

The car buyer's perspective has been chosen, because the buyer, as market participant, has an essential impact on the future demand of private vehicles and is therefore a determining factor for the market development.

3 Method

To get a clear view, how the both assayed car types can meet different decision criteria of car buyers, at first the whole private transport sector is separated into different segments. The chosen segmentation points out differences in the use of cars (travelled distance) depending on the engine output. As a result of these statistics a detailed pattern of car utilisation in the private transport sector is shown.

The next step is a meta-analysis of surveys, concerning determining factors on the car buyers' decisions to buy a new and alternative type of car.

Based on the identified criteria, fuel cell and battery electric vehicle are compared.

To evaluate the two car types from the car buyers' point of view, the requirements and use patterns are checked against the actual and future technological development status of both car types. Values for the car buyers' requirements are taken, if listed in the before mentioned surveys. Otherwise actual average values for each criterion are used for the comparison. Also the spread of the actual and future technological development status is shown.

Because of the variety of boundary conditions some assumptions and simplifications are used:

Other alternative forms of public mobility (e.g. cars using biofuels, hybrids, battery electric vehicle with range extender) are not part of this analysis.

Statistical data for Germany are used, which reflect the typical car utilisation in Germany. In other countries the car utilisation could be completely different.

A further simplification is the consideration, that driven kilometres and the private car equipment will be the same in the future.

Also forms of political influence are not integrated in this analysis.

The characteristics of the battery electric vehicles are constrained on lithium-ion batteries because they offer the best combination of power and energy density and the biggest amount of research promotion for batteries.

For fuel costs it is considered, that in future perspectives hydrogen and electricity for driving purposes will completely be produced from renewable resources.

4 Results

The segmentation concerning the engine output shows that more than half of all cars between 15 and 400 kilowatts are located between 50 and 79 kW [3]. The daily or yearly driven distance increases in general with incremental engine output. The daily data is calculated on the basis of the average of yearly driven kilometres for each engine output class [3] and the assumption, that the car is used on 350 days in a year. In result the yearly and daily driven kilometres are 60 percent higher for cars with engine outputs between 100 and 400 kW as in those with 15 to 49 kW.

Also second and third cars of households are analysed concerning their patterns of utilisation. The percental share of different distances in all travelled ways of first, second and third cars are compared. For the German example the shares are nearly the same. Despite it is probably, that the whole amount of driven distance is different, but there is no data available to confirm this.

Many recently published surveys concerning the determining factors on the car buyers' decisions to buy a new and alternative car (e.g. [4, 5, 6, 7, 8, 9, 10, 11]) are part of a meta-analysis. The surveys are analysed by picking out the criteria, which are mentioned the most times or with the highest rates of importance in the decision for or against buying a new and alternative car. Following key factors are identified:

- Purchase costs
- Fuel costs
- Range
- Refuelling time

The purchasing decision also depends on other aspects like safety, design and the image that is connected to the car, but they seem to play a minor part and are not considered further.

The general results of the comparison of battery electric and fuel cell vehicles are listed below. Advantages of battery electric vehicles especially appear in the actual purchasing costs and their fuel costs. Today battery electric vehicles cost mostly between double and triple the price, in comparison with a conventional car. The range of estimated costs for current fuel cell vehicles fluctuates broadly. A reason for this is the small number of produced cars (only prototypes), which are, in contrary to battery electric vehicles, not available to the market right now. The predicted purchase costs for fuel cell vehicles are actually significantly higher. The energy consumption inside the battery electric vehicle, as well as the production and distribution is more energy efficient, than it is for fuel cell vehicles and the hydrogen production and distribution. This effect lowers fuel costs for battery electric cars, which also will remain on a lower level in the future. On the other hand fuel cell vehicles meet the requirements towards range and refuelling time in a better way. The charging time of the battery electric vehicles has a broad range because there are a lot of different technical concepts. The car could be charged with usual power level, high power or inductive. Another possibility would be a change of the used battery against a charged one. Options with fast refuelling times (high power charging and change of batteries) would be better accepted from car buyers, but up to now they cause some problems, like shorter life time and different battery quality. The time of refuelling fuel cell vehicles doesn't clearly differ from the time to refuel conventional cars, what means a clear advantage for this car type today and probably also in the future. Another advantage of fuel cell vehicles is given by meeting range requirements of the car buyers. In future the range of fuel cell vehicles could nearly be on the level of actual conventional cars. On the other hand the possible range of battery electric vehicle will certainly increase, but under real driving conditions these vehicles won't be able to reach the ranges, that actual cars do.

Based on the accomplished segmentation and the considered car buyers' key criteria, the comparison, answering the central question of this study, shows, that not only one car type appears to be completely advantageous. Strength and weakness of the cars are very dependent of their end-use. Battery electric vehicles become advantageous for patterns of utilisation of smaller cars (cars with less engine output), which are used in cities. Fuel cell vehicles meet the demands concerning the four main criteria in higher vehicle classes better, which are primarily used as the first car of households and travel longer distances.

As an effect both car types will coexist. But there will be different emphases in the segments. These aspects show, that it is extremely important to handle the results in a differentiated way.

Successful research for one of these technologies could also have a positive effect on the other technology. One example is the research on batteries for driving purposes. Fuel cell vehicles as well as battery electric vehicles use batteries, for which reason the research on batteries will have positive economic and technological effects on both technology pathways.

5 Further Requirement of Research

As a conclusion, future research and development for battery electric and fuel cell vehicles should not only be focused on technological progress (supply-side). It is also important to find out, which political support and which business model should be used for different market segments to cause the most effective development at the right time (demand-side).

This is closely linked to the question, how to build up the hydrogen and charging infrastructure in a combined and economic as well as ecological optimal way.

Additional to the results of the comparison of battery electric vehicles and fuel cell vehicles in this study, some general aspects should be mentioned.

It is possible, that the patterns of the mobility utilisation could change in terms of significantly more or less distance travelled with private cars and via a growing use of public transport and carsharing. As an effect, range requirements towards private cars could decrease and battery electric vehicle could become more interesting. This leads to the research task, to monitor patterns of car utilisation and car buyers' expectations by statistics and surveys.

In this study a gap of information about these types of future cars and between the car buyers' real mobility demand and what is expected from the car is identified. There is a need for a lot of information work in the future. Especially the integrated view is still missing in the car buyers' considerations. Examples are total cost of ownership over the whole lifetime and the consideration of consumption by doing a well-to-wheel-analysis.

Contrary to the patterns of utilisation in Germany the private car use in many other countries in the world is on a significantly lower level. In these countries the individual mobility with cars will start and be especially focussed in the cities, so range requirements will be lower and battery electric vehicles could probably have a higher market share than fuel cell vehicles. This will give a lot of scientists the opportunity to implement individual market analyses for different regions.

For both car types technological development has to enhance criteria like range, refuelling time, and the efficiency of the energy use as well as life time, infrastructure, safety, variety of design, materials, weight etc. But the most important fact is two lower the price of those cars to enhance the car buyers' interest and desire. In addition there are many political possibilities to make these car types more interesting for customers in the coming years. Some instruments might be: Support of R&D, CO_2 tax, tax concessions, buy promotion, ability to use environmental zones with entry restrictions.

Furthermore there are many new business models for car manufacturers, power supply companies and mobility providers possible, which could be an interesting alternative to the old model of purchasing the whole car and paying for each litre of fuel.

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