The two Zero Regio demonstration sites: Frankfurt, Rhein Main region, and Mantova, Lombardia region

Multi-energy station in Frankfurt, Germany

• Project co-financed by the European Commission
ZERO REGIO (2004 – 2009)

Project aims
ZERO REGIO aims at developing and demonstrating zero emission transport systems in European cities based on hydrogen as an alternative motor fuel. This is being achieved by building hydrogen infrastructure consisting of hydrogen production, compression, storage and distribution in public service stations and operating these for refuelling dedicated fleets of fuel cell vehicles deployed in real life applications in urban areas. Accompanying technical and socio-economic analyses will lead to methods for quicker market penetration of hydrogen and fuel cell technology in transport.

Experience gained during the field tests and results obtained in this project will contribute to the objective of the European Commission of 5% substitution by hydrogen as an alternative motor fuel in the road transport sector by the year 2020.

Project implementation
Phase I, Construction (Nov. 2004-Nov. 2006):
- Design, development and construction of modern multi-energy public service stations
- Design and construction of hydrogen infrastructure - transport lines, production, compression and distribution equipment and their integration in the service stations
- Infrastructure certification assuring overall safety
- Preparation of demonstration activities - data acquisition systems, training of drivers

Phase II, Demonstration (Nov. 2006-Nov. 2009):
- Acquisition, testing and operation of fleets at both sites
- Acquisition of data related to fuel cell vehicles and refuelling infrastructure
- Analysis and evaluation of data on energy efficiency, performance and emissions
- Analysis and evaluation of data on socio-economic aspects
- Dissemination and exploitation of project results.

Two demonstration sites
Frankfurt in Rhein-Main region, Germany: by-product hydrogen from chemical plant is conditioned, compressed and transported to service station. Service station has one dispenser each for 350 bar and 700 bar \( \text{GH}_2 \) and \( \text{LH}_2 \).
A fleet of 5 A-Class F-Cell vehicles (one FCV with 700 bar storage) from Daimler is deployed.

Mantova in Lombardia region, Italy: hydrogen transported from an industrial plant as well as on-site production plant is employed to supply the service station. One hydrogen dispenser for 350 bar refuelling is installed. A fleet of 3 fuel cell Pandas from Fiat is deployed.

ZERO REGIO in numbers
16 Project partners from 4 EU countries, coordinated by Infraserv Höchst, Germany
Project duration 5 years
Total personnel effort estimated = 554 person months
Total project budget > 21 M€
EC contribution requested = 7.46 M€

This pocket-book presents project status, some results obtained, difficulties experienced and the future prospects.

• Project co-financed by the European Commission
Fuel Cell Vehicles:
Employing hydrogen as motor fuel
Emitting only water vapour from the tail pipe

How do the FCV’s work?
FCV’s are propelled by a fuel cell (FC) powered electric motor. A fuel cell is an electrochemical device that converts the chemical energy of the reaction of hydrogen with oxygen into electric power and heat. Hydrogen, at a pressure of 350 bar or 700 bar, is stored in one or more tanks on board. The fuel cells are supplied with air by a two-stage air compressor. In FCs hydrogen and oxygen are combined, generating electric power and H₂O (water) as the product, released to atmosphere via the exhaust. The FCV’s are therefore zero emission vehicles.

How much electricity from the fuel cells?
Each cell produces a voltage of about 0.7 volts and a current leading to typically up to 1 W/cm² power. Many cells are joined together in series to form a stack in order to provide the voltage and power required to feed the electric motor via a DC-AC converter.

Mercedes-Benz A-Class (Long-Version)
- F-Cell: PEM, 72 kW (97 PS)
- Electric-Asynchron-Motor: 65 kW
- Max. Torque: 210 Nm
- Storage capacity:
  1,8 kg of hydrogen @ 35MPa
- Mileage: 170 km (NEDC)
- Max. speed: 140 km/h
- Acceleration: 0-50 km/h in 4,5 s
- Battery:
  NiMh, air-cooled
  Power (av./max.): 15 kW/20 kW
  Capacity: 6,5 Ah; 1,4 kWh
Panda Hydrogen features

The Panda has 384 cells installed in 3 separate stacks assembled together, housed in the bottom of the car.

- Pure Fuel cell system
- Fuel cells PEM 70 kW stack from Nuvera
- 30 - 50 kW electric AC induction motor
- Two stage air compressor
- Carbon fibre hydrogen tank
- Storage capacity: 2,35 kg of hydrogen @ 35MPa
- Range: 300 km
- Vehicle weight: 1400 kg
- Acceleration: 50 km/h within 5 s
- Maximum speed: 130 km/h

- FUEL CELLS
  - max 70 kW
- Hydrogen tank
  - 110 litres @ 350 bar
- Air compressor
  - 200 Nm³/h @ 1.7 bar
- Electric motor
  - 30 kW nom - 50 kW max
- Power electronics
- Cooling heat exchanger

CHARACTERISTICS
- Full power fuel cell vehicle
- PEM fuel cells
- New generation air compressor
- Hydrogen tank reinforced with carbon fiber
- AC induction electric motor

*Project co-financed by the European Commission*
Refuelling, Driving & Assessing Fuel Cell Vehicles

Source of hydrogen
A large amount (over 30 mil. Nm³/yr) of hydrogen is available as a by-product of a chlorine plant at the Industrial Park Höchst. This is transported via a high pressure transport pipeline over a distance of 1.7 km to feed the dispensers at the Agip service station on the south entrance of the industrial park.

In Italy industrial hydrogen as well as that produced on-site is available. On-site production plant is operating from June 2008 and so far hydrogen from the industrial production plant of Sapio has been used. Until August 2007 the Pandas were supplied by the mobile distributor of SAPIO srl, in the campus of the hydrogen production plant near Valdaro in Mantova. Since September 2007 hydrogen has been truck transported from the industrial plant, stored and fed to the dispenser at the multi-energy ENI Station, Valdaro in Mantova.
Who can drive the FCV’s
The fuel cell vehicles in Germany and Italy are driven by project personnel who have attended the pilot training courses held at both demonstration sites. In all 26 drivers are qualified in Italy. The training was provided by CRF in collaboration with Mantova Town Hall, Sapio srl and Labter-Crea. Cars are driven in Mantova area. Over 30 drivers have been trained at Fraport and Infraserv in Germany. Pilot training is provided by Daimler AG. Cars are driven at the Frankfurt airport, in Frankfurt city and within the industrial park Höchst in different missions.

Where to park
Some attention is required for parking the present FCV’s, in particular for over-night parking. The garages should be tempered to above 1°C in winters. Covered garages are employed at Fraport and Infraserv meeting the above requirements. The Panda garages were built on purpose, within SAPIO’s hydrogen production plant, in accordance with the parameters of safety against fires, explosions, vandalism, theft, heat control, etc. An air conditioning system maintains the internal temperature above 1°C in winter.

Data acquisition and assessment
Cars are equipped on-board with data acquisition systems. Base stations, consisting of a PC, are installed near the parking areas to receive the data from the acquisition systems. At the end of each daily mission, the vehicles stop by the base station for an automatic download of mission data. This includes the distance travelled, the hydrogen consumption, speed variation with time and also average speed, the average consumption of hydrogen per km, etc. Any peculiarities or unexpected car behaviour are noted by the drivers. The base station encloses the daily data in a database from which analytic reports can be elaborated for daily, weekly, monthly, etc. performance trends. The data analysis is performed by CRF and Daimler in collaboration with the European Community Joint Research Centre in Ispra. Socio-economic assessment is an important activity in the project. Studies on acceptance and public outreach are performed. Many school visits are organised at both stations.
Zero Regio multi-energy service stations

Zero Regio has built one modern multi-energy public service station in Germany and Italy each. In addition to all the traditional fuels (petrol, diesel, bio-diesel, CNG, LPG etc.) hydrogen has been integrated in these stations. Both the stations are public. Both have small photovoltaic renewable energy supplying units as well.

Each station is described briefly in separate sections below.

ENI Service station in Mantova, Italy
Hydrogen is supplied here from different sources. Until summer 2008 hydrogen was trucked-in to the multi-energy station from the Sapio production unit in Valdaro, which produces 17,000 Nm³/h of H₂ from methane through a chemical process called Steam Reforming.

From summer 2008 onwards, hydrogen is produced on-site the multi-energy station from compressed natural gas (CNG) – that is methane 86% by volume – via an ENI proprietary reformer. This will be the first Italian refuelling station characterised by the presence of an on-site hydrogen production unit. This unit is a small reactor producing about 20 Nm³/h of hydrogen, more than needed for the project.

A stationary PEM fuel cell is installed at the station by ENI to make use of the surplus hydrogen and produce electric and thermal energy for the station.

On-site hydrogen production unit in Mantova
This unit is a chemical plant producing 99.995% hydrogen as required by the fuel cells. The heart of this plant is the reactor, which makes use of an ENI proprietary chemical process called Short Contact Time-Catalytic Partial Oxidation (SCT-CPO).

Methane, mixed with air and steam, is converted into H₂ by a high temperature catalyst in a few thousandths of a second, considered a very short contact time. The reactor is preceded by a section for the desulphurisation of natural gas and is followed by a hydrogen purification system.

The hydrogen compressor
Hydrogen produced on-site as described above or transported from Sapio industrial plant, is then compressed to over 400 bar by a membrane compressor. A pressure vessel, storing the compressed hydrogen, supplies the dispensers.

• Project co-financed by the European Commission
Agip Service station in Frankfurt, Germany

At the Agip service station in Germany both hydrogen gas and liquid can be refuelled. The LH$_2$ refuelling system consists of a 10 m$^3$ storage tank, a transfer pump and a dispenser. Liquid hydrogen is trucked in to fill the storage tank. This system is used to fill in hydrogen vehicles such as BMW’s outside the project. Project’s demonstration activity focuses on hydrogen gas refuelling.

Compression Scheme

The GH$_2$ refuelling system consists of collection of by-product hydrogen, compression up to 1000 bar with a series of compressors including an ionic liquid compressor, pipeline transport of high pressure hydrogen to the service station, a cold fill and two dispensers (one for 350 bar and one for 700 bar refuelling) at the station. For the 700 bar dispenser communication between the vehicle and dispenser is employed in order to achieve quick refuelling independent of the vehicle tank size. For passenger vehicles 3 minutes is the target refuelling time.
Hydrogen: features and technical data

Physical properties
At room temperature and ambient pressure hydrogen is an odorless and colorless gas. To obtain hydrogen in liquid form at ambient pressure (1.013 bar) the temperature must fall down to 20.39 K (-253 °C), while to solidify it the temperature should be further reduced to 14.01 K.

Hydrogen is a very light gas. Under Normal conditions (273.15 K, 1.013 bar) the density of gaseous Hydrogen is $\rho = 0.0899 \text{ kg/m}^3$, 14 times less than that of air. For this reason, when $\text{H}_2$ escapes from containers, it tends to reach the higher layers in the atmosphere and escape to interstellar space.

The density of liquid hydrogen (LH$_2$) is 70.79 kg /m$^3$, 14 times less than that of water and about 10-11 times less than that of gasoline.

Energetic properties
The Heating Value expresses the energy that can be obtained from the combustion of a given volume or mass of a fuel. The Lower Heating Value (LHV) is defined when among the combustion products in the exhaust gases water is in the gas phase as vapour. The Higher Heating Value (HHV) is defined when water has been condensed from the combustion products in the exhaust gases and its latent heat of condensation has been recovered from the user.

<table>
<thead>
<tr>
<th></th>
<th>Lower Heating Value (LHV)</th>
<th></th>
<th>Higher Heating Value (HHV)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10.8 MJ/Nm$^3$</td>
<td>3.00 kWh/Nm$^3$</td>
<td>119.93 MJ/kg</td>
<td>33.32 kWh/kg</td>
</tr>
<tr>
<td></td>
<td>12.75 MJ/Nm$^3$</td>
<td>3.54 kWh/Nm$^3$</td>
<td>141.86 MJ/kg</td>
<td>39.41 kWh/kg</td>
</tr>
</tbody>
</table>

Specific heat capacity at constant $p$: $C_p = 14,199 \text{ kJ/kg k}$
Specific heat capacity at constant $v$: $C_v = 10,074 \text{ kJ/kg k}$

The energy content of 1 Nm$^3$ of hydrogen is equivalent to 0.34 L gasoline.
1 L liquid hydrogen is equivalent to 0.27 L gasoline
1 kg hydrogen is equivalent to 2.75 kg gasoline (based on the Lower Heating Value)
Need for compression

Lower volumetric and higher gravimetric energy content of hydrogen leads to the need for compression in order to store reasonable amounts of energy on board and realise driving distances similar to vehicles based on conventional fossil motor fuels.

The Lower Heating Value of some fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>kWh/mass</th>
<th>kWh/volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>33.3 kWh/kg</td>
<td>3.00 kWh/Nm³</td>
</tr>
<tr>
<td>Methane</td>
<td>13.9 kWh/kg</td>
<td>9.97 kWh/Nm³</td>
</tr>
<tr>
<td>Natural gas (82-93% of CH₄)</td>
<td>10.6-13.1 kWh/kg</td>
<td>8.8 - 10.4 kWh/Nm³</td>
</tr>
<tr>
<td>Propane</td>
<td>12.88 kWh/kg</td>
<td>25.89 kWh/Nm³</td>
</tr>
<tr>
<td>Butane</td>
<td>12.7 kWh/kg</td>
<td>34.39 kWh/Nm³</td>
</tr>
<tr>
<td>Gasoline</td>
<td>12.0 kWh/kg</td>
<td>8.8 kWh/L</td>
</tr>
<tr>
<td>Gas oil</td>
<td>11.9 kWh/kg</td>
<td>10.0 kWh/L</td>
</tr>
<tr>
<td>Town gas*</td>
<td>7.6 kWh/kg</td>
<td>4.54 kWh/Nm³</td>
</tr>
<tr>
<td>Town gas* (% in volume)</td>
<td>51%H₂</td>
<td>18%CO</td>
</tr>
</tbody>
</table>

Hydrogen: some safety features

In ambient conditions, hydrogen is neither toxic nor corrosive or oxidising. It is not radioactive, it does not decompose, it does not pollute water and it is not carcinogenic.

Density and coefficient of diffusion

Hydrogen is the chemical element with the lowest mass and smallest atomic radius. It is much lighter than air and its diffusion coefficient is four times higher than that of natural gas (mainly methane). For these reasons it tends to escape from tanks easily and quickly disperse in the air.

Flammability in air

Hydrogen gives flammable mixtures with air in an interval ranging from 4.0 to 75.0% by volume of hydrogen. To make a comparison, the range of flammability of air-methane mixtures varies from 5 to 15% by volume of CH₄. This interval ranges from 1.0 to 7.6% by volume for gasoline vapour.

The Ignition Energy of air-hydrogen mixtures is 0.02 mJ; very low when compared with air-methane mixtures of 0.29 mJ and with mixtures of gasoline-air of 0.24 mJ.

So, compared to air-hydrocarbon mixtures, air-hydrogen mixtures are more likely to ignite due to the wider flammability range and lower ignition energy threshold.

Hydrogen burns very quickly and the flame, almost invisible in daylight, consists of a thin vertical plume. Since the flame drains the tank quickly, the damage is less serious than those produced by hydrocarbon flames.

Moreover, the product of the combustion reaction of hydrogen and oxygen is water vapour.
Preventive Measures

The primary precautions must include avoiding leaks and the formation of explosive mixtures, by establishing the support infrastructures outdoors together with adding inert gases (such as nitrogen) and installing vents, etc.

Secondary precautions mainly consist of avoiding sources of flames and other triggers of ignition of any type (electrostatic or mechanical sparks).

Tertiary care should aim to minimise damage in case of explosion. This can be achieved with cement barriers, with containing systems that reveal the explosion, with devices that interrupt the flow of hydrogen, with fire extinguishing systems, etc..

Fuel cell vehicles and safety

The FCV’s used as demonstration fleets in Zero Regio are inherently safe. They are homologated today as prototypes and the rules imposed by the new European directive ECE (2008) will be employed in near future. These vehicles are equipped with the most advanced safety devices. The hydrogen components are certified by the respective producers. The performance of the vehicles has met all the expectations with high availability and no need for extra ordinary maintenance practices.

In the process of homologation, the cars have passed an impressive series of stringent tests on their electromagnetic compatibility, the functionality of their sensors and control systems, the level of protection from electric shock and the braking system. Finally, repeated tests were performed, concerning the refuelling at different pressure levels.

Hydrogen tanks

The cylinders installed to store hydrogen on board are built in a composite material (thermoplastic liner and carbon fibres). According to the international technical code, the pressure outbreak of the cylinder must be at least over 2 times the maximum operating pressure; rupture tests of the cylinders used have met these standards. In Italy rupture tests of the storage cylinders have been performed successfully up to 2.6 times the maximum operating pressure of 350 bar. Further research is in progress to reduce the costs.
Control and safety valves
Different safety and regulating valves, both in the tank and in the hydrogen distributing line are used.

A Stop Valve (normally closed), placed in the tank, hermetically blocking the release of hydrogen in the event of collision, pipeline ruptures, user charges (engine or fuel cell) faulty or off, etc. Hermetic sealing also happens when the key is removed from the dashboard. The mass of hydrogen remaining in fuel lines is negligible.

A Calibrated-Diaphragm (pressure relief valve PRV) to a pressure of security, which comes into action in the event of abnormal surge.

A Fuse-Valve (PRD) calibrated to 104°C, which is intended to evacuate the gas in the event of fire, to prevent the rupture of the cylinder.

One Excess Flow Valve that protects the mechanical system from failures due to excessive flow, for example, if experiencing a gas leak; the valve immediately detects the loss and reacts by stopping the flow.

Hydrogen concentration sensor
In addition to the sensors for temperature and pressure, the vehicle is equipped with a hydrogen concentration sensor, placed in the rear of the passenger compartment. The sensor is positioned at the top because, as mentioned earlier, hydrogen being much lighter than air will escape to the top of the passenger cabin. The concentration of hydrogen is measured in ppm (parts per million) and the signalling is both visual and acoustic: a special icon on the display begins to flash, while a beep is heard. When the hydrogen concentration sound alarm begins to operate (> 20,000 ppm) the control system activates the vehicle’s automatic shutdown system.

Some difficulties experienced during the Project
The short project description presented in this booklet will be incomplete if some of the difficulties experienced in the project are not stated. Due to the lack of any European regulations for building hydrogen refuelling and distribution facilities, the approval formalities for hydrogen infrastructure in Italy turned out to be rather cumbersome and time consuming. This delayed the project progress in Italy. A legislation has been in effect from August 2006 in Italy for hydrogen distribution facilities and it is expected that for future hydrogen public refuelling stations it will be more convenient to obtain building approvals. Experience gained in Zero Regio will be valuable in future projects on hydrogen infrastructure in Italy.

Similar difficulties have been experienced to obtain homologation of FCV’s in Italy. Inspite of successful testing of the vehicles it has been extremely difficult to get permission to tank them up to 350 bar. Presently the vehicles could be driven only with storage up to 200 bar. This pressure limitation was not imposed for refuelling facilities.

Efforts and projects are underway at the EC to obtain harmonised approval procedures all over Europe to solve the above problems. Building approvals for hydrogen infrastructure in Germany were obtained more or less on time. Operational difficulties have been experienced with the ionic liquid compressor, this being the first prototype for a 900 bar application. For sure this experience will lead to improvements in this new technology, which has a potential for the future.

Future prospects
Energetic and environmental superiority of the fuel cell vehicles has been demonstrated in the project Zero Regio. New infrastructure systems have been developed and demonstrated. High pressure pipeline transport of hydrogen, onsite hydrogen production, new compression systems developed and tested have future potentials. Amounts of hydrogen available at both sites are sufficient for larger fleet demonstrations. Socio-economic studies and assessments accompanying the technical investigations provide insight and ways for achieving quicker public acceptance and market penetration. In short the facilities and know-how developed within Zero Regio are well suited for larger demonstration projects planned for the future, provided larger vehicle fleets are available.
Comune di Mantova
Regione Lombardia

Partners

www.zeroregio.com

Project co-financed by the European Commission