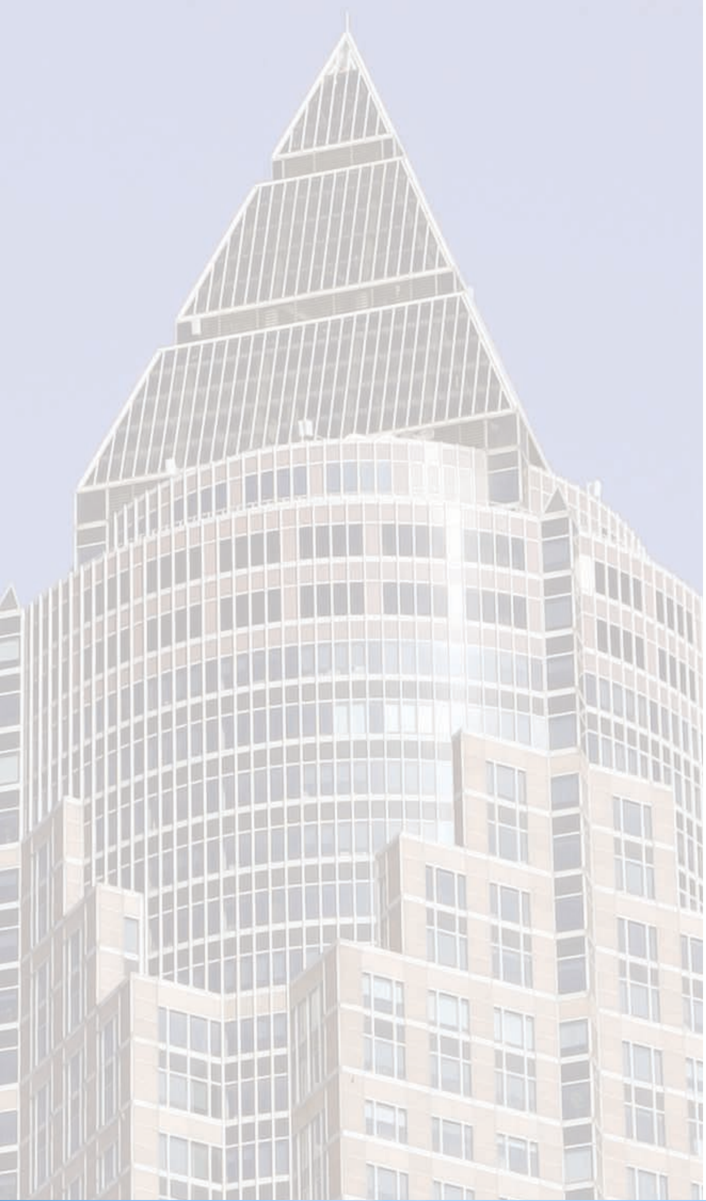
Demonstration of Fuel Cell Vehicles & Hydrogen Infrastructure

Summary of Results



MesseTurm, Frankfurt

Service Station, Frankfurt

Project Zero Regio:
November 2004 - May 2010

http://www.zeroregio.com

Zero Regio Project Consortium – 16 Partners from 4 EU Countries

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Project Zero Regio is co-financed by the European Commission

Lombardia & Rhein-Main towards Zero Emission: Development and Demonstration of Infrastructure Systems for Hydrogen as an Alternative Motor Fuel

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The two demonstration sites

Preface – European Commission – Hydrogen-Based Road Transport

Hydrogen has great potential as an alternative motor fuel capable of providing sustainable mobility while meeting today's major energy and environmental challenges, including energy supply security, mitigation of climate change and improved local air quality. Together with electricity and biofuels, hydrogen is expected to contribute significantly to the European Commission's goal to reduce fossil fuel dependency and to strongly decarbonise the transport sector by 2050. The European Commission continues therefore to invest significant effort in transport projects based on hydrogen with an objective of bringing hydrogen-based transport to maturity and commercial viability.

The European Commission is following a dual approach to demonstrating hydrogen, focussing both on public bus transport as well as on private cars. Zero Regio has been the first demonstration project co-financed by the European Commission, which has focussed on fuel cell passenger cars and the associated hydrogen refuelling infrastructure. Experiences and results obtained in this project will certainly pave the way for the next steps.

Zero Regio has made important progress, including:

- Using by-product hydrogen for the demonstration fleet of fue cell vehicles. By-product hydrogen will be an important source during the initial phase of using hydrogen as a vehicle fuel.
- Transporting hydrogen via high pressure pipeline. Pipeline networks will be the ultimate means for distributing this energy carrier - as in today's highly developed natural gas networks.
- Developing 700 bar refuelling technology. Next generation fuel cell vehicles will mostly employ 700 bar storage in order to achieve comparable autonomy with today's gasoline fuelled vehicles.
- Integrating hydrogen infrastructure in multi-fuel public service stations.
- Developing national guidelines for hydrogen filling stations, such as in Germany.
- Demonstrating the performance and durability of first generation fuel cell vehicles - these have performed much better than expected.
- Studying socio-economic aspects of hydrogen-based transport systems.

Frankfurt skyline

Zero Regio, being one of the first hydrogen car demonstration projects, has also highlighted some of the barriers which could inhibit early introduction of hydrogen across Europe. For example, there are different regulatory and safety standards in different member states, calling for European harmony in regulatory practices. Harmonisation of regulatory issues should therefore be pursued and improved while promoting hydrogen all over Europe.

The evolving European Union political framework and priorities are favourable for clean, low-carbon fuels such as hydrogen. In addition to the Commission's long term goal of decarbonising transport by 2050, increasingly demanding policies are being adopted by the European Union to achieve targets for energy efficiency, security and climate change. The oft-cited '20-20-20 by 2020' targets correspond to reducing greenhouse gas emissions by 20% by 2020 compared to 1990, 20% reduction in primary energy use and achieving at least a 20% share of renewable energy sources in the energy mix.

The Commission has complemented these policy initiatives with concrete, legislative measures to regulate pollutant and CO_2 emissions, to promote public procurement of clean vehicles, and to provide support for research and demonstration of clean vehicle technologies including conventional, electric and hydrogen-fuelled vehicles. The recent, rapidly growing interest in battery and hybrid electric vehicles will strengthen the development of fuel cell electric vehicles, due to the synergies at both component and infrastructure level. Electric vehicles, based both on batteries and fuel cells, will not only drive the development of key components such as batteries, motors and hybrid drive trains, but also the build-up of renewable electricity supply infrastructure. Renewable electricity can either be used to produce hydrogen to fuel vehicles directly, or store electricity for load levelling.

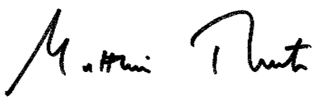
Filling station in Frankfurt

Further R&D is needed to develop and prove these technologies and synergetic concepts. The Commission therefore established the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) public private partnership to implement strategically planned research, development and demonstration activities in order to accelerate market introduction. Transportation and refuelling infrastructure is a major application area of the FCH JU which aims to create the conditions for the introduction of several thousand fuel cell vehicles in the field by 2015 and a series production of hydrogen refuelling and distribution infrastructure.

FC-Panda at the FCV parade Copenhagen, Nov. 2009

It is encouraging to see that, in spite of the prototypical nature of the fleet and infrastructure demonstrated in Frankfurt and Mantova within Zero Regio, the experience gained is very relevant to the next generation of larger demonstration projects. Let me therefore encourage the Zero Regio project consortium and other stakeholders in the field to build on this experience while working on new projects on hydrogen-based road transport.

Mercedes-Benz A-Class F-CELL serving A-380



Matthias Ruete
Director-General
Mobility and Transport
European Commission

Introduction

Project Overview

Zero Regio is a project co-financed by 16 European organisations and the European Commission within the 6th Framework Programme. Zero Regio aims at developing and demonstrating zero-emission transport systems in European cities based on hydrogen as an alternative motor fuel.

This has been achieved by building a hydrogen infrastructure consisting of hydrogen production, transport, compression, storage and distribution in public service stations and operating these to refuel dedicated fleets of fuel cell passenger vehicles.

Vehicles and the infrastructure are operated inreal-life urban conditions over a period of three years. Operational data acquired on vehicles and infrastructure is analysed and evaluated with respect to energy efficiency and environmental and socio-economic impact. Analysis results are compared with the state-of-the-art technologies and conclusions are drawn on the status and potential of the new technologies (fuel cell power train and hydrogen) demonstrated in the project.

The present report provides a summary of important results and experiences obtained in the project.

Zero Regio at a Glance

Project Organisation	
Duration of the Project	66.5 months; 15. Nov. 2004 - 31. May 2010
Number of Project Partners	16; 4 EU Countries
Total Personnel Effort	573 Person Months
Total Project Investment	19.75 million Euro
Investment Partners; European Commission	12.29 million Euro; 7.46 million Euro
Number of Demonstration Sites	2, Frankfurt-Germany; Mantova - Italy
Fuel Cell Vehicles	
Number of Fuel Cell Vehicles Demonstrated	8; 5 A-Class F-CELLs (Daimler); 3 New Pandas (Fiat)
Total Distance Covered	95000 km.
Total Hours of Operation	2670 hrs.
Average Availability	91%
Total Number of Drivers	30
Number of Accidents	1
Hydrogen Infrastructure	
Number of Stations; Dispensers	2; 4
Average Availability of Dispensers	86.5%
Hydrogen Refuelled (GH_2; LH_2)	1550 kg (incl. 350 kg outside Zero Regio); 3707 kg
Hydrogen Supply Paths	4
Number of Accidents	4
Safety & Environmental Impact	
Injuries to Humans or Environment	None
CO_2 Emissions saved	15000 kg (TtW)

Infrastructure Systems

Hydrogen Sources

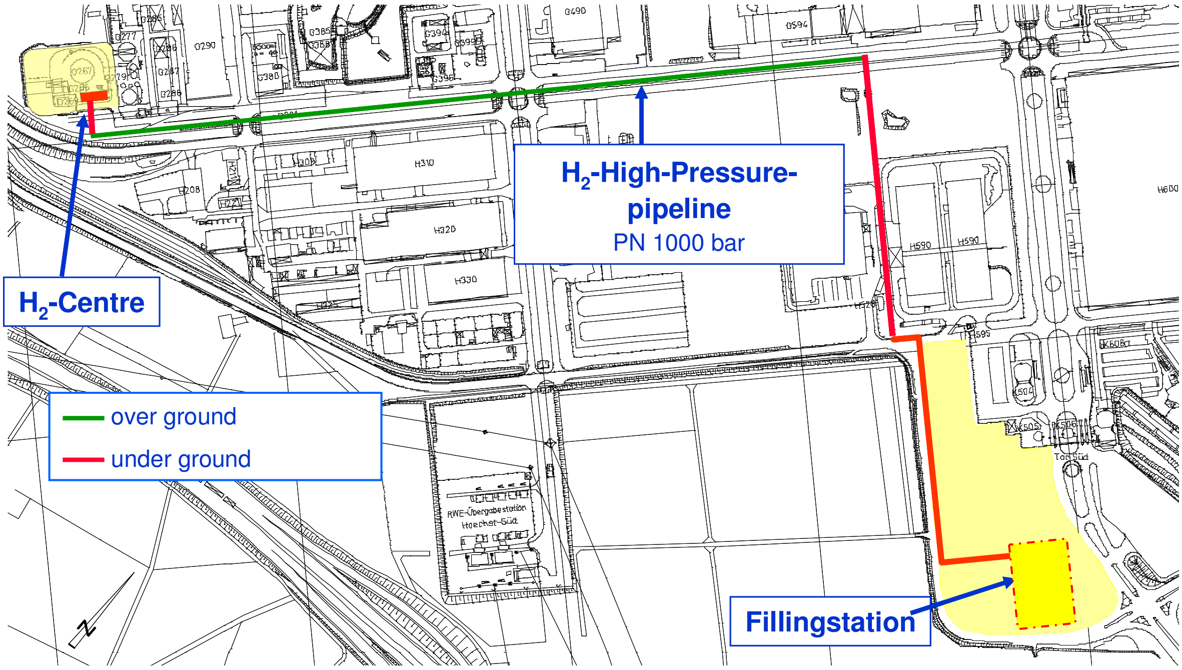
Four different hydrogen sources have been used in Zero Regio. A large amount (ca. 30 mil. Nm^3/yr) of hydrogen is available in Höchst as a chemical by-product. This is transported to the service station via a high pressure pipeline designed and built in the project. Liquid hydrogen is trucked-in to the station by Linde.

In Italy two different sources are employed. Industrial hydrogen from a nearby steam-reformer plant of Sapio is used in the initial phase of demonstration. This has been truck transported to the service station.

A modern multi-fuel Agip service station has been built in Frankfurt as well as in Mantova, selling hydrogen like any other motor fuel.

The service station in Frankfurt has two dispensers for compressed hydrogen (350 bar and 700 bar) and one for liquid hydrogen. In Mantova there is one dispenser for compressed hydrogen at 350 bar. All the dispensers are equipped with the necessary control systems and operate in an automatic manner.

Figure 1: High pressure transport pipeline in Höchst



In the later phase of demonstration hydrogen is produced on-site in a plant realised in the project. This plant is based on the SCT-CPO (short contact time-catalytic partial oxidation) process. This process converts Natural Gas, air and steam into Syngas (H_2+CO+CO_2). Syngas is further processed in a high temperature shift reactor followed by a cooler and a pressure swing adsorber delivering hydrogen with a purity of 99.995%.

Figure 2: On-site reformer realised in Mantova

Hydrogen Quality

PEM fuel cells used in automotive transmission require hydrogen of a certain quality for optimum operation and life time. Hydrogen quality has been monitored at regular intervals at both sites to make sure that quality standards are met. Some typical values are presented in the table below.

No	Component	Measured values at Infraserv (by-product H_2)	Measured values at Sapio (industrial H_2)	Measured values at Eni (on-site reformer)	SAE J2719 specification	OEM specification Daimler (Fiat)
	Grade	> 99.99%	99.999%	99.995%	> 99.99%	> 99.98%
1	CO	0.5 ppm	< 0.1 ppm	< 0.1 ppm	< 0.2 ppm	< 1 ppm
2	CO_2	0.42 ppm	< 0.1 ppm	< 0.07 ppm	< 1 ppm	< 1 ppm
3	S-compound	n. p.	n. p.	< 0.004 ppm	< 0.004 ppm	< 0.01 ppm
4	THC (C_nH_m)	0.3 ppm	< 0.1 ppm	< 0.02 (CH_4) ppm	< 2 ppm	< 1 ppm (0.5)
5	O_2	0.02 ppm	n. p.	n. m.	< 5 ppm	< 5 ppm
6	NH_3	n. p.	n. p.	n. p.	< 0.1 ppm	< 6 ppm
7	N_2, Ar, He	N_2 = 67 ppm	< 5, 0, 15 ppm	< 10, 0.1, 35 ppm	< 100 ppm	< 200 ppm (50)
8	H_2O (G+L)	0.76 ppm	< 5 ppm	n. m.	< 5 ppm	< 5 ppm (10)
9	Na^+	< 0.01 ppm	n. p.	n. p.	< 0.05 ppm	< 0.05 ppm
10	K^+	< 0.01 ppm	n. p.	n. p.	< 0.05 ppm	< 0.08 ppm

Table 1: Hydrogen quality - measured values compared with requirements

n. p. = not present; n. m. = not measured

Figure 3: Agip service station in Frankfurt

Hydrogen Pathways and Dispensers

The complete pathway of hydrogen in Höchst, Germany is shown below. The 900 bar compressor is an ionic liquid compressor and has been installed by Linde. The equipment upstream of this already existed at Infraserv Höchst before Zero Regio started and is used for feeding into the different networks in the industrial park.

The 700 bar refueling system in Frankfurt has been upgraded in accordance with Release A of SAE. Hydrogen is pre-cooled to -40°C in an ultra low cold-fill. Infra-red communication is installed between the dispenser and the vehicle leading to safe refilling of 700 bar vehicle tanks in 3 minutes for about 5 kg of hydrogen.

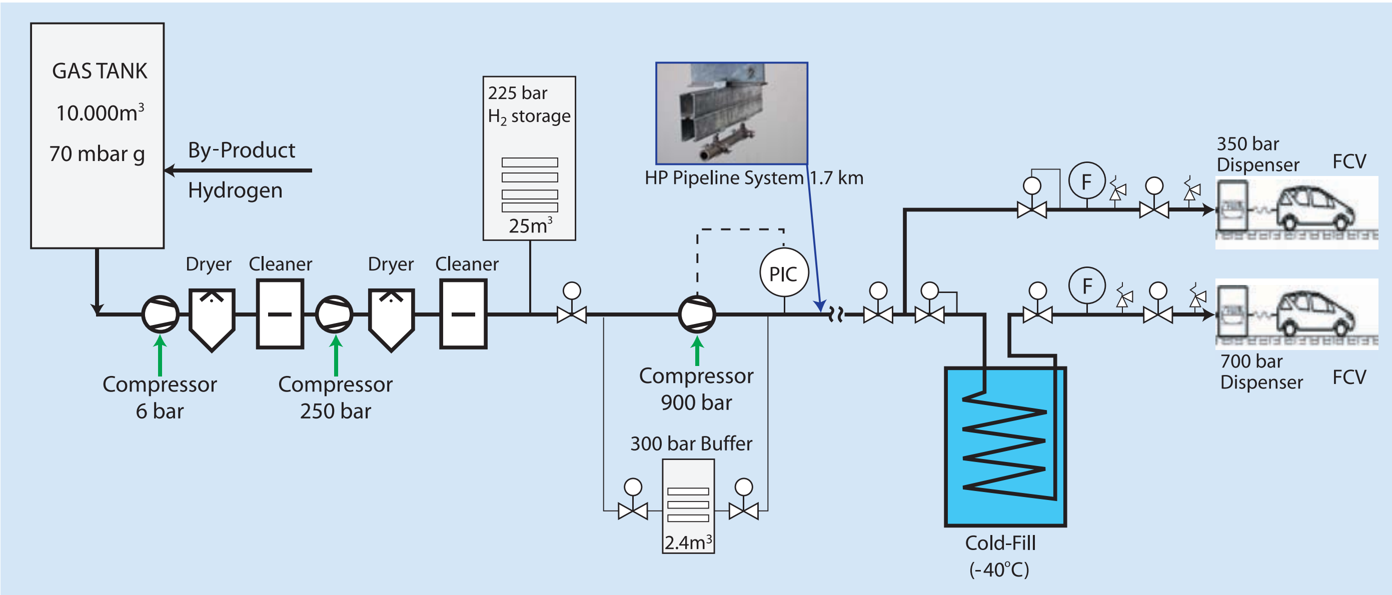


Figure 4: Complete refuelling system in Höchst, Germany

The hydrogen pathways in Mantova, Italy are shown below where either the industrial hydrogen or the hydrogen produced on-site is compressed, stored and fed into the 350 bar dispenser.

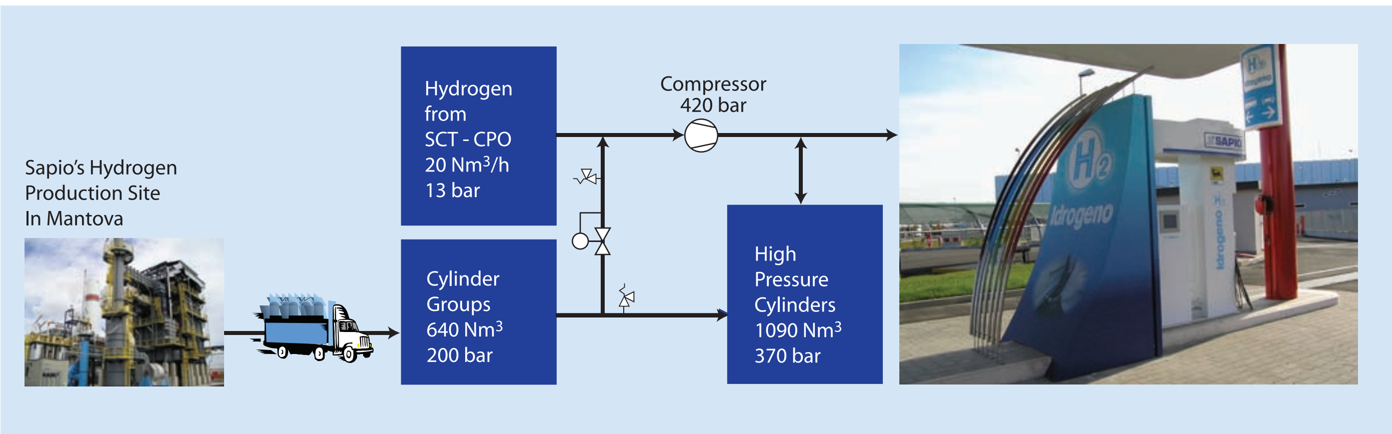


Figure 5: Complete refuelling system in Mantova, Italy

The refuelling system for liquid hydrogen at the Agip station in Frankfurt is shown below. Liquid hydrogen trucked-in is stored in a 10.000 litre storage tank and transported with a LH_2 transfer pump to the dispenser.

This dispenser has been employed to refill BMW Hydrogen 7 Ice vehicles (though outside the project) operated in the Frankfurt area.

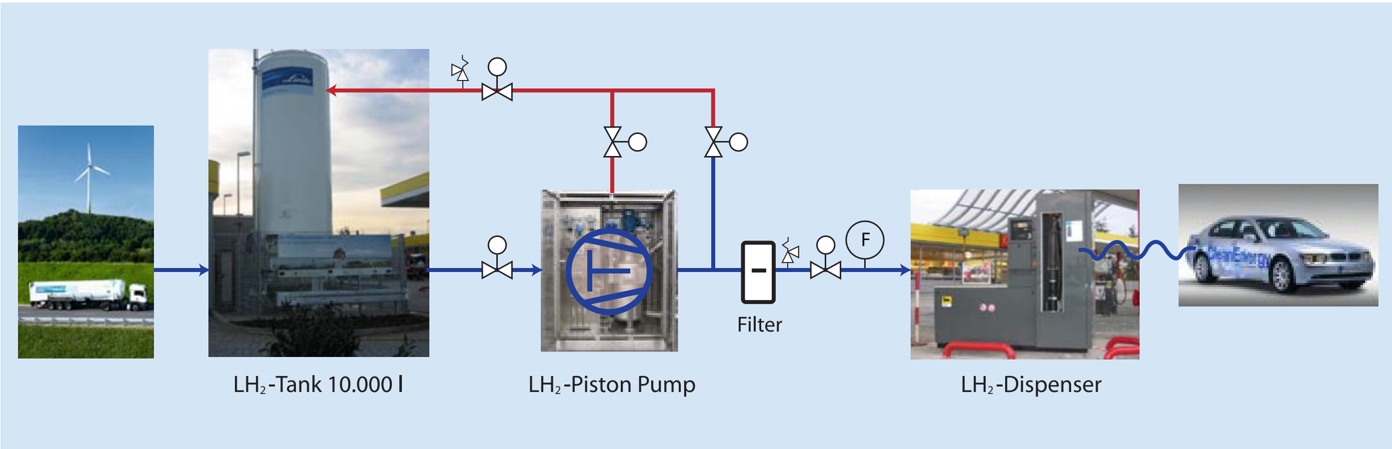


Figure 6: Complete LH_2 refuelling system in Höchst, Germany

Component	Availability %
Germany	
Transport Pipeline	96
Ionic Compressor	86
350 bar Dispenser	95.3
700 bar Dispenser	95; 64,1*
LH_2 Dispenser	99
Italy	
350 bar Dispenser	78
On-site Production Plant	**98

* including accident
** Operated batch mode

Table 2: Availability of infrastructure components

Figure 7: Hydrogen dispenser in Mantova

Figure 8: Hydrogen dispensers in Frankfurt

Availability of the dispensers can be considered to be satisfactory. The lower value for the 700 bar dispenser in Germany is due to an unusual accident which resulted in a downtime of over a year for this dispenser. In 2009 the supply system was upgraded and the construction time has been counted as downtime. The values shown in the table are therefore conservative.

Safety and Approval of Infrastructure

Although hydrogen does not present more safety issues than other fuels, as a result of its physical and chemical properties the issues are different. Important safety considerations stem from:

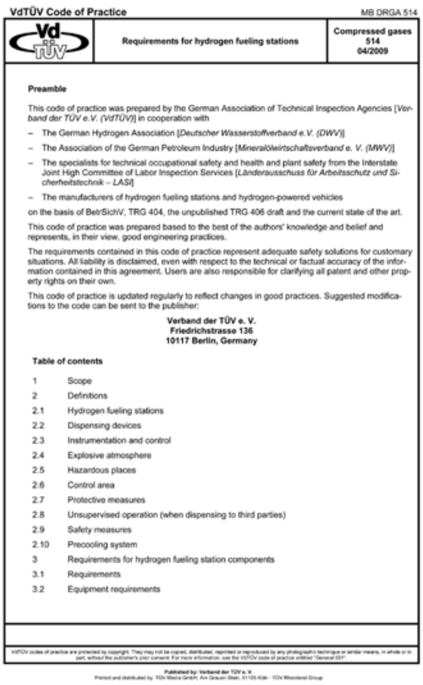
- Low density and broad explosion limits requiring ventilation of closed rooms/equipment and monitoring of concentration
- Low density makes hydrogen safer in open areas
- Low ignition energy of hydrogen
- Small molecules leading to leakage
- Affinity of hydrogen to metal embrittlement
- Negative Joule-Thompson coeff. at room temperatures
- Low volumetric and high gravimetric energy content needing high-pressure storage tanks
- These and many more precautions have been taken at the design & construction stages of the infrastructure as well as during operation via monitoring systems. Hazop studies have been carried out for all equipment.

Table 3: Properties of H_2, NG and Gasoline

Property	Units	H_2 (gas)	NG	Gasoline (liq.)
Density	g/l	0.089	0.72	745
Molar mass	g/mol	2.016	16.04	100.2
Specific heat Cp	kJ/kg K	14.199	2.22	2.24
Boiling point	K	20.3	111.6	371.6
Lower heating value	kJ/g	119.93	50	43.2
Explosion limits	vol% in air	4.0 to 77.0	4.4 to 17.0	1.1 to 6.7
Min. ignition energy	mJ	0.017	0.29	0.24
Self ignition tempr.	K	833	868	488

Approval formalities in Germany could be obtained on time although there have been no regulatory guidelines for hydrogen filling infrastructure at the time. In Italy, on the contrary, the formalities have taken much longer resulting in a delay for opening the service station in Mantova. The station began operation officially in September 2007 instead of November 2006. During this time refilling was performed with a mobile station at Sapio. Efforts in Zero Regio resulted in an Italian regulation issued by the Internal Affairs Ministry in Aug. 2006, which defines the safety standards for realizing hydrogen refuelling stations in Italy.

Infraserv initiated work on national guidelines in Germany for hydrogen refuelling systems based on the experience in Zero Regio. All the stakeholders on the national level were involved and this resulted in VdTÜV leaflet 514 on requirements for hydrogen (gas) filling stations in Germany with and without communication between the dispenser and the vehicle.
See: www.vdtuev.de.publikationen/merkblaetter



VdTÜV Code of Practice — MB DRGA 514

VdTÜV	Requirements for hydrogen fueling stations	Compressed gases 514 04/2009

Preamble

This code of practice was prepared by the German Association of Technical Inspection Agencies [*Verband der TÜV e.V. (VdTÜV)*] in cooperation with

- The German Hydrogen Association [*Deutscher Wasserstoffverband e.V. (DWV)*]
- The Association of the German Petroleum Industry [*Mineralölwirtschaftsverband e. V. (MWV)*]
- The specialists for technical occupational safety and health and plant safety from the Interstate Joint High Committee of Labor Inspection Services [*Länderausschuss für Arbeitsschutz und Sicherheitstechnik – LASI*]
- The manufacturers of hydrogen fueling stations and hydrogen-powered vehicles

on the basis of BetrSichV, TRG 404, the unpublished TRG 406 draft and the current state of the art.

This code of practice was prepared based to the best of the authors' knowledge and belief and represents, in their view, good engineering practices.

The requirements contained in this code of practice represent adequate safety solutions for customary situations. All liability is disclaimed, even with respect to the technical or factual accuracy of the information contained in this agreement. Users are also responsible for clarifying all patent and other property rights on their own.

This code of practice is updated regularly to reflect changes in good practices. Suggested modifications to the code can be sent to the publisher:

Verband der TÜV e. V.
Friedrichstrasse 136
10117 Berlin, Germany

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Figure 9: VdTÜV Leaflet 514

Fuel Cell Vehicles

Figure 1:
The A-Class F-CELL in customer hands at Fraport, Infraserv and Daimler AG
The New Panda in customer hands at Mantova Town Hall

Demonstration Fleet

Eight fuel cell vehicles were operated in the Zero Regio project (Figure 1).
In Germany there were 5 Mercedes-Benz A-Class F-CELLs including one vehicle with 700 bar storage and in Italy 3 Fiat New Pandas. Key technical data of the vehicles are shown in Tables 1 and 2.

Vehicle type	Fiat New Panda	
Fuel Cell System	PEM, 70 kW	
Drive	Electric Motor	
	Power	30 kW Peak 50 kW
	Max. Torque	130 Nm
Fuel	Hydrogen 350 bar	
Amount of Fuel	2.35 kg, 1 Cylinder	
Range	300 km	
Vmax	130 km/h (electr. limited)	
Battery	No Battery	

Table 1: Technical data New Panda

Vehicle type	Mercedes-Benz A-Class F-CELL extended version	
Fuel Cell System	PEM, 72 kW	
Drive	Electric Motor	
	Power	55 kW Peak 65 kW
	Max. Torque	210 Nm
Fuel	Hydrogen 350 bar (700 bar)	
Amount of Fuel	1.8 kg (2.8kg), 2 Cylinders	
Range	177 km (~280km)	
Vmax	140 km/h	
Battery	NiMh, air-cooled	
	Peak Power	20kW
	Capacity	6.5 Ah, 1.4 kWh

Table 2: Technical data A-Class F-CELL

Vehicle Demonstration

Germany

Starting at the end of 2006, A-Class F-CELL vehicles were delivered to the customers Fraport and Infraserv located in the Rhein-Main region of Germany. The aims of this field trial were to further develop the technology to a volume production level by seeing how the vehicles perform under real-world conditions and to establish what the infrastructure requirements will be.

A 700 bar A-Class F-CELL "Plus" vehicle was introduced to evaluate the 700 bar technology primarily from an infrastructure perspective. During the Zero Regio project, the Agip fueling station in Frankfurt was upgraded to meet Release A requirements for 700 bar refuelling.

Italy

Starting in 2007, New Panda fuel cell vehicles were delivered to Mantova Town Hall (MTH). The town's employees received training and then used the vehicles over the course of their daily activities in the Lombardia region of Italy. The vehicle demonstration took place in Torino and Mantova.

Kilometres of Operation

Within the Zero Regio a total distance of 94601 km was travelled by fuel cell vehicles in Germany and Italy. Over the course of the project, 32983 km were driven in Italy and 61618 in Germany.

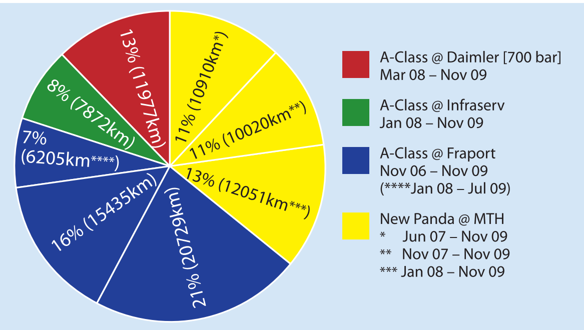


Figure 2: Total kilometres of operation per vehicle within the Zero Regio project (Nov 2006 – Nov 2009)

Operating hours

Vehicles were operated 881 hours in Italy and 1790 hours in Germany. During the project, eight vehicles operated a total of 2671 hours.

The amount of kilometres driven and the number of hours operated are evidence of the technology's tremendous advancements.

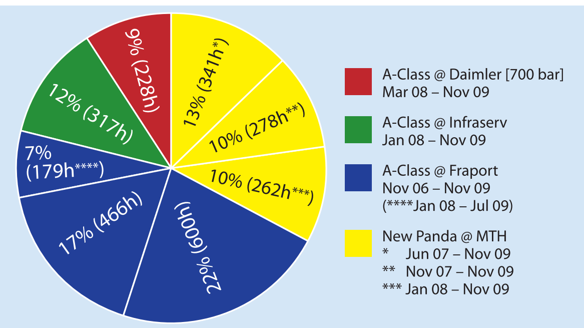


Figure 3: Total hours of operation per vehicle within the Zero Regio project (Nov 2006 – Nov 2009)

Total H_2 Consumption

The total consumption of hydrogen was approx. 1200 kg (approx. 350 kg in Italy and 850 kg in Germany).

These results were achieved in regular daily operation and not under a formal test program.

Fleet Availability

The fuel cell vehicles have shown a high availability within the Zero Regio project (see Table 3).

The value stated in brackets in Table 3 includes downtime due to certain events unrelated to vehicle operation such as H_2 contamination in 2007 and an accident caused by driver's negligence in 2009.

Vehicle	Availability [1)]
A-Class F-CELL in Germany	95% (92%)
New Panda in Italy	86 %

Table 3: Availability of fuel cell vehicles within the Zero Regio project (Nov 2006 – Nov 2009)

[1)] Outage due to fuel cell power train relevant maintenance only

Data acquisition and analysis
All data from the vehicles and the fuel cell systems is recorded while the vehicles are in operation. An analysis of the collected data makes it possible to quickly identify issues with the vehicles. The layout of the data acquisition and communication system is shown in Figure 4.

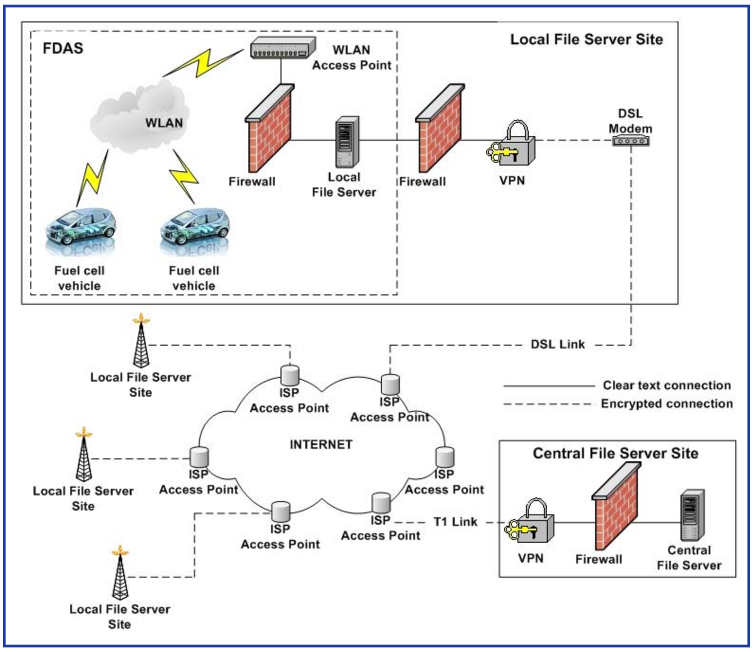


Figure 4: Layout of the data acquisition and communication system

Maintenance, Safety & Homologation

Germany

Daimler set up the vehicle workshops and offered special training to service personnel. Daimler also provided all the necessary tools, computer systems and software.

The A-Class F-CELL has passed the high safety standards set by Mercedes-Benz. The brake system, lightening, exterior noise, seats, technical data (dimensions, weight/axle load), and the safety concept of the new technology (safety electronics, H_2-safety, H_2-tank-system), among other things, were approved by an authorised expert (TÜV) and the vehicles got individually approved and registered according to the German laws (§ 21 StVZO).

These vehicles are equipped with the most advanced safety devices certified by the respective producers.

Italy

The vehicles were only prototypes and were thus periodically revised in order to verify the status of the stack. Some intervention on the cells of the stack was necessary in order to guarantee vehicle performance throughout the entire course of the road testing.

The balance of plant has been also monitored in order to ensure reliability of the auxiliary components. For these reasons, the vehicles were unavailable ten to fifteen percent of the time during the period of fleet deployment.

The Panda hydrogen vehicle is inherently safe. They are homologated today as prototypes and the rules imposed by the new European directive ECE (2008) will be employed in the near future. Up until now, the vehicles could be driven with only up to 200 bar storage. These vehicles are equipped with the most advanced safety devices certified by the respective producers. In the process of homologation, the cars have passed a series of stringent tests on their electromagnetic compatibility, the functionality of their sensors, the level of protection from electric shock and the brake system. Finally tests were repeatedly performed concerning the refuelling at different pressure levels.

Next Generation Fuel Cell Vehicles: B-Class F-CELL

Vehicle type	Mercedes-Benz B-Class F-CELL	
Fuel Cell System	PEM, 80 kW	
Drive	Electric Motor	
	Power	100 kW
	Max. Torque	320 Nm
Fuel	Hydrogen (700 bar)	
Range	385 km (NEDC)	
Vmax	170 km/h	
Battery	Li-Ion, liquid cooled	
	Peak Power	30kW
	Capacity	6.8 Ah, 1.4 kWh

Table 4: Technical Data B-Class F-CELL

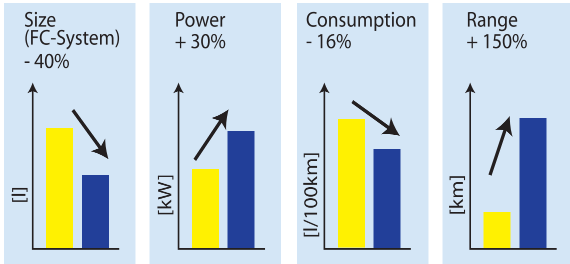
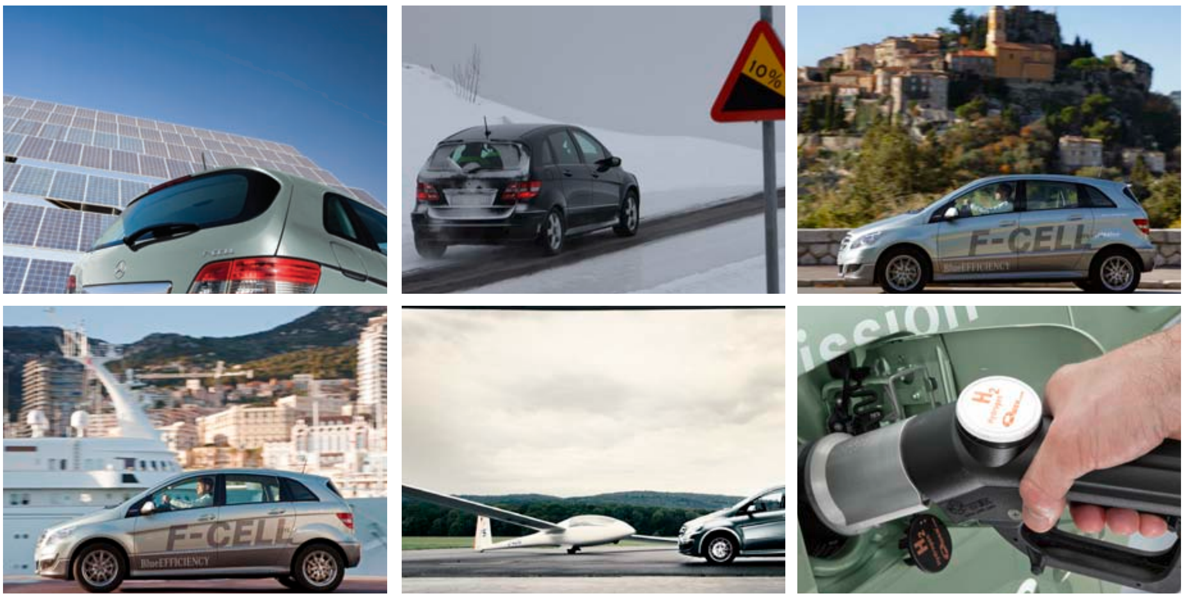


Figure 5: Development improvements from the existing A-Class F-CELL to the next generation B-Class F-CELL

The key challenge for the next generation of fuel cell vehicles was a cold start capability below 0°C. The B-Class F-CELL has a freezing start capability of -25°C. The size of the fuel cell system has been reduced by 40% with a 30% increase in power to 100kW. The fuel consumption has been reduced about 16%. A longer range (+150%) and the usage of a Li-Ion battery have also been key drivers for improving the new generation of fuel cell vehicles - the B-Class F-CELL.

The B-Class F-CELL




F-CELL
zero emission
BlueEFFICIENCY
driving the future

Environmental Impact

The final aim of electrifying the road transport in Europe and in particular the use of hydrogen as a fuel is to minimize its overall environmental impact and to diversify energy sources, reducing dependency on fossil fuels. Vehicles were tested in the VELA laboratory of JRC at Ispra and analyses of laboratory data as well as real-life data on the vehicles and infrastructure were performed.

Vehicles

How is the hydrogen energy distributed through the power train of a fuel cell vehicle?

The Mercedes-Benz A-Class F-CELL and FIAT New Panda fuel cell vehicles are powered by an electrical motor installed between the front wheels. The fuel cell stack produces all the electricity needed through a reaction between oxygen (from the air) and hydrogen, which is stored in pressurized tanks. The electrical flow is managed by an electronic module which also controls several accessory systems.

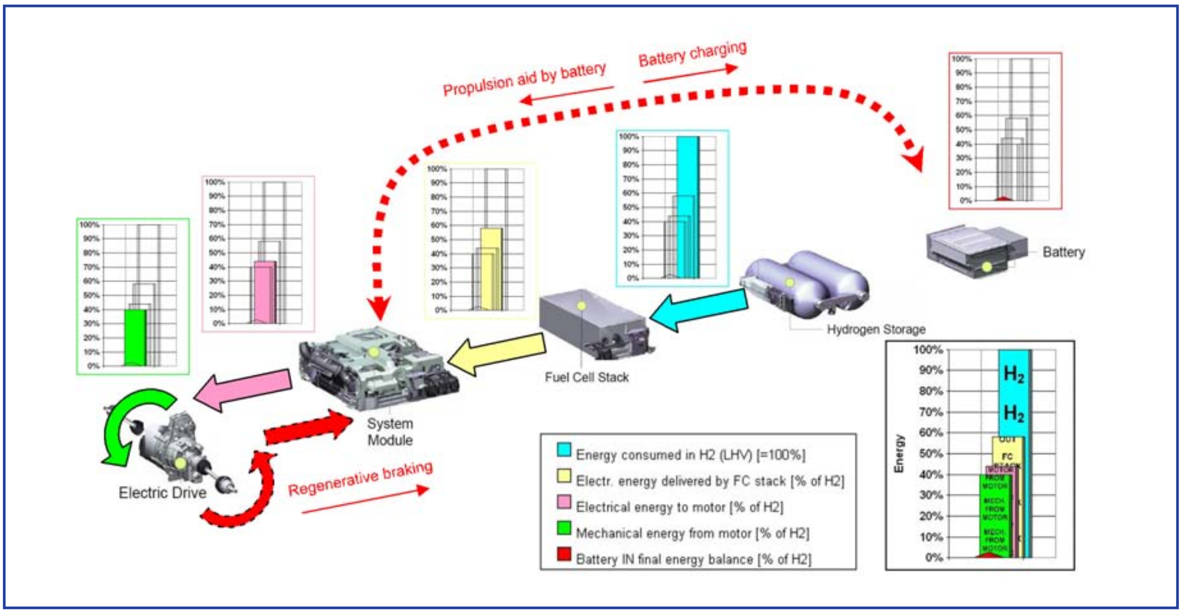
The Mercedes-Benz vehicles are also fitted with a NiMh battery pack. The battery is used to store energy regenerated during braking when the motor acts as a generator, and to give extra power to the motor during accelerations. The battery's differential energy balance must be accounted for when computing the efficiency at the wheels and the fuel consumption.

The principle of the energy distribution pattern shown (Figure 3) applies for both types of vehicles, except for the FIAT vehicle there is no battery for recovering braking energy.

Figure 1: A-Class F-CELL in Vela Laboratory

Figure 2: New Panda in Vela Laboratory

Figure 3: Typical energy distribution pattern of a Fuel Cell power train



How efficiently is the hydrogen used to propel the FC vehicles?

A comparison (see Figure 4) of the typical efficiencies over a normalized test cycle (NEDC) between a conventional gasoline engine vehicle and a FC vehicle shows that for the same amount of equivalent consumed fuel energy, the FC vehicle will deliver significantly more energy both at the level of the fuel converter and to the wheels.

Furthermore, the efficiency of the fuel cell stack remains quite constant over a large operating power range while the efficiency of an internal combustion engine (ICE) is only at its best in a very narrow range of power.

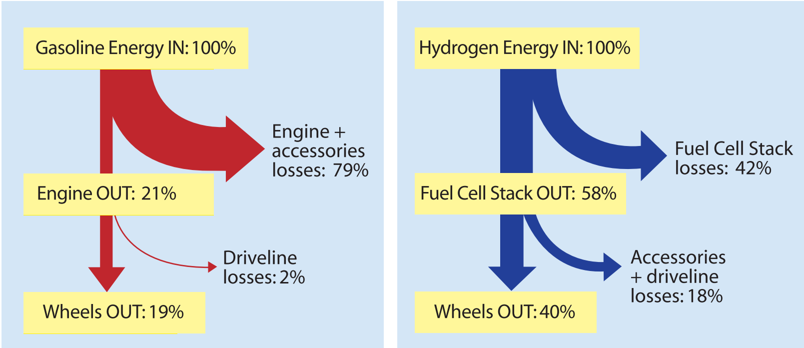


Figure 4: Typical efficiency of a conventional 1.6 l gasoline car (left) and a Fuel Cell car (right) over a NEDC test cycle

What is the energy consumption of a FC vehicle?

The graph (Figure 5) compares the specific consumption over the same normalized test cycle of different types of cars of similar power and size. With 1kg hydrogen, the Mercedes-Benz FC runs typically 104 km and the FIAT FC 114 km.

To ease the comparison with the ICE cars, their consumption has been converted into liters of gasoline equivalent, based on the energy content of the respective fuels. It is clear that the Zero Regio FC vehicles have a favorable specific consumption.

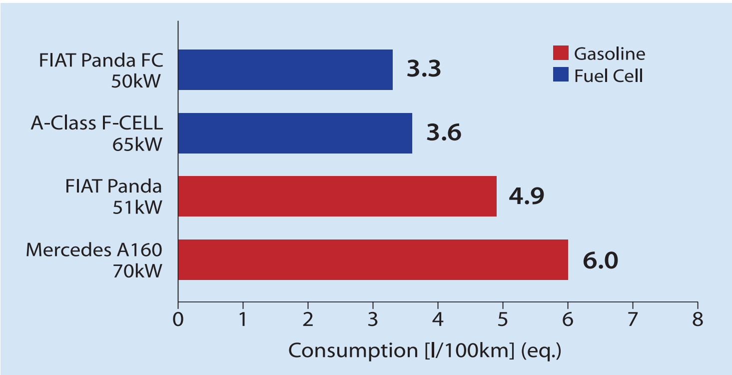


Figure 5: Consumption over a NEDC test cycle (1kg H_2 converted in 3.73 l gasoline)

In terms of emissions, how well does a FC vehicle perform?

This is obviously one of the main benefits of the fuel cell technology: there is no emission of pollutants as there is no combustion. The combination of the hydrogen stored on-board with the oxygen of the air just produces water and no CO, CO_2, NO_x, unburned hydrocarbons, particulate matters or toxic compounds.

In short: Zero emissions at the tailpipe of a fuel cell car. Figure 6 quantifies the CO_2 emissions of the latest generation cars of similar power and size. Fuel cell vehicles do not produce CO_2 at all. Another feature of the FC vehicles is their quiet operation and absence of vibrations.

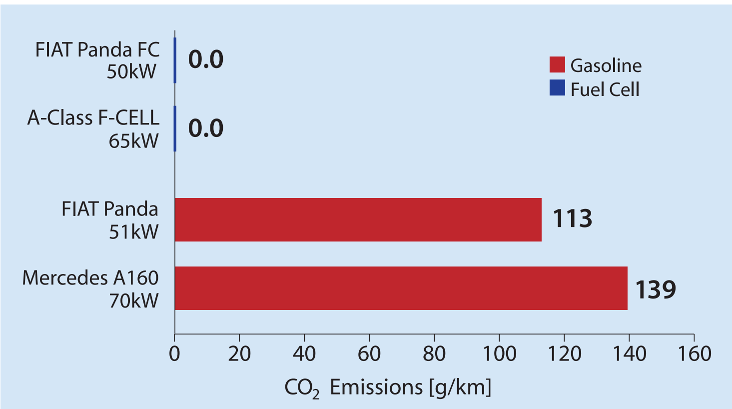


Figure 6: CO_2 emissions over a NEDC test cycle

Infrastructure

Given that there are no emissions from the vehicles, how much H_2 production and distribution contribute to the emissions?

In a transport system based on hydrogen the overall environmental impact (Well-to-Wheel - WtW) of the fleet depends also on the Well-to-Tank part of the system, i.e. the primary energy needed for hydrogen production and delivery.

A Well-to-Wheel analysis of primary energy demand and greenhouse gas emissions was carried out for both refueling stations at Frankfurt and Mantova and compared with standard technologies; i.e. gasoline, diesel and compressed natural gas (CNG) (Figure 7). At the Höchst site in Frankfurt the hydrogen is produced as by-product of an on-site chlorine production plant.

Although hydrogen is a by-product, a fraction of the total energy consumed by the plant has been considered as energy consumption for hydrogen production. In Mantova the hydrogen was centrally produced by gas reforming in an industrial site and transported by truck to the refueling station. In both cases the energy spent in ancillary equipment as pumps and compressors has been also taken into consideration.

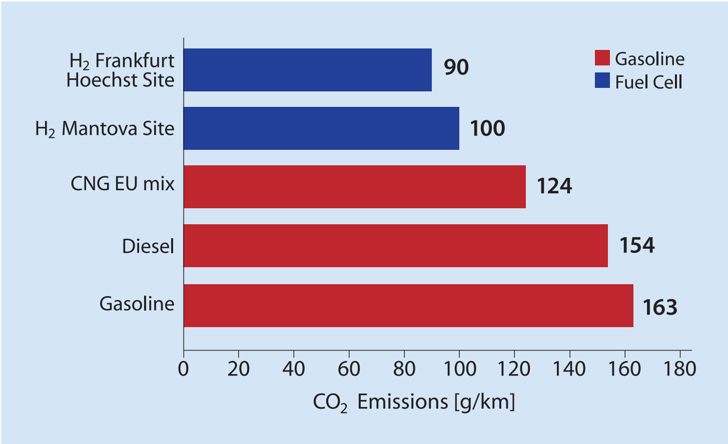


Figure 7: WtW Green House Gas emissions for the hydrogen pathways of this study compared with Compressed Natural Gas - CNG, Gasoline and Diesel.

Figure 7 shows the WtW green house gas (GHG) emission per km driven by the vehicles. As it is shown in figure 7 the WtW GHG emissions of FC vehicles are less than that from traditional technologies.

Furthermore, the WtW emissions of FC vehicles are only released at the production site and not at the user's end, which are normally densely populated large cities .

In conclusion the WtW analysis indicates that

- With current production pathways, total emissions from hydrogen are reduced, but not dramatically, in comparison to CNG, gasoline and diesel.
- More substantial reduction in the overall GHG emissions can be achieved through fuel supply routes using renewable energy sources for hydrogen production.

Socio-Economic Impact

Acceptance

Two sets of end users were asked about their reactions to H_2 technology.

One set was 41 drivers. The other was 700 Italian teenage students participating in Zero Regio demonstrations.

Key findings:

- End users are impressed by the cleanliness of H_2. This is a key factor for their acceptance. Acceptance is significantly reduced, if H_2 production turns out to be based on controversial energy sources, such as coal or nuclear power.
- End users are happy about the H_2 cars, except for their limited driving range.
- Drivers emphasize the need for improved driving range and refuelling options, but are tolerant about the present short-comings and prepared to allow some time for improvements.
- Drivers are almost satisfied with the user end of refuelling technology (when it works).
- Drivers find that the reliability of H_2 delivery is much below expectations. This constitutes an acute acceptance problem. There is no tolerance for situations where refuelling is not possible or waiting time is necessary.
- End users do not worry much about any hazards associated with H_2.

Students:
Percentage that agrees with each of the following statements

75%	H_2 cars give me more confidence in the future.
20%	H_2 cars increase my desire to have a car.
22%	H_2 cars make me think we are too occupied with technology.

Students:
To power your car, motorcycle or scooter, what would you prefer?

Petrol	Biofuel	Battery	H_2	Natural Gas	Other answer	Total
29%	7%	13%	30%	13%	8%	100%

Drivers:
If Japan and the U.S. decide to reduce support for H_2, what should Europe do?

Reduce support	Increase support	Maintain support	Don't know	Total
10%	51%	34%	5%	100%

Negative comments by passengers

Occasionally ↑	Will always be too expensive
	Oil companies will not accept
	Too dangerous
	Too high-tech
	Cannot solve traffic pollution
Rarely ↓	Don't believe what you are saying

In the future, hydrogen might come from coal or nuclear power. Would that influence your view on hydrogen vehicles?

Percentage of respondents that would become more negative

	Drivers	Students
Coal	84%	39%
Nuclear	65%	47%

Economics

Prices at the Agip station in Frankfurt

Fuel cell electric vehicles are expected to become affordable at some point in 2015-2025. For the same driving distance, what will it take to make the hydrogen bill cheaper than the petrol or diesel bill?

The Zero Regio study found that cost competitive hydrogen requires high fuel taxes, a high oil price and highly efficient hydrogen production.

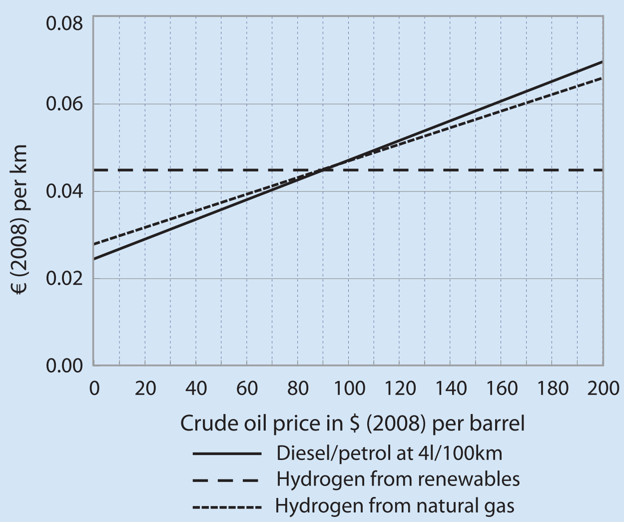
Special low tax rates for hydrogen are not necessary. High fuel taxes make more fuel-efficient cars more competitive, even if all fuels are taxed at the same rate. Electric cars are the most fuel-efficient cars and therefore they will be more competitive at higher tax rates.

Fuel tax rates are already high in Europe. The minimum rates in the EU are in the region of €10 per GJ, but they are much higher in most of the "old" EU countries. At a €15/GJ tax rate for all fuels there is a tipping point at a crude oil price of $90-100 per barrel. Above this price hydrogen would be cheaper than petrol or diesel for the same distance driven.

Alternatively, tax rates might be differentiated according to CO_2 emissions and energy use in fuel production. Adding a €44/tCO_2 tax rate to the €10/GJ would give the same competitiveness to hydrogen as the €15/GJ fuel tax, but the combined tax would amount to only €11-14/GJ.

Are oil prices above $90 beyond 2015 realistic? Leading oil market analysts such as the International Energy Agency now expects future oil prices to be $100-150 per barrel.

Highly efficient production and handling is necessary as well, even with high oil prices and fuel taxes. The Zero Regio project shows that it is possible to operate a hydrogen filling station even at 700 bar pressure continuously with practically no leaks of hydrogen. On the other hand, compression and cold-fill technology consumed electricity corresponding to 11-12% of the hydrogen. Thus, the total energy use in production and handling of 700 bar hydrogen can hardly be less than 30%. The above results depend critically on achieving this. Just a few per cent extra energy loss could jeopardize hydrogen competitiveness.



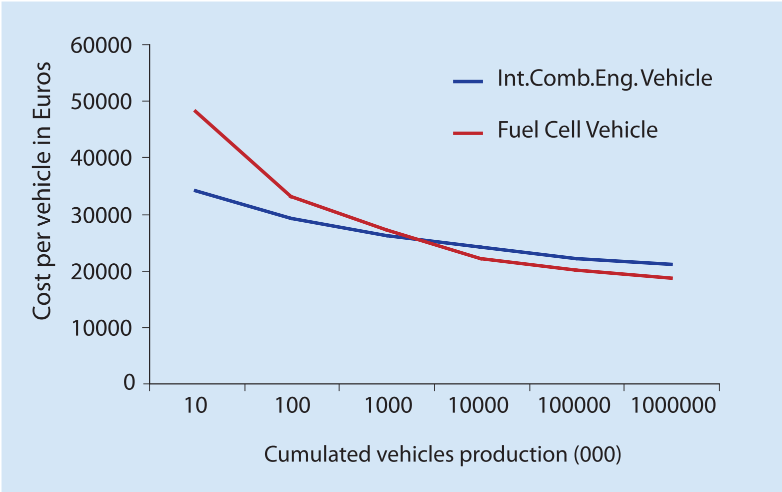
How fuel cost per km depends on the oil price. Tax rates €10/GJ and €44/tCO_2.

Trajectories for Cost Reduction

The Zero Regio project leaves no doubt about the practical feasibility of a transport system based on hydrogen fuel cell vehicles, or about the potential public acceptance of such a system. Costs need to be greatly reduced, however, and this requires a forceful movement down technological trajectories that are promising from this perspective.

The study of such trajectories leads to these key results:

- Fuel cells are now very expensive, but have a strong potential for cost reduction through learning.
- For other key hydrogen vehicle components, a relatively fast decrease in costs is also expected.
- While hydrogen vehicles have a large potential for cost reduction through learning, this is not the case for large-scale hydrogen production, which is already a mature technology.
- Production of hydrogen from natural gas (steam reforming) is the least-cost alternative at present, but the learning potential is not encouraging.
- Coal is another low-cost source of hydrogen, but it also has low potential for learning.
- Production based on renewables and nuclear technology has important environmental benefits, but remains costly. However, there is a significant learning potential in these pathways.
- Small-scale hydrogen production at the refuelling station is now 2-3 times as expensive as centralised hydrogen production. This cost differential is expected to be significantly reduced due to technological improvements in the storage, compression and distribution phases.



Learning estimations for H_2 vehicles

Cost data obtained in the Zero Regio project were used to compare centralised and small-scale hydrogen production, based in all cases on steam reforming of natural gas. The results are shown in the table:

Technology	Costs c€/kWh
Centralised, conventional	2.73
Centralised with carbon capture and storage	3.35
On-site (in refuelling stations)	7.14

Production costs for steam reforming

Dissemination

Promotion

Much effort has been deployed in project promotion and communicating the results obtained to the public at large, scientific community, interested stakeholders and schools. The table below shows some statistics of the project website as well as some promotional activities, e.g., presentations at fairs, conferences, workshops, school visits, publications, distribution of project information via CD-ROM, USB and printed flyers.

Zero Regio website statistics	
Unique visitors	327943
Page impressions	712224
PDF downloads	34116
Presentations	
Conference presentations	40
Project int. workshops	3
Fair presentations	35
Popular articles	21
TV broadcasts	15
Project films	4
Distribution brochures	> 20000
CD-ROM, USB etc.	> 1600
School visits	304
Visits at stations	45

One of the many school visits

The project's dissemination plan has been updated each year. The project team has taken active interest and communicated with other related EC projects. The project coordinator has maintained frequent contact with the EC on technical and financial issues on behalf of the project consortium.

Communication with different national and international hydrogen and fuel cell associations as well as other demonstration projects world wide has enhanced project promotion.

Some high visibility activities have been:

- Opening ceremonies of the service station in Frankfurt and Mantova attended by prominence from science, industry and politics
- 'Highlight der Physik 2007' in Frankfurt
- International project workshop in Italy at the WHTC 2007
- Loreto event 'Agora 2007' in Italy
- Large overseas groups visiting the service stations
- Television broadcasts in Italy & Germany
- Ecomondo fair in Italy in 2008
- FCV parade in Copenhagen in 2009 and many more.

Service station opening in Frankfurt

Reaction of the public at various fairs and exhibitions has been very positive. People who have driven the vehicles at many "ride and drive" events have shown great interest and acceptance.

The European and international media have been keenly interested in the project and have given it very positive coverage.

Exploitation of Results

As regards exploitation of results obtained in the project following items have high potential:

- Services regarding approval formalities
- Design and construction of hydrogen transport lines
- 700 bar refuelling technology
- Exploitation of by-product hydrogen during the initial phase of commercialisation
- On-site production plants
- Large demonstration projects

Both service stations are public stations and are open to all hydrogen cars outside the project Zero Regio. The refuelling station in Frankfurt is being used by project-external clients such as Opel, Honda and Mazda.

The 700 bar filling station, one of the first ones with infrared communication will be used by the Mercedes-Benz B-Class F-CELL vehicles after the project.

FCX Clarity of Honda refueling at the Agip station in Frankfurt

"Today over 95% of new cars have internal combustion engines. In 2030 may only be 40%. Hybrid and electric drives are then in the majority. To achieve the 60% share of hybrid and electric cars, we will need appropriate signals coming from policy-makers. In addition, we must make sure that the power sector is decarbonised in a timely manner." Dr. Fatih Birol, Chief Economist, IEA

Service station opening in Mantova

Zero Regio was presented at the Ecomondo (Eco-World) fair, one of the most significant events in Italy on sustainable development and renewable energy.

Zero Regio at Ecomondo

Concluding Remarks & Next Steps

Zero Regio Reporting and Organisation	
Number of deliverable-reports	65
Number of prototypes delivered	17
Major milestones realised	16
Number of project meetings	14
Extraordinary meetings	1
Number of new partners	none
Number of parties excluded	none

Fuel cell vehicles have operated extremely well and their energetic and environmental superiority has been demonstrated. The next generation vehicles are expected to operate even better with higher mileage and efficiency. The issues of procurement cost and series production plans are also moving in the right direction.

Hydrogen infrastructure systems have been developed and demonstrated successfully at two European urban sites. Different H_2 sources and pathways have been used. Use of by-product hydrogen with pipeline transport can be exploited during the initial phase, which is now, of hydrogen era. The project Zero Regio has provided valuable experience with ionic compression systems which have a substantial potential in the future.

Table above gives an impression of the reports, deliverables and milestones realised in the project. Most of these have been realised on time. The project has concluded within the original budget with some redistribution amongst project partners during the project span of 66 months.

H_2 dispensers and A-Class F-CELL in Frankfurt

Some difficulties and disappointments experienced in the project are related with the approval formalities to be fulfilled in Italy both for hydrogen infrastructure and fuel cell vehicles. Vehicles have been subjected to a pressure limit of 200 bar in Italy. Harmonised regulations all over Europe must be in place to overcome such difficulties.

Amounts of hydrogen and infrastructure capacity at both sites are sufficient for refuelling much larger vehicle fleets. Experience and know-how developed in the project on management, technical and socio-economic assessments and of course on regulatory procedures in Germany and Italy are well suited for larger demonstrations leading to quicker market maturity and penetration. Time is ripe for performing inter-regional demonstrations now that we have tested and demonstrated the hydrogen and fue cell technology in local islands.

FC Panda at Mantova Cathedral. Zero-emission mobility protects historic architecture

Message from Some Project Partners

Infraserv GmbH & Co. Höchst KG

As the infrastructure providers of Industrial Park Höchst, Frankfurt, we are pleased to take the credit for developing and operating in the project Zero Regio new infrastructure systems such as a 1000 bar transport line for hydrogen and a public refuelling station for hydrogen at 700 bar, both for the first time world wide.

Dr. Roland Mohr, CEO, Infraserv Höchst
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Linde AG

During the past decade we focused on the technical feasibility. The Zero Regio project with its advanced fuelling technologies played a significant role in achieving that. Now we must take decisive steps towards standardization, modularization and cost reduction along the hydrogen value chain to enable a large-scale hydrogen infrastructure build-up and a commercial roll-out of fuel cell vehicles.

Markus Bachmeier, Head of Hydrogen Solutions & Advanced Customer Applications
Linde AG

Daimler AG

Fleet trials and co-operative projects are essential for the success of the fuel cell technology as a future technology. Input from politics, the energy industry, science and the first innovation-loving, forward-looking pilot customers is necessary and welcome. The experience gained from the Zero Regio project is a substantial contribution for the development of future, fully competitive fuel cell vehicle generations like the B-Class F-CELL.

Dr. Christian Mohrdieck, Director Fuel Cell & Battery Drive Development
Daimler AG

Fraport AG

For Fraport AG the multi-year on-road test of four fuel cell vehicles with hydrogen tanks was a win-win project in terms of gathering experience with CO_2-reduced vehicle technology. The successful test operation at Frankfurt Airport gives additional impetus to our mobility concept, which defines the share of vehicles with alternative drive technology at our airport at 60 percent by 2020.

Dr. Stefan Schulte, CEO
Fraport AG

TÜV Hessen GmbH

TÜV Hessen, one of Germany's major inspection agencies, was proud to support the project Zero Regio by contributing its extensive knowledge of ensuring compliance with technical requirements and vehicle inspection standards, assisting industry in developing automobiles and satisfying energy supply chain requirements with a special focus on safety and regulatory requirements.

K. Börsch, Managing Director
TÜV Hessen GmbH

Eni Deutschland GmbH

Our focus is always linked to the mobile customer and his specific needs. Therefore we are proud to offer our customers besides our well-known fuels, lubricants and shop services, also a variety of multi energy products. Eni enjoys being a partner in such an innovative and visionary project as Zero Regio.

Giuseppe Busà, Managing Director
Eni Deutschland GmbH

European Commission, DG Joint Research Centre

The Joint Research Centre (JRC) is a research based policy support organisation and an integral part of the European Commission, DG Joint Research Centre. At the Institute for Environment and Sustainability, we are pleased to have provided the environmental analysis of both the vehicle fleet and the refilling stations for the project Zero Regio. We have teamed up in this consortium to further understand the potential of hydrogen fuel cell vehicles in reducing the environmental burden of road transport.

Prof. Leen Hordijk, Director, Institute for Environment and Sustainability
EC, DG JRC, Ispra

Regione Lombardia

The experience and the quantity of experimental data acquired in Zero Regio project allowed Regione Lombardia to define the plan for the development of technologies fostering road transport with near-to-zero emission. On the basis of this experience, Regione Lombardia is starting programmes both to keep in operation the infrastructures set up during the project (Mantova refuelling station) and to increase the number of H_2 refuelling units and of vehicles as well as to develop other high-efficiency and low-emission technologies.

Dr. Massimo Buscemi, Regional Ministry,
Regione Lombardia

SAPIO S.r.l.

Gruppo SAPIO, as market leader in Italy for merchant Hydrogen, strongly supports the realisation of a gaseous hydrogen refuelling Infrastructure in Italy, in order that the FC Vehicles can be developed further to reach a sustainable transportation system. We are proud to have been involved in the realisation and operation of one of the most technologically advanced multi-fuel refuelling stations in Italy which was realised in Zero Regio and will be used further.

Dr. Alberto Dossi, Vice-President,
SAPIO Produzione Idrogeno Ossigeno S.r.l.

Mantova Town Hall

Zero Regio brought Mantova Town Hall into the world of hydrogen, an ideal alternative fuel. Our level of commitment and involvement in the project in its various aspects - approval procedures, demonstration and dissemination activities - has been substantial. Mantova's community has gained scientific and technical knowledge and culture, structures and infrastructures, while gaining wide experience in European projects but, above all, Mantova has gained a strengthened hope for a zero-impact mobility future.

Carlo Saletta, Assessor for Sustainable and Participated Development
Mantova Town Hall

Centro Ricerche Fiat

We as hydrogen automotive technologies experts and operators of Fiat Research Centre in Orbassano (TO-Italy) are pleased to take the credit of developing and operating in the Zero Regio project our advanced prototypes of hydrogen vehicles as the world wide smallest cars with a pure fuel cell traction system.

Dr. Paolo Delzanno, Project Manager
Centro Ricerche Fiat

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Hydrogen mobility demonstrated in Mantova, a Unesco World Heritage Site. ©Toni Lodigiani

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Significant Results from Zero Regio

- By-product hydrogen from chlorine electrolysis plants is suitable for fuel cell vehicles and should be exploited more.
- Transport of hydrogen with high pressure pipelines is technically feasible.
- Hydrogen refuelling at 350 bar has reached the maturity required in practice.
- Quick refuelling (3 min. for 5 kg) at 700 bar is functional and needs to be demonstrated in daily practice.
- Approval formalities for hydrogen refuelling in Italy have been more complex and time-consuming than those in Germany. This calls for initiatives to harmonise approval practices in Europe.
- Fuel cell vehicles (A-Class F-CELL and New Panda) performed very well.
- FCV's in Italy could be homologated only for storage pressures up to 200 bar. Approval formalities for hydrogen vehilcles also must be harmonised all over Europe.
- There seem to be no fundamental acceptance problems for hydrogen as motor fuel.

Service Station, Mantova


Clock Tower, Mantova

http://www.zeroregio.com

Project Zero Regio is co-financed
by the European Commission