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RECONSTRUCTION OF EXISTING CITY BUSES ON DIESEL FUEL FOR DRIVE ON HYDROGEN

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Abstract:
The global energy and environmental situations have intensified the use of alternative and clean fuels. This is true for city buses, taxis, delivery vehicles and personal cars. The unique properties of hydrogen make it suitable as a fuel for vehicles powered with both, internal combustion or electric engines, too. However, the problems associated with the production and storage of hydrogen currently limits the application of pure hydrogen as engine fuel for vehicles. As a contribution to the global strategy, this paper focuses on designing of city bus for hydrogen power using an original propulsion system. The concept of gaseous hydrogen storage under high pressure is analyzed here. In the bus on hydrogen, the cylinders with this fuel are mounted on the roof because of reasons of little available space. In the paper is proposed a method for the reconstruction of the bus, with respect to the installation of specific components for the use of compressed hydrogen gas as well as for the implementation of fire protection system.

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1. INTRODUCTION

The European transport industry represents (6.3%) of the Union's GDP and employs nearly 13 million people [1].

However, our transport systems and habits are too dependent on oil, which will become scarcer and is a serious polluter of our planet. Transport accounts for about (63%) of oil consumption and (29%) of all CO_2 emissions. Unless the present trends are corrected, the economic costs of traffic congestion will increase by about (50%) by 2050, the accessibility gap between central and peripheral areas will widen and the social costs of accidents and pollution will continue to rise [1].

Trucks, buses and coaches produce about a quarter of CO_2 emissions from road transport in the EU and some (5%) of the EU's total greenhouse gas emissions a greater share than international aviation or shipping. The European Commission has therefore set out a strategy to curb CO_2 emissions from these Heavy Duty Vehicles (HDVs) over the coming years. The EU has so far put a range of policies in place aiming to lower emissions from the sector. These include [1]:

- aviation has been included in the EU emissions trading system;
- a strategy is in place to reduce emissions from cars and vans, including emissions targets for new vehicles;
- a strategy for reducing heavy duty vehicle fuel consumption and CO_2 emissions;
- a target is in place to reduce the greenhouse gas intensity of fuels;
- rolling resistance limits and tire labelling requirements have been introduced and tire pressure monitors made mandatory on new vehicles;
- legislation encouraging national authorities to deploy gas and electricity infrastructure; and,
- Public authorities are required to take account of life time energy use and CO_2 emissions when procuring vehicles.

In addition to these measures influencing vehicle emissions, the EU also supports stronger use of public transport as well as low-emission means of transport.

European transport research contributes to finding solutions to the increasing mobility of

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people, with low-carbon technologies, clean vehicles, smart mobility systems and integrated services for passengers and freight. Efficient transport is a fundamental condition for sustainable prosperity in Europe. Transport provides citizens with essential means of mobility and contributes to employment, growth and global exports.

In the transport sector, research is at the core of developing new technologies for greener, smarter, more efficient transport means and innovative solutions for safer, more sustainable and inclusive mobility.

In accordance with the above strategies, the paper analyses the use of hydrogen as a fuel of mobile systems in the transport sector. As a special contribution, it was proposed technical solution for the reconstruction of the existing buses on diesel fuel, for drive on hydrogen. The technical solution is applicable and during the production of new types of buses, with original engine for this gaseous fuel.

1.1 Hydrogen as fuel for motor vehicles

All gases are good fuels for Otto engines: a mixture with air is high quality and ready for complete combustion, the work of engine is economical, with lower exhaust emissions and extended oil and engine life.

Hydrogen is one of two natural elements that combine to make water (in a fuel cell hydrogen combine with oxygen to make water and electricity). Using hydrogen as a fuel for motor vehicles is just one of many possible applications. The greatest environmental benefit of using hydrogen as fuel is the dramatic reduction of exhaust gases in city bus for example, (figure 1).

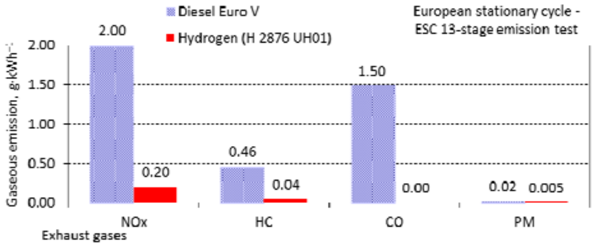


Fig. 1. Exhaust emissions reduction by application of hydrogen engine instead of diesel in city bus

Combustion of hydrogen does not produce CO_2, or Sulphur emissions. Compared to the equivalent diesel engine, nitrogen oxide (NOx) and hydro carbon (HC) emissions are (80%) lower, carbon monoxide (CO) emission is eliminated, and there are around zero particulates matter (PM) [2].

In accordance with the latter, hydrogen is the perfect alternative energy source from an ecological point of view. Hydrogen is good for the communities, because hydrogen buses, as example, will provide clean, quiet and zero-emission transportations. But there are two sides to every coin.

On the one hand, in use, hydrogen can be easily transported and storage poses no ecological problems. As a fuel it can replace the fossil fuels, petrol and diesel, and has the further advantage that is combustion in the engine products no CO_2.

On the other hand, since elemental hydrogen is rare on earth, it needs to be produced. Therefore, hydrogen is considered to be secondary energy form and as such has to be produced from variety of primary sources.

2. PROTOTYPE BUS DESIGN

2.1 Gaseous hydrogen storage and propulsion system demonstrated on city bus

Five years ago in the Republic of Serbia it was attempting the production of city buses with compressed natural gas (CNG) drive [3]. After that, bearing in mind the experience of leading manufacturers of buses, the design engineers from domestics Production Company in Kragujevac, have started the work on a prototype of fully low floor city bus with hydrogen propulsion system. The prototype bus is equipped with the original stoichiometric naturally aspirated gas engine. Engine is designed to work only on compressed gaseous hydrogen (CGH_2), so that their structural characteristics and projected operating cycle, ensures maximum dynamism and efficiency.

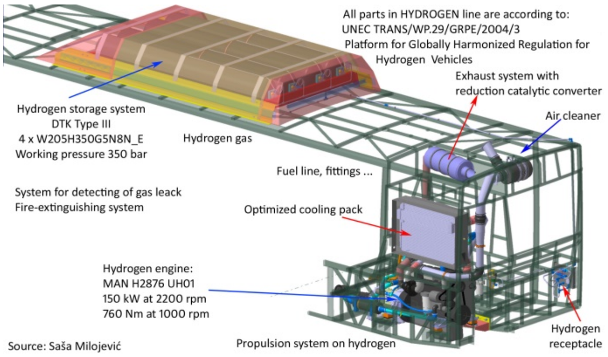
On the (figure 2) are shown parts of the installation for CGH_2 supply from bus roof mounted gas cylinders to the engine that is proposed to prototype version of HyS bus.

All parts inside of the CGH_2 installations are designed and approved according to the global platform for harmonization of legal requirements for road vehicles (regulation UN ECE WP29) [4].

The retrofit of the diesel bus into a dedicated hydrogen vehicle begins with the joining of the CGH_2 cylinders with the original rack, (figure 2), to the bus roof. It was selected CGH_2 storage system that includes type III cylinders composed of an aluminium 6061 liner reinforced by carbon fiber in epoxy resin (Dyne-cell®), with a favorable ratio between weight and volume (0.3–0.4 kg·l^{-1}) [5,6].

During the retrofit, we have considered the existing regulations regarding the dimensions and gross vehicle weight. Specifically, we took into account the requirements relating to the correct joining of the main parts of the CGH$_2$ fuel line and gas cylinders, all legislated by regulation UN ECE WP29 [4].

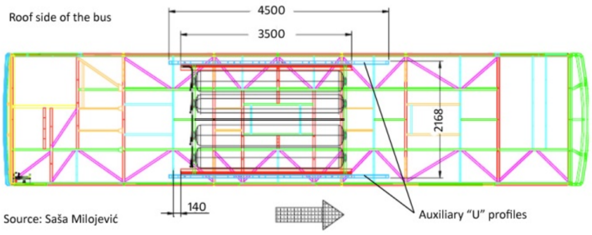
The position of the new center of gravity is calculated, taking into account the added weight of the CGH$_2$ cylinders with the rack on the bus roof.



Source: Saša Milojević

Fig. 2. Sketch of the CGH$_2$ fuel line equipment installed on the bus

According to requirements for vehicles of categories M3 and N3, (resistance to destruction of the roof structure during deceleration of 6.6·g in the longitudinal and 5·g in transverse direction), we calculated and accepted the mounting of CGH$_2$ cylinders assembly to carry through the auxiliary "U" profiles, (figure 3) [4,7].



Source: Saša Milojević

Fig. 3. CGH$_2$ cylinders rack position on the bus roof

2.2 Hydrogen engines and combustion concepts

First deployed in mobile applications the late 19th century the internal combustion engine (ICE) is the most indispensable technological precondition for today's road transportation. Substituting conventional fuels (gasoline and diesel) by hydrogen in road transport can be achieved by introducing to the market new vehicles ex-factory equipped with hydrogen engines, or as a first step, by converting engines of existing vehicles to run on hydrogen.

The design and operation of hydrogen engine is typically based on natural gas engine, requiring an ignition system inside off the spark ignite the fuel mixture. As example, (figure 4) shows the picture of proposed hydrogen engine maker MAN with associated equipment specified bellows [2].

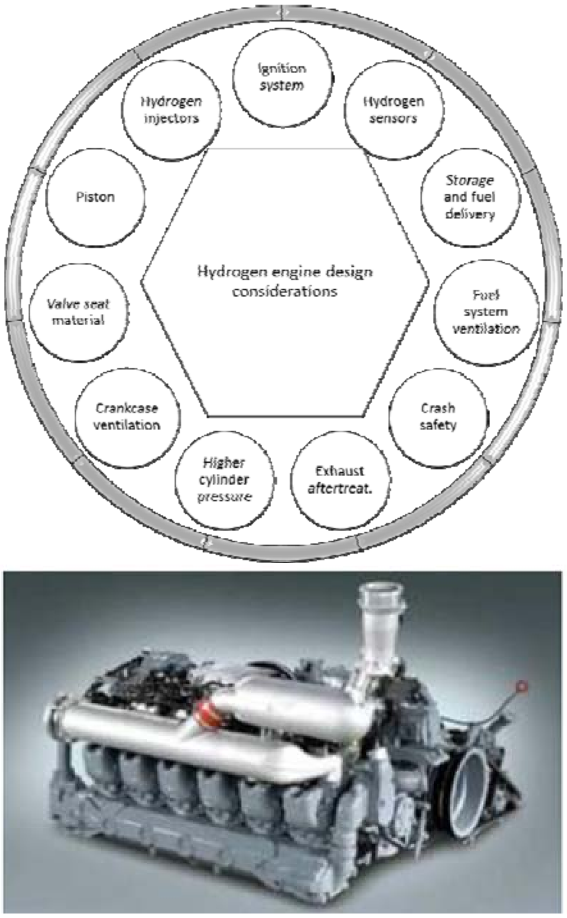


Fig. 4. Hydrogen engine maker MAN type H2876 UH01 and associate equipment

Lean-burn hydrogen engines for HDV application were popular due to their lower engine-out NOx emissions and higher fuel efficiency compared to stoichiometric engines. A modern, closed-loop electronically controlled lean-burn hydrogen engine can achieve Euro V or lower emission levels for both NOx and PM. For optimal emission performances, these engines should be equipped with appropriate optimized oxidation catalyst after-treatment.

To meet the most stringent Euro VI emission standard for NOx, it is necessary to switch to stoichiometric combustion combined with exhaust gas recirculation (EGR) and three-way catalyst after-treatment.

The exhaust emission of the proposed hydrogen engine maker MAN type H2876 UH01 achieved according to ESC emission test is presented on the (figure 1). This is naturally aspirated engine with applied stoichiometric combustion and external mixture formation.

2.3 Hydrogen as an additive to diesel fuel

One of options for existing buses can be the use hydrogen as an additive where are possible two main options:

- hydrogen can be added to the intake air of a diesel engine, with the aim of improving the combustion process characteristics; and,
- hydrogen can be injected into the exhaust system to increase temperature for regeneration of the diesel particulate filter or trap inside of after treatment system.

3. INSTRUCTIONS FOR HYDROGEN BUSES SAFETY PROJECTING AND SERVICING

Before discussing the second design features that are recommended for hydrogen buses and their fuel equipment, it is important to understand what makes this fuel different from natural gas, gasoline or diesel. The items below summarize the basic differences between the properties of gaseous and liquid fuels [8]:

- hydrogen CGH_2 fuel systems store fuel at approximately 35−70 MPa;
- unlike gasoline vapors, natural gas and hydrogen are both lighter than air and in gaseous form at atmospheric conditions. This property allows these fuels to quickly rise and disperse in the unlikely event of a leak. Although lighter than air fuels have safety advantages, roofs and ceilings of maintenance garages must be designed without any unventilated "pockets" in the ceiling space that could trap gas. Liquid fuels such as gasoline and diesel will form a pool of liquid with a vapors layer above;
- CNG and hydrogen both have an ignition temperature of around 480−650 °C, whereas gasoline is approximately 260−430 °C and diesel is less than 260 °C. This relatively high ignition temperature for CNG and hydrogen is an additional safety feature of these fuels. To ensure a safe environment in the maintenance garage, the surface temperature of equipment that could contact a gas leak is usually limited to 400 °C; and,
- natural gas has a very selective and narrow range of flammability-that is, the mixture of gas in air that will support combustion (between 5% and 15% natural gas in air by volume-ratios outside of this range will not support combustion). In other words, with less than (5%) natural gas in air the mixture is too lean and will not burn, and with greater than (15%), the mixture is too rich and will not burn. Maintenance facilities must be designed to quickly and automatically remove the risk caused by a leak, using ventilation to dilute then exhaust any leaked gas.

According to previous, ventilation systems in the garages for hydrogen fueled buses must be designed that typically provides between (5−6) air changes per hour (ACH) (the requirement is for 425 $l\cdot min^{-1}$ per $1\cdot m^2$ of ventilated area). The conclusion is that this is no additional airflow requirement and cost, according to existing diesel facilities designed for a baseline ventilation rate of (4−6) ACH.

In developing the bus safety concept, the fundamentally conceivable damage events were assumed. This is structured as follows:

- prevention of an explosive atmosphere in the buses engines compartment by means of leak monitoring of the hydrogen supply line in combination with fire suppression system;
- continuous monitoring of the garages air and a powerful ventilation system; and,
- prevention of ignition sources due to the explosion-protected design of electrical devices.

3.1 Fire protection of buses on hydrogen

Fuel can be dangerous if handled improperly. Gasoline and diesel are potentially dangerous fuels, but over time we are learned to use them safely. The same is true with liquefied petroleum gas and natural gas, as well as hydrogen.

Fire onboard buses may be caused by internal or external factors. Internal factors include events such as electrical short circuits, excessive temperature of bus components including the braking system, the turbo compressor, and the exhaust pipe in combination with combustible materials including polymeric materials, oil, dust and debris. Experience shows that fires usually start in the engine compartment.

As far as external causes are concerned we can mention human error during maintenance (use of open flame), vandalism and propagating fires from nearby vehicles or infrastructure.

Related to the previous, HyS bus is equipped with a fully automatic fire suppression system for the engine compartment and possible separate heating areas (figure 5).

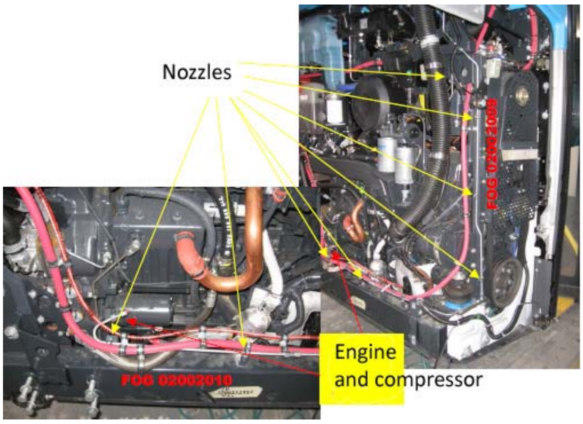


Fig. 5. Nozzles of the fire-extinguishing system, positioned in the engine compartment

The system is activated hydro-pneumatically and works without any power supply (figure 6). When releasing, the suppressant is sprayed through nozzles that break down the fluid into pillar-shaped mist clouds that cool the temperature and force the air out. The suppressant is mainly based on anti-freeze water. The releasing time is normally between (3–5) seconds and the effective suppression time is normally (50–75) seconds.

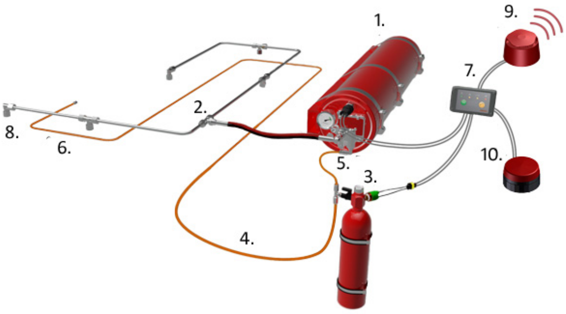


Fig. 6. Overview of fire suppression system components

In case of fire, one liter of extinguishing fluid absorbs 540,000 kilocalories and produces 1,700 liters of water mist at the same time.

The piston accumulator with extinguishing fluid, pressurized to (10-10.5) MPa (1) is connected to a distribution system with a distribution hose and pipe as well as patented nozzles (2). The detector bottle (3) pressurized to between (2.4 and 3.1) MPa (depending on model) is connected to a detection system made of polymer tube (4). The piston accumulator and detector bottle is inter-linked via a patented valve (5) that keeps the piston accumulator closed when the pressure in the detector bottle is normal.

If there is a fire the detection tube bursts (6), the pressure falls in the detection system and the valve in the piston accumulator opens. The pressure switch warns the driver via the alarm panel (7) sounds (9) and light signals (10). The extinguishing fluid is pressed through the distribution system's nozzles and a water mist is spread in the protected compartment (8).

Scheme of Installation the component system for detecting and fire extinguishing on the bus is shown in (figure 7).

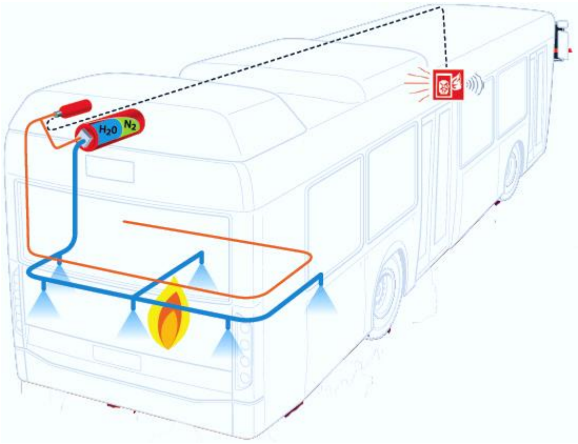


Fig. 7. Overview of fire suppression system components and where in a bus they are positioned

4. ON-BOARD STORAGE OF HYDROGEN

If hydrogen is to be used as the primary energy source, then the vehicle must be able to store the hydrogen on-board, or have an efficient on-board fuel reformer. At the present time, hydrogen storage modes on board a vehicle fall into three types to be considered: Hydrogen can be stored as a compressed gas, cryogenic liquid or in a metal hydride, due to its low volumetric energy density. To make clearer the energy differences, the (table 1) shows a comparison between various forms of hydrogen and diesel fuel [2].

Table 1. Comparison of hydrogen and diesel fuel energy densities

Energy content of:	› is equivalent to:
$1 \cdot Nm^3$ of gaseous hydrogen	0.30 liters of diesel
1 liter of liquid hydrogen	0.24 liters of diesel
1 kg of hydrogen	2.79 kg of diesel fuel

Storage in liquid form (LH_2) at about (–253 ˚C) and pressure of 1·MPa, allows useful volumetric and gravimetric densities to be achieved, similar to CNG. However this requires cylinders with extensive thermal insulation, to minimize evaporation. Hydrogen's low boiling point makes liquefaction very energy intensive.

Storage of hydrogen on substrates, in absorbed form, particular on metal hydrides, exhibits very attractive volumetric density, but very low gravimetric density. Moreover, the kinetics, temperature and cycling pressure remain, along with other issues, among the difficult points yet to be mastered.

4.1 On-board storage of hydrogen under pressure

High pressure cylinders are classified into four categories. Type I cylinders are steel liner, while type II cylinders are steel liner wrapped with filament windings (usually glass fiber) around the cylindrical part, (figure 8) [5].

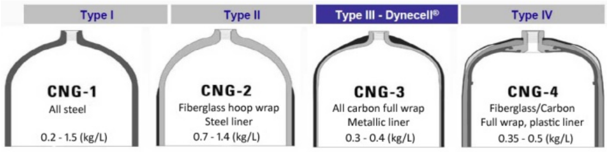


Fig. 8. Comparative analysis of the (mass/volume) ratio of various cylinder types (example CNG cylinders)

Type III are made of composite materials (initially fiberglass, and increasingly carbon fiber), with a metal liner initially aluminium, lately in steel. Type IV cylinders are composite (mainly carbon fiber) with a polymer liner (mostly thermoplastic polymers, of the polyethylene or polyamide type).

A schematic of a typical high-pressure CGH_2 storage composite cylinder is shown in (figure 9). Their low weight meets key targets, and the cylinders are already commercially available, well-engineered and safety-tested. They also meet codes that are accepted in several countries for pressures in the range of (35-70) MPa.

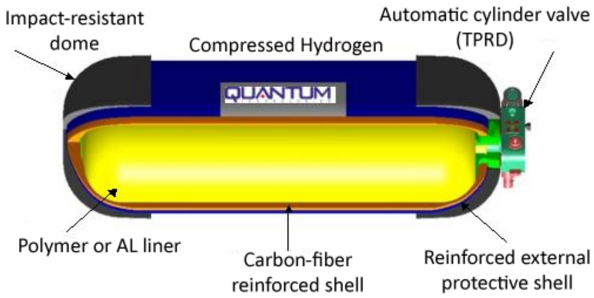


Fig. 9. Schematic of a typical CGH_2 cylinder

According to the author's experiences about the introduction of CNG buses in urban transport in Kragujevac city and Republic of Serbia, it is selected the Type III cylinders [3]. On the (figure 2), presented is CGH_2 cylinders rack position on the bus roof.

On the bus roof need to be mount gas rack with minimum seven (7) CGH_2 cylinders type "W205H", with a total water capacity of 1435 l, (figure 10). The weight of one cylinder was about 92.4 kg (0.308 $kg \cdot l^{-1}$). The composite cylinders are lightweight cylinders for the storage of CNG and CGH_2.

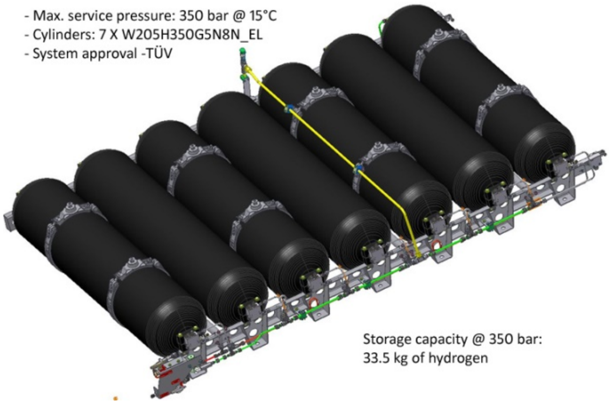


Fig. 10. CGH_2 cylinders rack W205H for bus application

Selected CGH_2 cylinders for working pressure of 35 MPa or 70 MPa used for bus prototype are equipped with automatic safe valve type BV-350, (figure 11), or BV-700 [5].

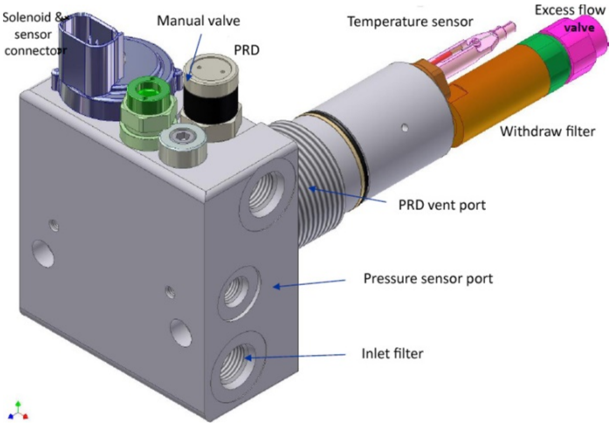


Fig. 11. Automatic cylinders' valve type BV-350

4.2 Hydrogen market supply and buses filling

The security of the CGH_2 supply is required to continue the introductions of hydrogen vehicles in city transport.

The source-to-tank CO_2 emissions for hydrogen depend on the primary energy sources and productions method. Hydrogen can be produced from a number of CO_2 neutral sources, such as renewable electricity, biomass, and nuclear power.

Large-scale, industrial hydrogen production from all fossil energy sources can be considered a commercial technology for industrial purposes, though not yet for utilities.

A principle sketch of hydrogen distribution from a natural gas or solar based centralized hydrogen production plant is presented in (figure 12). Hydrogen from a central production plant could be delivered to the filling stations via pipeline or with bulk transport, with trucks and trailers.

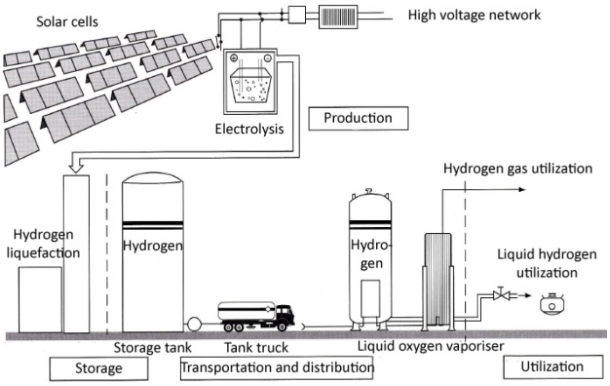


Fig. 12. Principle sketch for large scale centralized hydrogen production with CO_2 capture

There are a number of hydrogen pipeline systems that currently exist to serve the industrial market. These include systems in the North of Europe, (covering The Netherlands, Northern France and Belgium), Germany (Ruhr and Leipzig areas), UK (Teesside) and in North America (Gulf of Mexico, Texas-Louisiana, California). In all the pipelines total around 1500 km in Western Europe, with around 900 km in the USA. Smaller systems also exist in South Africa, Brazil, Thailand and Indonesia. Overall, these pipeline lengths are tiny when compared to the natural gas distribution pipeline system, which amounts to approximately 1,850,000 in EU25 and 1,750,000 in the USA [9].

One possibility for rapidly expanding the hydrogen delivery infrastructure is to adapt part of the natural gas delivery infrastructure to accommodate hydrogen. Converting natural gas pipelines to carry a blend of natural gas and hydrogen (up to about 20% hydrogen) may require only modest modifications to the pipeline; converting existing natural gas pipelines to deliver pure hydrogen may require more substantial modifications. Current research and analysis are examining both approaches.

Second, real option is bulk transport of CGH_2 under standard pressure. As example, a trailer with CGH_2 can deliver (300-600) kg of this fuel [5]. One delivery will thus only last for a very limited span of time. Unless two trailers are parked on site, the schedule for exchanging them will be tight and has to work on a strict just in- time basis to guarantee fuel supply for the buses, (figure 13).

Fig. 13. Cube for bulk transport of CGH_2

Compared to liquefaction, the energy demand for compression is significantly less (depending on input and output pressure). Gaseous hydrogen, once filled into a pressure vessel, will remain there without losses.

As already pointed out, the volumetric energy density of hydrogen gas under ambient conditions is much lower than that of gasoline or diesel. Hydrogen is therefore need to be compressed in order to reduce the size of the filling station storage, to keep space requirements on-board the vehicle at a reasonable level, and to ensure enough range for daily bus operation. This is not entirely new as it also applies to natural gas, but the volumetric energy density of hydrogen compared to methane

One solution for compensating this disadvantage is to move to higher on-board gas pressures, from 20 MPa (standard technology for mobile applications so far, both hydrogen and natural gas) to 35 MPa, and most likely 70 MPa in the future. The main components of a filling station for CGH_2 storage and dispensing are compressor, storage vessels and dispenser with filling nozzle, (figure 12).

LH_2 performs about as well as CNG at 20 MPa regarding volumetric energy density, even when considering the volume for the insulation of the cryogenic tank. Liquid hydrogen storage can be employed both at stations and in vehicles. London demonstrates external supply of LH_2 and its storage on site at the station. Liquid on-board storage is difficult to be realized as buses have sufficient room on the roof to accommodate pressure vessels to enable the desired range. The main components for a filling station for CGH_2

dispensing with LH_2 storage are cryogenic vessel, cryogenic pump for pressurizing the liquid, vaporizer and dispenser.

Other equipment at both types of station is, for example, hydrogen sensors and other safety equipment, depending on local or country-specific standards (e.g. flame detectors, fire suppression system installations etc.)

5. CONCLUSION

Hydrogen is considered to be an ideal energy carrier in the foreseeable future. During combustion in ICEs, only by-product is water or water vapor (if air is used for flame combustion of hydrogen, small amounts of NOx are produced).

Use of Compressed Gaseous Hydrogen as an alternative fuel is an effective, currently available way to help solve environmental and fuel resource problems. In fact, hydrogen has safety advantages compared to gasoline and diesel: it is non-toxic, neither carcinogenic nor corrosive gas, and has no potential for ground or water contamination in the event of fuel release.

Hydrogen production capacities are limited, and that in order to ensure reliable supplies for users an efficient and practical infrastructure must first be established. The introduction or expansion of hydrogen vehicles use will require investment in new refueling infrastructure.

It can be produced from water by using a variety of energy sources, such as solar, nuclear and fossils, and it can be converted into useful energy forms efficiently and without detrimental environmental effects.

When deciding to introduce or expand the use of hydrogen buses, one must evaluate the appropriate hydrogen engine technology. Lean-burn hydrogen engines for HDVs application were popular due to their lower engine-out NOx emissions and higher fuel efficiency compared to stoichiometric engines. To meet the most stringent Euro VI emission standard for NOx, it is necessary to switch to stoichiometric combustion combined with EGR and three-way catalyst after-treatment.

By installing the gas rack with cylinders for gaseous hydrogen storage of Type III and with projecting the equipment of the bus according to the UN ECE WP29, was achieved great progress from the aspect of vehicle safety in traffic.

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