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APPLICATION OF HYDROGEN AS AN ALTERNATIVE FUEL FOR PROPULSION SYSTEMS IN CITY BUSES OVERVIEW

ABSTRACT: Engine 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. The properties of hydrogen make it suitable as a fuel for vehicles powered with both, internal combustion engines or indirectly for electric engines inside of fuel cell propulsion systems, too.

The global energy and environmental situations have intensified the use of alternative and clean fuels. This is reality in domain of city buses, taxis, delivery vehicles and personal cars. However, the problems associated with the production and storage of hydrogen currently limits the application of pure hydrogen as engine fuel in vehicles. This paper represents our designing proposition of a low-floor city bus for hydrogen power using an original propulsion system. The concept of gaseous hydrogen storage under high pressure is analyzed here.

Hydrogen from the production plant to the vehicle`s engine, requires processing including external energy to make it suitable for the use as fuel. Usually, at a reciprocating compressor`s fueling station, the hydrogen is compressed and provided to vehicles, where it is stored as compressed gaseous hydrogen under pressure of about 35 MPa up to 70 MPa, according to the characteristics of used storage system. For application inside of low-floor city buses, hydrogen cylinders have to be installed on the roof for reasons of space. In addition, regarding to the lack of available information, the paper demonstrates an overview about safety regulations for vehicles with regard to the installation of specific components in hydrogen fuel line.

KEYWORDS: Hydrogen buses, Safe vehicle, Emission, City transport

INTRODUCTION

For almost forty years now, automotive engineers from all over the world have been engaged in the intensive researches to find a technically and economically viable alternative to gasoline or diesel fuels. Research efforts in this domain begin back in the late Sixties and were spurred on by the oil crisis in 1973. At the time, with development work on alternative solutions still in its infancy, the industrial nations' economic dependency on oil was made eminently clear [4]. Today, the availability of improved and alternative propulsion systems is not only a question of ensuring economic and political independence. The main concern now is to conserve available resources and reduce carbon dioxide (CO_2) emissions from the combustion of fossil fuels, alleviating the associated environmental problems.

Eco-friendly transport is a fundamental condition for sustainable prosperity all over the world. Transport provides the mobility of citizens and contributes to the growth of employment and global exports. The European transport industry as example represents about 6.3% of the Union's GDP and employs nearly 13 million people. Transport accounts for about 63% of oil consumption and 29% of all CO_2 emissions [4].

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Nowadays research aims to strengthen the competitiveness of transport and to develop a better transport system for the benefit of all. Related to previous facts, after confirmed experience with natural gas powered buses, we decided to start our researches in domain of hydrogen propulsion systems for city buses, too. According to the latter we would like to thank you to any readers and colleagues to understanding our starting effort about.

Hydrogen as Fuel for Motor Vehicles

Over 90% of the universe is made of hydrogen. It is lightest chemical element (1.00794 $g \cdot mol^{-1}$), lighter then helium. At room temperature, hydrogen is a colourless and odourless gas. Hydrogen has high energy content per weight, nearly three times as much as gasoline, but the energy density per volume is low at standard conditions, so it needs to be stored under pressure or as a cryogenic liquid. Difference in the density of energy of different fuels which used for motor vehicle is presented on the Figure 7 [4].

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 requires a small amount of energy to ignite. It has a wide flammability range; it can burn when it makes up 4 to 74% of the air by volume. It burns with a pale blue, almost-invisible flame [4].

The environmental benefit of using hydrogen as fuel for motor vehicles is the reduction of exhaust gases. Combustion of hydrogen does not produce CO_2, or sulphur emissions. Compared to the exhaust emission of equivalent diesel engine in city bus, as example, 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), Figure 1. Second example is a fuel cell, inside of the hydrogen reacts with Oxygen to make water and electricity [1,4].

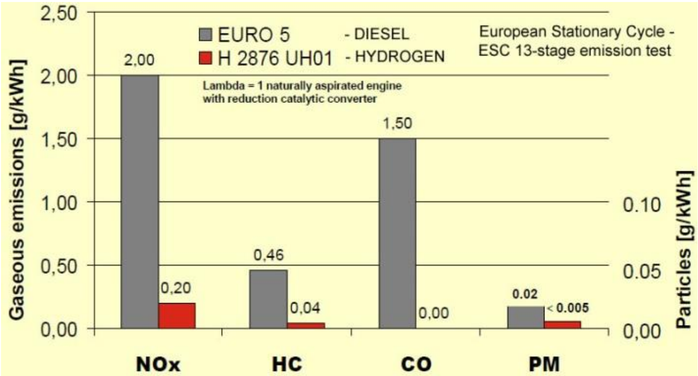


Figure 1 Exhaust emissions reduction by application of Hydrogen engine instead of diesel in city bus

In accordance with the latter, hydrogen is good for the communities, because hydrogen buses, as example, will provide clean transportations with lower noise. 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. On the other hand, since elementary hydrogen is rare on earth, it needs to be produced. Therefore, hydrogen is considered to be secondary energy form and as such need to be produced from variety of primary sources, Figure 2 [4].

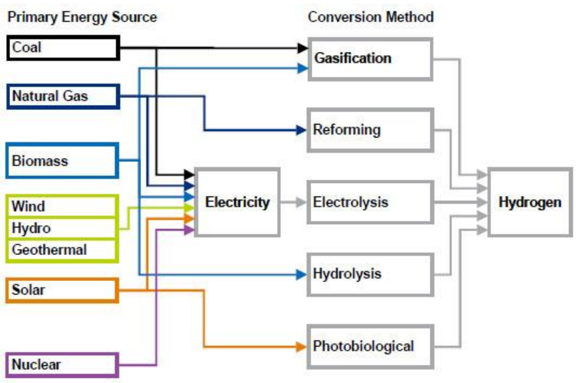


Figure 2 Some of the energy sources and processes that can be used to produce hydrogen

Two most popular means for producing of hydrogen are by steam methane reforming of natural gas as fossil source and electrolysis. It is the fact that hydrogen production capacities are limited and that in order to ensure reliable supplies for users, an infrastructure must be established first. Hydrogen can be used in vehicles, but this also requires the development of a national hydrogen refuelling infrastructure.

PROTOTYPE BUS DESIGN PROPOSITION

Options of gaseous hydrogen storage and propulsion system demonstrated on low floor city bus

Five years ago in the Republic of Serbia it was attempting the production of city buses with Compressed Natural Gas (CNG) drive. After that, we have started the work on prototype of fully low floor city bus with similar hydrogen propulsion system. The prototype bus needs to be equipped with the original internal combustion engine (ICE) designed to work only on compressed gaseous hydrogen (CGH_2).

Figure 3, shows 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 regulation UN ECE TRANS/WP.29 – Global Platform for Harmonization of Legal Requirements for Road Vehicles [5,6].

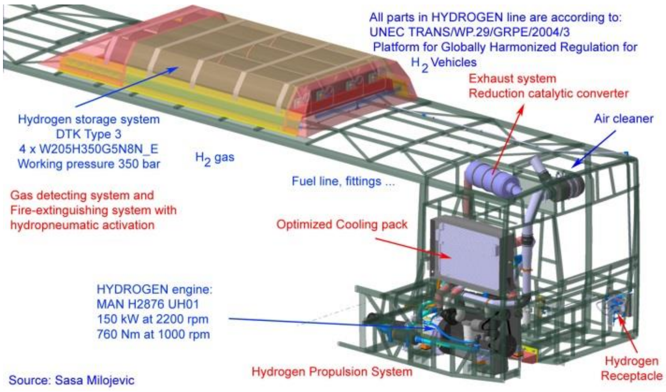


Figure 3 Sketch of the CGH_2 fuel line equipment installed on the bus

The retrofit of the existing diesel bus into a dedicated hydrogen vehicle begins with the joining of the CGH_2 cylinders with the original rack to the bus roof, Figure 3 and Figure 9. We propose CGH_2 storage system that includes type III cylinders composed of an aluminum 6061 liner reinforced by carbon fiber in epoxy resin (brand Dyne-cell®), with a favorable ratio between weight and volume (0.3 kg/L to 0.4 kg/L) [5].

During the retrofit, need to be considered existing regulations regarding to 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 TRANS/WP.29 [6]. The position of the new center of gravity is depending of the added cylinders' weight with the rack on the bus roof.

According to requirements for vehicles of categories M3 and N3, (resistance to destruction of the roof structure during deceleration of $6.6 \cdot g$ in the longitudinal and $5 \cdot g$ in transverse direction), we calculated and accepted the mounting of CGH_2 cylinders assembly to carry through the auxiliary steel "U" profiles, Figure 4 [2,3,6].

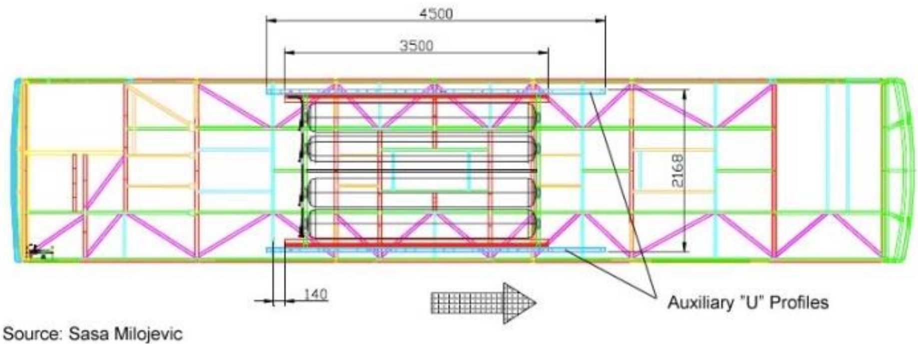
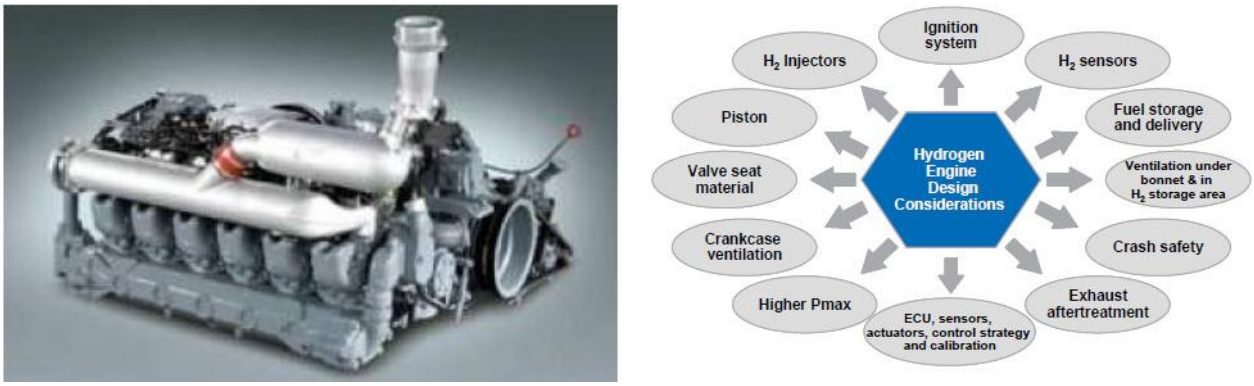


Figure 4 CGH_2 Cylinders Rack position on the bus roof

Hydrogen Engines – Combustion Concepts

Substituting conventional fuels (gasoline and diesel) by hydrogen in road transport can be achieved by introducing to the market new vehicles equipped with hydrogen engines, or as a first step, by converting engines of existing vehicles to run on hydrogen as an additive.

The design and operation of hydrogen engine is typically based on CNG engine, requiring an ignition system inside off the spark ignite the fuel mixture. As example, Figure 5 shows the picture of original hydrogen engine maker MAN with associated equipment specified bellows [1,4].

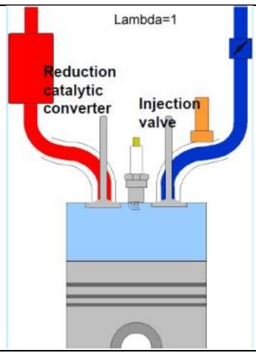
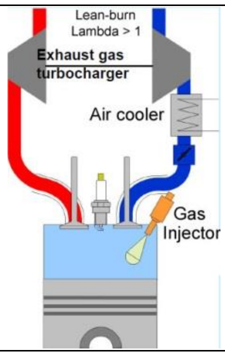


(a) (b)

Figure 5 Hydrogen propulsion system (a) Engine maker MAN type H2876 UH01 (b) Design and Consideration

The exhaust emission of the analysed 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, Table 1 [1,4].

Table 1 Difference between combustion concepts applied inside of MAN´s hydrogen engine

ENGINE	MAN H2876 UH01	MAN H2876 LUH01
Combustion concept		
Engine power	150 kW @ 2200 rpm	200 kW @ 2000 rpm
Engine torque	760 N·m @ 1000 rpm	1000 N·m @ 1200 rpm
Concept features	✓ Lambda=1 naturally aspirated stoichiometric engine ✓ External air/fuel mixture formation with injector ✓ Spark ignition system ✓ Power regulation with a throttle valve ✓ Exhaust after-treatment with reduction catalytic converter ✓ Low fuel injection pressure, no complicated air/fuel mixture preparation ✓ Conventional technology generating low costs …	✓ Lambda>1 lean-burn engine with turbo-charging and charge air cooling ✓ Internal air/fuel mixture formation with injector-direct gas injection system ✓ Low injection pressure (< 1 MPa) ✓ Early start of injection after inlet valve closes ✓ Spark ignition system ✓ Power regulation with a throttle valve and variable air/fuel ratio (lambda>2) ✓ No exhaust after-treatment ✓ Low fuel injection pressure, no complicated air/fuel mixture preparation ✓ No backfiring ✓ Partially throttled operation ✓ No spillage on filling …

Lean-burn heavy-duty CGH_2 engines 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 CGH_2 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, Table 1.

According to above specified characteristics of the hydrogen engines and combustion concepts, inside of Table 2, presented are the control measures needed to be integrated inside of new improved engines.

Table 2 Hydrogen engine control measures

Challenges - Problems	› Control Measures
• Auto ignition in the combustion chamber • Limits rich lambda range and therefore limits torque output	• Improved combustion chamber cooling (exhaust valves) • Low hydrogen injection temperature
• Auto ignition in the inlet manifold - backfire	• Direct injection will give least risk of backfire • Careful control of inlet and exhaust valves limits the risk of backfire
• NOx is the main emission from hydrogen ICEs • NOx formation is dependent on combustion temperature	• Lean mixture, apply exhaust gas recirculation (EGR) • Lower hydrogen injection temperature • Optimize cooling strategies • Optimize injection timing • NOx after treatment system
• Port injection natural aspiration hydrogen ICEs produce less power and torque then gasoline ICEs	• Boosting • Direct injection • Stoichiometric operation

Hydrogen Use as an Additive

One of options for existing buses can be the use of 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.

INSTRUCTIONS FOR BUSES SAFETY PROJECTING AND SERVICING

Before discussing the rest design features that are recommended for hydrogen buses and their propulsion system, it is important to understand what makes this fuel different from natural gas, gasoline or diesel. The items below summarize the basic differences between of their properties [4]:

- ✓ Hydrogen CGH_2 fuel systems store fuel at approximately 35 MPa, and as high as 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 demands, roofs of service facilities 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 vapor layer above. Liquid fuels remain in a concentrated form after a leak, causing on-going safety and environmental concerns.
- ✓ CNG and Hydrogen (H_2) both have an ignition temperature of around 480 to 650 degrees Celsius (°C) - whereas Gasoline is approximately 260 °C to 430 °C and diesel is less than 260 °C. This relatively high ignition temperature for CNG and (H_2) is an additional safety feature of these fuels. To ensure a safe environment in the service facilities, the surface temperature of equipment that could contact a gas leak is usually limited to 400 °C.

According to previous descriptions, ventilation systems in the services for hydrogen fuelled buses must be designed to provide between 5 and 6 Air Changes per Hour (ACH) (the requirement is for 425 L/min 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 to 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.
- ✓ Continuous monitoring of the air and a powerful ventilation system inside of service facilities.
- ✓ Prevention of ignition sources due to the explosion-protected design of electrical devices …

According to previous, the selected CGH_2 cylinders for working pressure of 35 MPa or 70 MPa used for bus prototype are equipped with automatic valve type BV-350, Figure 6, or BV-700 [5]. Automatic cylinders' valves are equipped with Pressure Relief Devices (PRD), with ultra-fast activation and high flow. Cylinders are also equipped with electric shut-off valves with unique stop fill function to stop and open the CGH_2 flow in fuel line. In the valve is integrated temperature sensor with thermal switch that quickly respond to increasing temperatures more than 110 ^{0}C as fire protection. That is so called Temperature triggered Pressure Relief Device (TPRD).

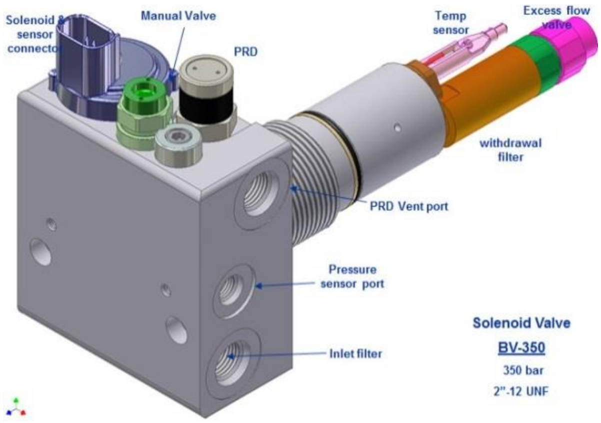


Figure 6 Automatic cylinders' valve type BV-350

HYDROGEN ON-BOARD STORAGE

At the present time, on board a vehicle Hydrogen can be stored as a compressed gas, cryogenic liquid or in a metal hydride. To make clearer the energy differences, the Table 3 shows a comparison between various forms of hydrogen and diesel fuel [1,4].

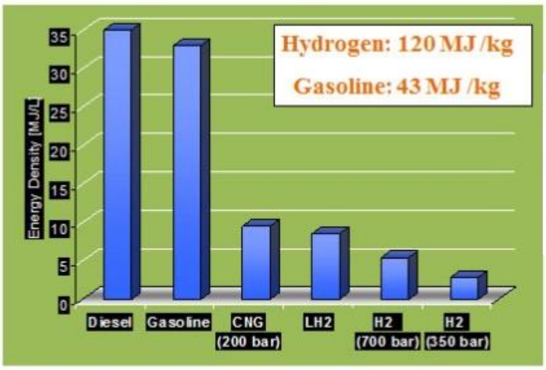
Table 3 Comparison of hydrogen and diesel fuel energy densities

The energy content of:	› is equivalent to:
1·Nm^3 of gaseous hydrogen	0.30 liters of diesel fuel
1 liter of liquid hydrogen	0.24 liters of diesel fuel
1 kg of hydrogen as metal hydride	2.79 kg of diesel fuel

Storage and bulk transport of hydrogen in compressed form allows satisfactory gravimetric density to be achieved, with composite cylinders. Compressed gas at maximal 35 and 70 MPa is the most likely form of hydrogen storage to be used for large vehicles such as buses and heavy duty vehicles (HDVs).

Storage in liquid form (LH_2) at about (-253 ^{0}C) and pressure of 1·MPa, allows useful volumetric and gravimetric densities to be achieved, similar to CNG, Figure 7 [1,4]. 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.



Basics: 500 km mileage range		Diesel	LH_2	CGH
Weight in kg	Fuel	25	5	5
	Tank System	30	80	120
Volume in L	Fuel	30	74	124
	Tank System	36	150	210
Storage density in kWh/ kg	Tank System	35	3,1	1,4
Storage density in kWh/ L	Tank System	30	1,1	0,8

Figure 7 Hydrogen Energy Density vs other Fuels

On-Board Storage of Hydrogen under Pressure in Gaseous State

The available gas cylinders for on-board storage of hydrogen 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. Type III cylinders are made of composite materials (initially fiberglass, and increasingly carbon fiber), with a metal liner (i.e. the inside facing, acting as H_2 barrier) – initially aluminum, lately in steel. Type IV cylinders are composite (mainly carbon fiber) with a polymer liner (mostly thermoplastic polymers, of the polyethylene or polyamide type), Figure 8 [5].

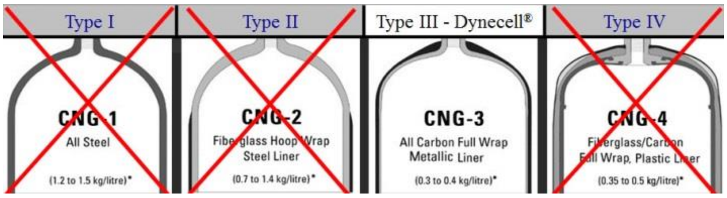


Figure 8 Comparative analysis of the (mass/volume) ratio of various cylinder types (example CNG cylinders)

In our case, on the bus roof need to be mount Gas Rack with minimum seven CGH_2 cylinders, as example type "W205H", with a total water capacity of 1435 L, Figure 9. The weight of one cylinder was about 92.4 kg (0.308 kg /L). The selected composite cylinders are lightweight cylinders for the storage of CNG and CGH_2. They consist of a thin-walled, seamless aluminum internal vessel whose entire surface is wrapped with a high-strength carbon fiber reinforcement (Type III = "fully wrapped metal liner") [2,3,5]. On the Figure 4, presented is CGH_2 Cylinders Rack position on the bus roof.

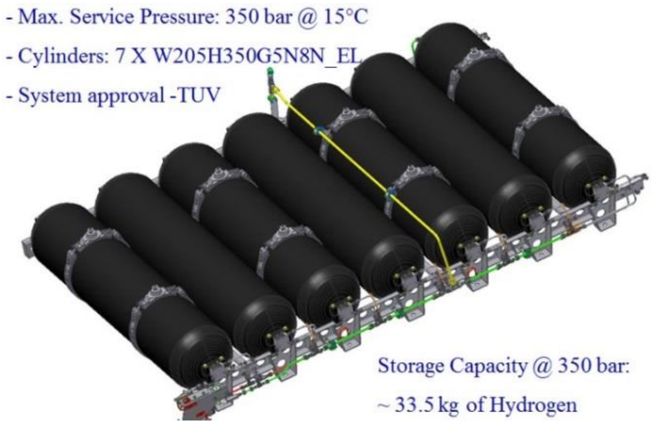


Figure 9 CGH_2 cylinders rack W205H for bus application

Hydrogen Market Supply and CGH_2 Buses Filling

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, nuclear power, Figure 2. Hydrogen from a central production plant could be delivered to the filling stations via pipeline, Figure 10. In Europe, however, only 1,000 km of hydrogen pipelines exist. The security of the CGH_2 supply is required to continue the introductions of hydrogen vehicles in city transport [4].

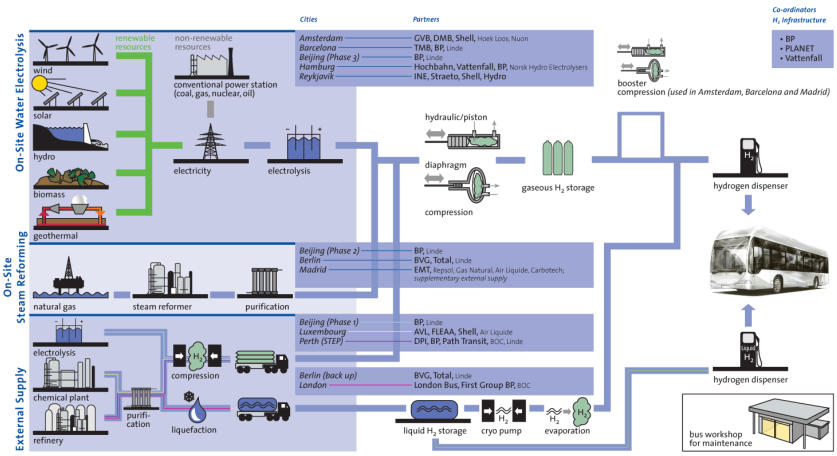


Figure 10 Hydrogen Supply Options in Cities

As second option, a truck for supply of LH_2 can carry up to about 3.3 tons of LH_2, equivalent to about 36,700 Nm^3. A drawback of liquid supply is that, due to the very low temperatures, all storage vessels have to be very well insulated. Small amounts of hydrogen can also be lost if the station is not being used for refueling for prolonged periods as hydrogen can start to boil and has to be vented in order to stay below the maximum pressure of the vessel. Another disadvantage is the high energy demand for liquefying hydrogen. It amounts to about one third of the energy contained within the LH_2 ($1 \cdot Nm^3$, containing 3.54 kW·h, requires more than 1·kW·h). Given the comparably short distances from central production sites to hydrogen customers, gaseous delivery is dominant in Europe [4,5].

Third options, bulk transport where is CGH_2 stored under pressure of 200 bar, while maximum pressure currently being 300 bar. A trailer can deliver between 300 and 600 kg of CGH_2. 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 11 [5].

(a) (b)

Figure 11 The 300 bar Modules (a) ISO 20 ft Container (b) 10 ft Cube for Bulk Transport of CGH_2

CONCLUSION

(1) Use of Compressed Gaseous Hydrogen as an alternative fuel is an effective, currently available way to help solve environmental and fuel resource problems. Generally, hydrogen has safety advantages compared to gasoline and diesel: it is non-toxic, neither carcinogenic nor corrosive gas.
(2) The introduction or expansion of hydrogen vehicles will require investment in new refueling infrastructure.
(3) When deciding to introduce or expand the use of hydrogen buses, one must evaluate the appropriate hydrogen engine technology. Lean-burn heavy-duty hydrogen engines 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 exhaust gas recirculation and three-way catalyst after-treatment.
(4) By installing the Gas Rack with Cylinders for gaseous hydrogen storage of Type III and rest fuel equipment homologated according to the UN ECE TRANS/WP.29, it was achieved progress from the aspect of vehicle safety in traffic.

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