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Description of selected FCH systems and infrastructure, relevant safety features and concepts

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Table of Contents

1. Glossary

INERIS	National Institute for the Industrial Environment and Risks
MMR	Measurement and control of risks
NWP	Nominal working pressure
PAC	Fuel cell
PEM	Proton Exchange Membrane
PhD	Hazardous phenomena
PRD	Pressure Relief Device or thermal fuse activated when a pressure threshold is exceeded
SEI	Irreversible effects threshold
SEL	Lethal effects threshold
SELS	Significant lethal effects threshold
TRD	Thermally activated Relief Device or thermal fuse activated when a temperature threshold is exceeded

2. Introduction

The development of new hydrogen and fuel cell (FCH) technologies require a better understanding by first responders the risks associated with hydrogen.

Hydrogen production methods (e.g. electrolysis or natural gas reforming), its storage, refuelling stations, FC vehicles (e.g. cars, buses, forklifts) and hydrogen-based energy storage systems remain unknown to first responders. In addition, there are no standardized procedures for intervention in the event of possible accidents or incidents.

It is quite likely that first responders would deal with accidents/incidents on FCH systems and infrastructures, for which they neither have sufficient knowledge nor technical documentation, which will assist them in the better understanding of certain critical situations. Taking into account specific risks related to FCH technologies in general and to hydrogen gas in particular it is very important to provide first responders with the description of the technical elements of the selected FCH systems in order for them to evaluate/assess the risk situations properly.

Indeed, the standardization and uniformity of safety devices for first responders do not yet exist. The first responders are expected to have permanently and easily exploitable document view of a guide to better understand the situation in the presence of hydrogen.

It is essential to create a common language between industrials and first responders to facilitate collaboration which help the integration of first responder’s difficulties during the design phase.

This document represents the work carried out within task 2.1-Selection, analysis and description of the HFC applications, their safety concepts and safety feature (WP2). It does not purport to be complete but will allow the first responders to find the essential information on elements of FCH installation or equipment that will be needed for basic understanding and appropriate decision making.

3. Hydrogen production

Hydrogen can be produced by water electrolysis or steam reforming of a natural gas.

3.1. PEM hydrogen electrolyser

3.1.1. Description

Figure 3-1: Overview of the process

PEM Electrolyser converts electrical energy into chemical energy and can be seen as the opposite device of the Fuel Cell (see $7.2.1). Conversion takes place in two rooms which are separated by a Proton Exchange Membrane (PEM). By application of a continuous tension, water is dissociated out of hydrogen (H_2) at the negative pole and oxygen (O_2) at the positive pole (Figure 3-2). The gases are collected in containers of recovery.

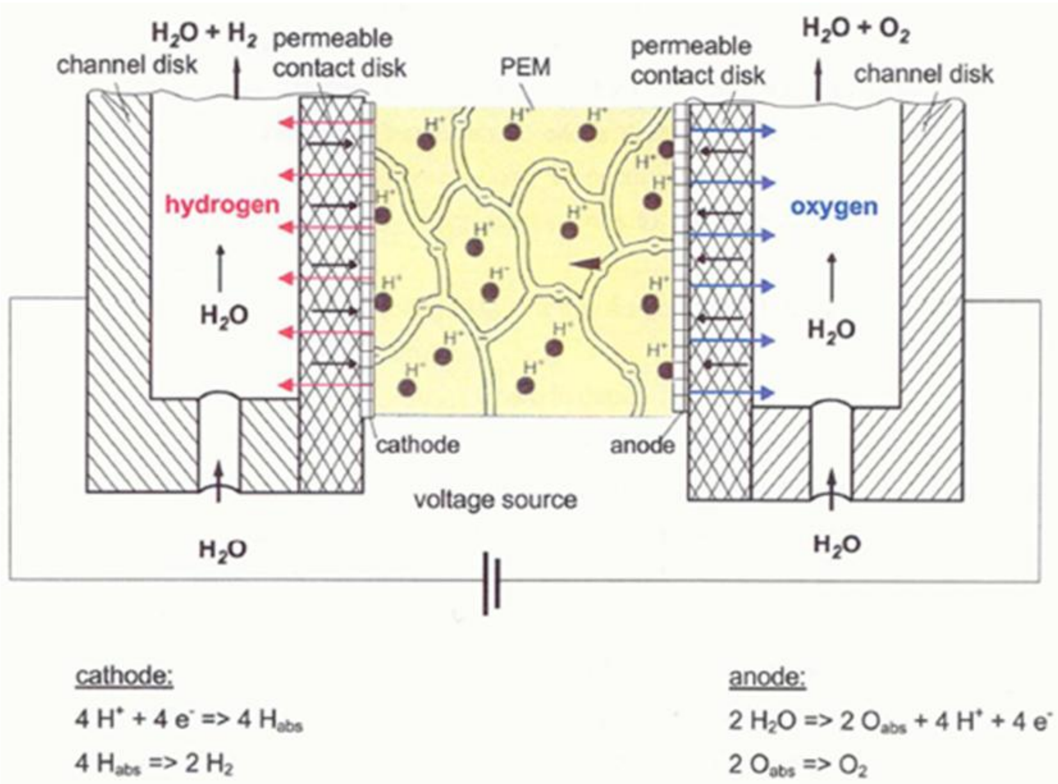


Figure 3-2: Functioning of an Electrolyser type PEM.

The electrolyser includes:

- A process cabinet gathering all the process components (valves, piping, gases and water, stack, pressurized vessels, pumps, etc.)
- An electrical cabinet gathering all electrical components (Instrumentation and control, cabling, power conditioning).
- A cooling system for electrolysis process heat dissipation (no figured in the view here below).

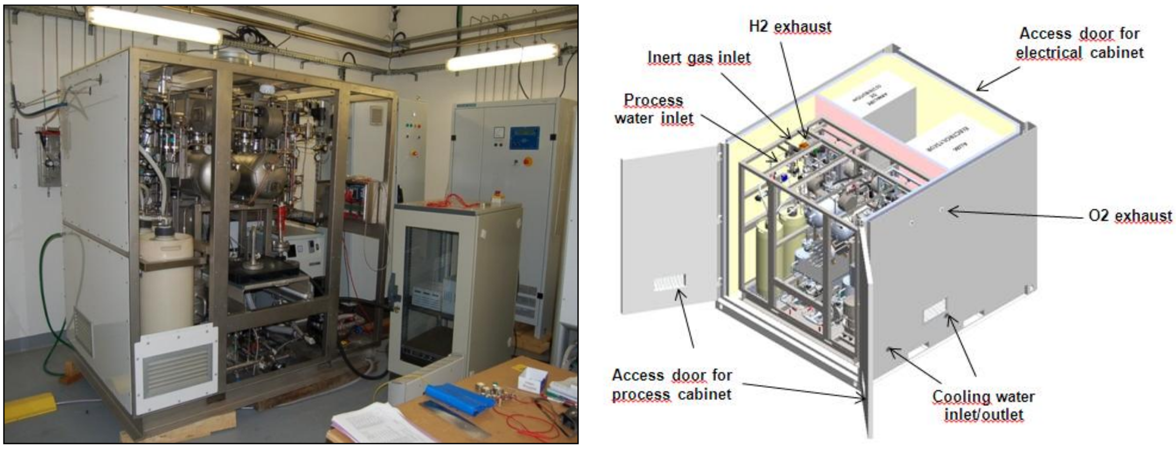


Figure 3-3: Technical specification and picture of AREVA Stockage d'Energie New Stack PEMFC generation.

In a practical way, the electrodes (anode and cathode) and the membrane are associated to form a Membrane Electrode Assembly called MEA and a stacking of Fuel Cell is called a stack.

This system will comprise a weather-proof container enclosing (Figure 3-4):

- an electrolyser that uses electricity to split water into hydrogen and oxygen;
- control system and automation;
- thermal management system (water/air heat exchanger);

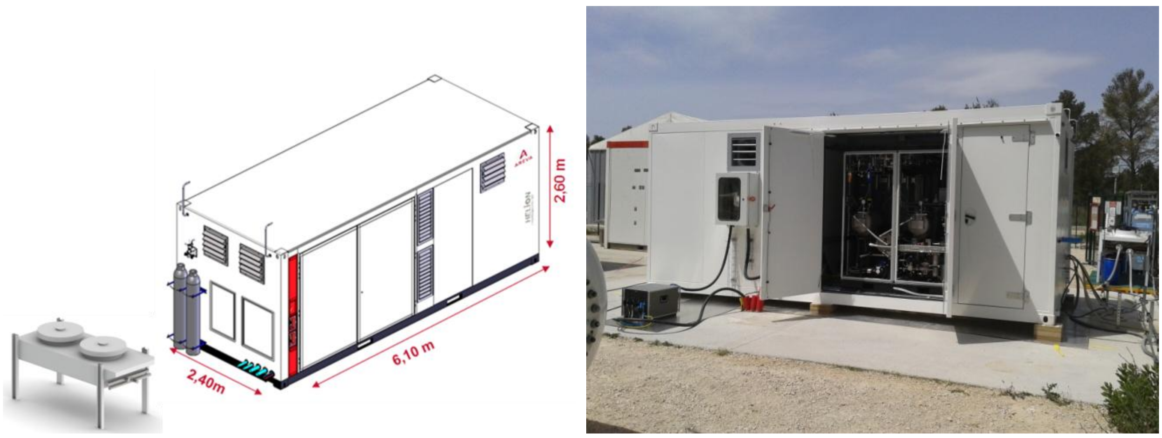


Figure 3-4: Technical specification and picture of AREVA Stockage d'Energie New Stack PEMFC generation.

A typical integrated electrolyser system is presented in Figure 3-3. The hydrogen flow rate has been increased and the operating range (RES coupling) has been extended to high pressure i.e. 35 barg while gaining efficiency. The system has also been optimised using SKID integration.

Technical specification of a PEM electrolyser is provided in the table below. Such system is installed on MYRTE platform in Corsica (see §8.2).

Criteria	Performance level
Production technology	PEM Electrolyser
Nominal flowrate	10 Nm3 H2 / h
Maximum flowrate	15 Nm3 H2 / h
Nominal pressure	35 bar g
Overall electrical consumption	< 5 kW.h / Nm3 at Nominal flowrate
Purity	H2O : dry at dew point < 6°C O2 : < 0,01%
Operating range (in % of Nominal flowrate)	10 – 150 %
System power	Power from local grid connection 400 V TRI
Standards	Certification

Table 3-1: Technical specification of AREVA Stockage d'Energie New Stack PEMFC generation.

3.1.2. Safety features and concepts

Two unwanted events are expected:

- Formation of an ATEX in the process compartment
- Formation of an ATEX in the separator

To avoid the accumulation of hydrogen in the process compartment, the overall following measures are taken:

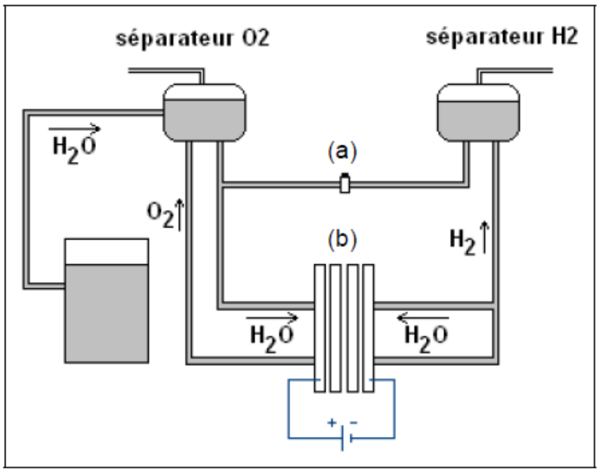
- Control of pressure and pressure difference in-between H2 and O2 lines
- Control of H2 concentration in the container (< 0.4% H2 vol.)
- Limit as possible the quantity of H2 in the gas layer of the separator to avoid the formation of a flammable H2-air mixture in the container in case of catastrophic leak

In case of the activation of these safety functions, the electrolyser will shut-off, which involves not only the closing of the isolation electro-valves connected to the storage tanks but also the depressurization of the system through the normally opened electro-valves.

As shown on the Figure below, there are two possible paths for the formation of a H_2-O_2 ATEX in the separator:

- path (a): dysfunction of the water transfer line;

- path (b) : membrane perforation



The following safety measures are considered:

- Impose a minimum water level in the gas separator above 55 % of their height
- Control the water level in the H_2 and O_2 gas separators
- Control of pressure and pressure difference in-between the H_2 and O_2 lines
- Control of H_2 concentration in at the exit of the O_2 gas separator

In case of the activation of these safety functions, the electrolyser will shut-off, which involves not only the closing of the isolation electro-valves connected to the storage tanks but also the depressurization of the system through the normally opened electro-valves.

3.2. Alkaline electrolysers

3.2.1. Description

Alkaline electrolysis is a well matured technology for hydrogen production and also the most employed in the world of Industry. Alkaline electrolysis uses the same principle as the PEM electrolysis that is the conversion of electrical energy into chemical energy.

Alkaline electrolysis is characterized by having 2 electrodes immersed in a liquid alkaline electrolyte composed with a caustic potash (potassium hydroxide or KOH) solution at a level of 25% at 80°C up to 40% at 160°C. Caustic potash is preferentially used in regard with caustic soda because of its higher ionic conductivity, its lower chloride impurity contents and its lower saturated steam pressure.

The 2 electrodes are separated by a diaphragm (Figure 3-5). This diaphragm has 2 functions: first to keep the product gases (namely hydrogen and oxygen) apart from another and secondly to be permeable to the hydroxide ions (OH-) and water molecules.

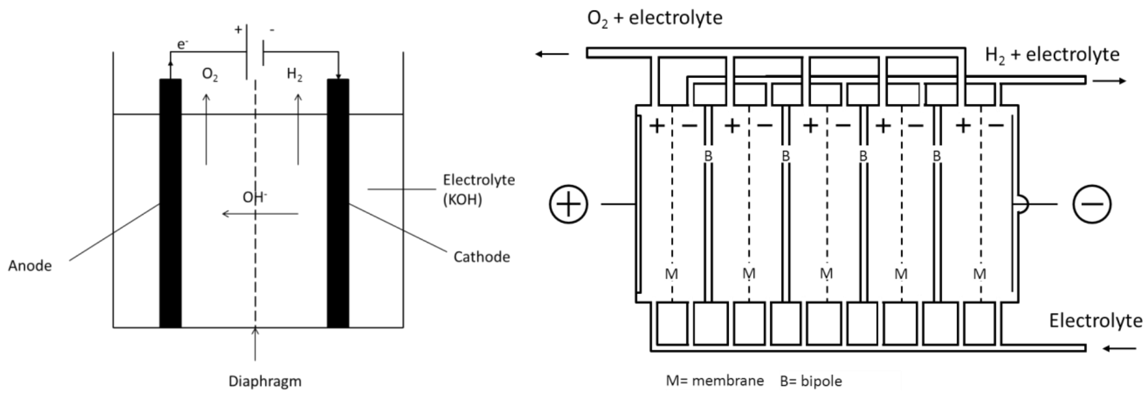


Figure 3-5: Functionning of the alkaline electrolysis

The reaction is:

<u>At the anode</u>: $2\ OH^- \rightarrow ½\ O_2 + H_2O + 2\ e^-$

<u>At the cathode</u>: $2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$

<u>Total reaction</u>: $H_2O \rightarrow H_2 + ½\ O_2$

A typical alkaline electrolysis is composed of:

- Power supply and System of control and instrumentation,
- Electrolysis system (with unit of water purification, one of hydrogen purification, gas dryer, separators…)
- Compressor.

The figures below are examples of industrial alkaline electrolysers.

Figure 3-6: Alkaline electrolyser IHT type S-556, 760 Nm3/h and 30 bars

Figure 3-7: Outdoor and Indoor HySTAT from Hydrogenics, 10-60Nm³/h

3.2.2. Safety features and concepts

Same as PEM electrolyser, the main risks regarding the system are the formation of a hydrogen/oxygen mixture and then an internal explosion within the electrolyser.

Thus, some sensors are implemented (see the list below) in order to detect an electrolyser dysfunction:

- Measurement of the hydrogen concentration in the oxygen line,
- Measurement of tension,
- Measurement of the temperature at the entry and at the outflow of electrolysis cells,
- Measurement of the ionic concentration of the electrolyte.

Another risk is this one of the exposition to a corrosive product in the event of an electrolyte leak. The specification sheet of potassium hydroxide recommends the use of a leak tank in order to avoid the contact of caustic potash with the environment.

3.3. Reformer

3.3.1. Description of technology

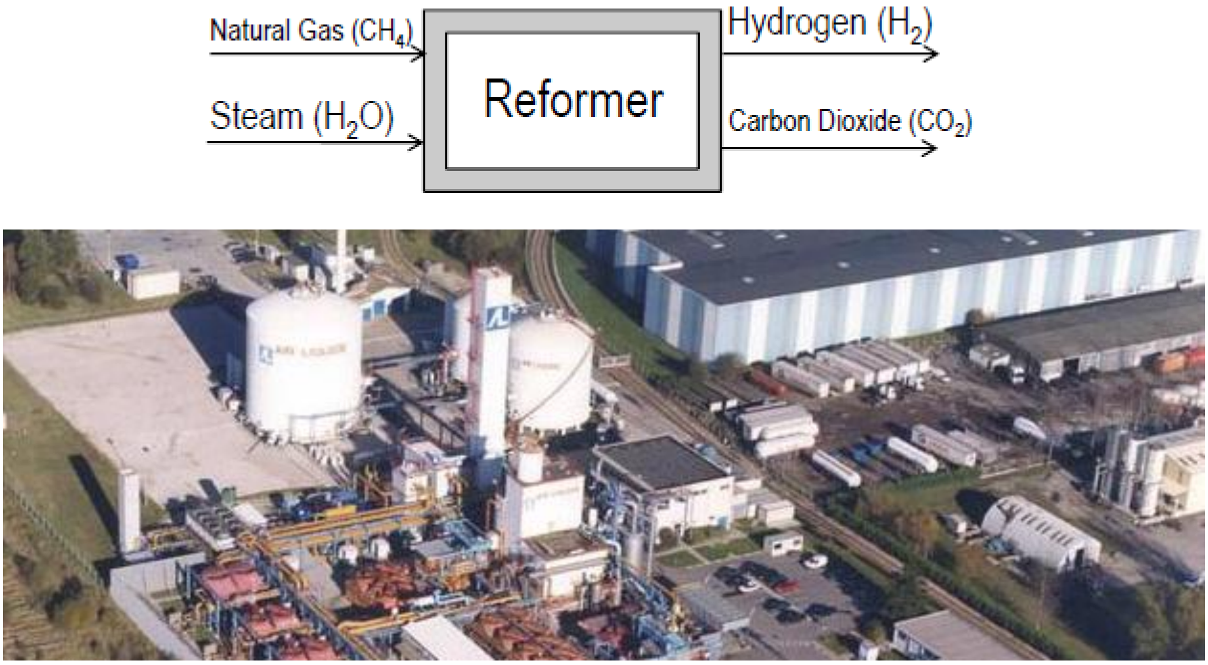


Figure 3-8: Overviews of the process and photography of the installation

Most of the time, reformer is used in industrial application. It produces hydrogen from natural gaz, (CH_4) steam and heat. The capacity ranges from a few 100 to more than 100 000 Nm^3/h. It can be operate all a year (7 days a week, 24 hours) and at constant load.

It took time (few days) to start it up, the process emits CO_2 and produced hydrogen is not very clean and is at atmospheric pressure.

3.3.2. Safety features and concepts

This technology is well established so there are no specific concerns.

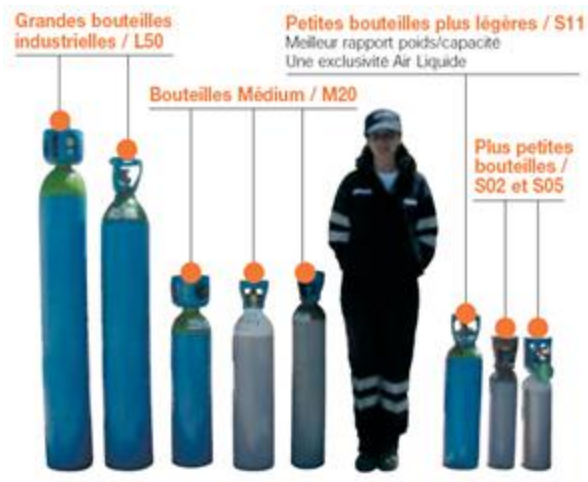
4. Stationary hydrogen storage

The storage of large quantities of hydrogen for long times is a key step in the build-up of infrastructure in order to regulate the hydrogen consumption and production and ensure continuity in supply. Various underground hydrogen storage schemes are investigated. One option is to store gaseous hydrogen in geological formations including depleted gas fields or aquifers, caverns … Another one is the underground storage in buried tanks, either in compressed gas form or in liquid form. Geologic storage is generally close to hydrogen production site, buried tanks are close to point of use such as refueling stations.

4.1. Gaseous hydrogen storage in racks or cylinders

4.1.1. Description

Cylinders could have different size and pressure. Most of them have a volume of 50 liters and are under 200 bar (could be 300 bar). As the example below, there are plenty of different cylinders:



For different application, cylinders could be interconnected in a bundle. Size and volume could be very different: from 20l to 300l from 200 bar to 700 bar.

Bundle

Basket for transportation

4.1.2. Safety features and concepts

This technology is well established so there are no specific concerns. In Europe, most of transportable cylinders have only a valve as safety barrier. In USA, for instance there is TRD on transportable combustible cylinders. This prescription is more and more controversial because they often create leak.

4.2. Gaseous hydrogen tanks

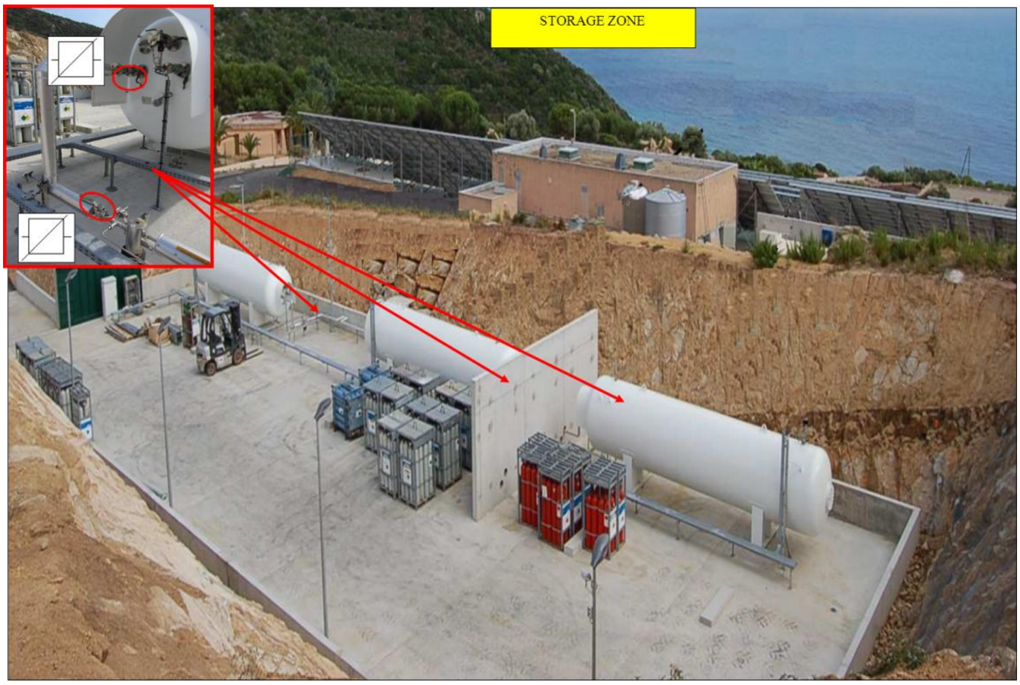
4.2.1. Description

The photo below presents the storage zone of the MYRTE platform (see §9.2).

4.2.2. Safety features and concepts

The photo below highlights typical location of the safety manual valves as closed as possible to the storage tank.

Each storage tank is equipped by a pressure relief device (PRD) connected to a vent. The tare pressure of the pressure relief valve is set so that the PRD actuates when the pressure within the reservoir reaches 1.15 of the maximal operating pressure.



Isolation valves with lock out capabilities are used to isolate portions of the pipe line in emergencies or for routine maintenance and inspection. These are installed should be installed in an accessible location since they may need to be manually closed on an emergency basis.

In case of power outrage or emergency stop, each storage tank is isolated by the electro-valves located close to each reservoir.

Non return valves, that are specifically designed to permit flow in one direction and to stop it in the reverse direction, may also be used in piping and storage systems.

Flow excess valves may also be used to stop massive leaks in case of catastrophic pipe rupture.

4.3. Liquefied hydrogen storage

Not addressed within HyResponse because it is not the main stream.

4.4. Hydride solid hydrogen storage

Not addressed within HyResponse because it is not the main stream.

5. Hydrogen distribution applications (materials handling)

5.1. Hydrogen transport by road

5.1.1. Gaseous trucks

5.1.1.1. Description

Status

Truck fleets are currently used by industrial gas companies to transport seamless steel vessels of compressed gaseous hydrogen for short distances (200-300 km) and small users (1 to 50 m^3/h) from centralized production. Single cylinder bottles, multi-cylinder bundles or long cylindrical tubes are installed on trailers (Figure 5-1). Storage pressures range from 200 to 300 bar and a trailer can carry from 2,000 to 6,200 Nm^3 of H_2 for trucks subject to weight limitation of 40 tons. The amount of hydrogen carried out is thus relatively small (from 180 to 540 kg, depending on the number of tubes or bundles), which represents ~ 1 to 2 % of the total mass of the truck. Current trailers utilize Type I storage cylinders (all-metal). To increase performance, bundles of light-weight composite hoop wrapped cylinders or tubes (Type II) can be used.

Figure 5-1: Two types of compressed gas hydrogen trailers operated by Air Liquide in Europe : tube trailer carrying 2,000 to 3,000 Nm3 of H2 (depending on the numbers of tubes) and Type II composite cylinder trailers carrying 6,200 Nm3 of H2 (540 kg)

The main cost factors in compressed gas truck delivery are capital costs, operation and maintenance including drivers' labor and fuel costs. The amount of time the trailer is stored at customer site is also a factor affecting delivery cost. The capital investment is low for small quantities of H_2 but it does not benefit of economy of scale with increasing demand and the costs increase linearly with delivery distance. This mode of delivery is relatively easy but it has to be adapted to hydrogen quantities and distances to be cost competitive.

Perspectives

The supply by gaseous truck (tube trailer, cylinders) is one of the most mature modes, preferred for short distances and small amounts of hydrogen. Limitations are the low weight storage capacity for high customer consumptions (requiring frequent delivery) and the low pressure of hydrogen delivered, which requires additional compression at the fuelling station site. Thus, alternative

technologies with higher pressure, higher hydrogen-carrying capacity and lower-cost systems are investigated as described hereafter.

Lincoln Composites develops higher volume tubes in composite structure (plastic liner fully wrapped with epoxy impregnated carbon fiber) for hydrogen gaseous tube trailer delivery. The TITAN^{TM} tank (1.08 meters in diameter, 11.5 meters in length, 8,400 liters in water volume, and 2,087 kg in weight) operating at 250 bar can deliver 2 to 3 times the amount of hydrogen of a steel tank of similar mass. Figure 5-2 shows the storage unit holding 4 tanks capable of storing 600 kg H_2 at 250 bar. Higher pressure tanks up to 350 bar are planned for 2010.

Figure 5-2: Container with 4 composite tanks developed by Lincoln Composites. Source: Lincoln Composites [20]

Hybrid technologies are explored at the Lawrence Livermore National Laboratory (LLNL) such as cryo-compression combining pressure and low temperature to increase the amount of hydrogen that can be stored per unit volume and avoid the energy penalties associated with hydrogen liquefaction. Compressed hydrogen gas at cryogenic temperatures is much denser than in regular compressed tanks at ambient temperatures. These new vessels would have the potential to store hydrogen at temperatures as low as 80 K under pressures of 200-400 bar. This approach requires development of insulated pressure composite tanks. Alternatively one could consider using cold hydrogen gas tanks that would require less cooling. There may be some optimum combination of pressure and temperature over the range of 80-200 K. Recently, LLNL has identified inexpensive glass fiber materials for cold hydrogen gas storage (~ 150 K and up to 500 bar), expecting 50% trailer cost reduction.

5.1.1.2. Safety features and concepts

The main safety device for on road gas storage is manual safety valves:

- according to ADR[1], during transportation all storage are isolated by a valve;
- in service, there is different safety devices & procedures:
    - The semi-trailer changeover procedure takes place as follows:
        - The driver parks the semi-trailer in the location provided,
        - The driver put chocks in position and deploys the leg stand,
        - The driver unhitches the tractor unit,

[1] ADR: Accord for dangerous goods by road

- The driver connects the hose from the full semi-trailer, tests the seal on the draw-off hose and disconnects the empty semi-trailer,
- The driver hitches the empty semi-trailer to the tractor unit and departs.

- A manual leak tightness test when connecting to a semi-trailer. This is done in the following stages. The operator connects the semi-trailer hose to the installation's connection post. Hose is pressurised. The operator Check for leak tightness using detection soap and stabilisation of the pressure measured locally using a pressure gauge.

5.1.2. Cryogenic liquid trucks

5.1.2.1. Description

Hydrogen can be transported by road in liquid form (cooled to 20 K or – 253 °C) to distribute larger quantities (hundreds of m^3/h). In terms of weight capacity, super-insulated liquid hydrogen trucks can transport up to 10 times more hydrogen than the tube trailers used for conveying compressed gas. Liquid H_2 trucks (Figure 5-3) operating at atmospheric pressure have volumetric capacities of about 50,000 – 60,000 liters and can transport up to 4,000 kg with a mass truck of ~ 40 tons. It is a preferred distribution mode for medium/large amounts of hydrogen and long distances, which explains the liquid H_2 business has been developed most extensively in North America (the hydrogen liquefaction capacity in North America is about ten times larger than in Europe). The liquid hydrogen transported in the truck is then vaporized to a high-pressure product for use at the customer site.

Figure 5-3: Road tanker operated by Air Liquide for conveying liquid hydrogen to user. Source: Air Liquide Image Bank

A main issue of this pathway is the liquefaction plant which is capital-intensive. Then, the liquefaction process is costly. The electricity input for liquefaction accounts for ~ 35 % of the lower heating value of hydrogen (compared to ~ 10 % for gas compression). Electricity costs account for 50-80 % of the liquefaction costs.

Distance is the chief deciding factor between liquid and gaseous hydrogen. The number of liquid trucks will depend on the hydrogen demand and the localization of the liquefaction point. However, the liquid truck capacity being much higher than that of a compressed gas truck, this mode of delivery is less dependent upon the transport distance. The truck capital cost and operating cost (fuel, labour) are much smaller. As a consequence, liquid trucking is more economical than gaseous trucking for long distances (from approximately 400 km to thousands of kilometers) and medium amounts of hydrogen.

However, one has to consider the availability of liquid hydrogen. Currently, the industrial hydrogen market is served by four liquefiers in Europe (the German's second H_2 liquefaction plant started in 2007) and ten in North America. Larger markets would justify the construction of new liquid plants.

Significant cost reductions due to scaling effects of liquefaction equipment are possible. However, this mode of delivery relies on the price of electricity and on the decision to install new liquefaction units. Better technologies could offer opportunities to reduce capital cost, improve energy efficiency of liquefaction process and reduce the amount of hydrogen lost due to boil-off during storage and transportation (the evaporation rate which depends on the size, shape, insulation of the container and time of storage, is typically of the order of 0.2 %/day for 100 m^3 container). Studies are underway to improve liquefaction technologies and propose novel approaches (for example, improvement of ortho-para conversion, development of magnetic refrigeration …).

5.1.2.2. Safety features and concepts

This technology is not addressed within HyResponse because it is dedicated to industrial technology and not to hydrogen energy applications. Nevertheless, we could precise that there is at least two safety valves with at least one pneumatic. PRDs limits the risk of the boil-off.

5.2. Pipe

5.2.1. Description

Overview of hydrogen networks

A number of commercial hydrogen pipelines are used today to distribute large quantities (tens of thousands of m^3/h) of gaseous hydrogen to the industrial market. Their lengths range from less than a kilometer to several hundreds of kilometers. The major actors are the industrial gas companies, namely Air Liquide, Air Products, Linde and Praxair. In response to an increased demand for hydrogen by refining customers, existing networks are expanding and new portions are built (in March 2009, Air Products, as an example, announced a 60-km extension to the U.S. Gulf Coast hydrogen pipeline network in Louisiana). The hydrogen network is estimated at around 1600 km in Europe and 1,100 km in North America. Most of the pipelines are located where large quantities of hydrogen are consumed in refining and chemical sectors. 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, Alberta). Smaller systems also exist in South Africa, Brazil, Thailand, Korea, Singapore and Indonesia. Overall, these pipeline lengths are tiny when compared to the worldwide natural gas transport pipeline system, which would exceed 2,000,000 km.

Figure 1 displays parts of the worldwide H_2 pipeline network. For example, the 240 km long pipeline in the Ruhr area of Germany (Figure 5-4-a) acquired by Air Liquide in 1998 has been in operation since 1938.

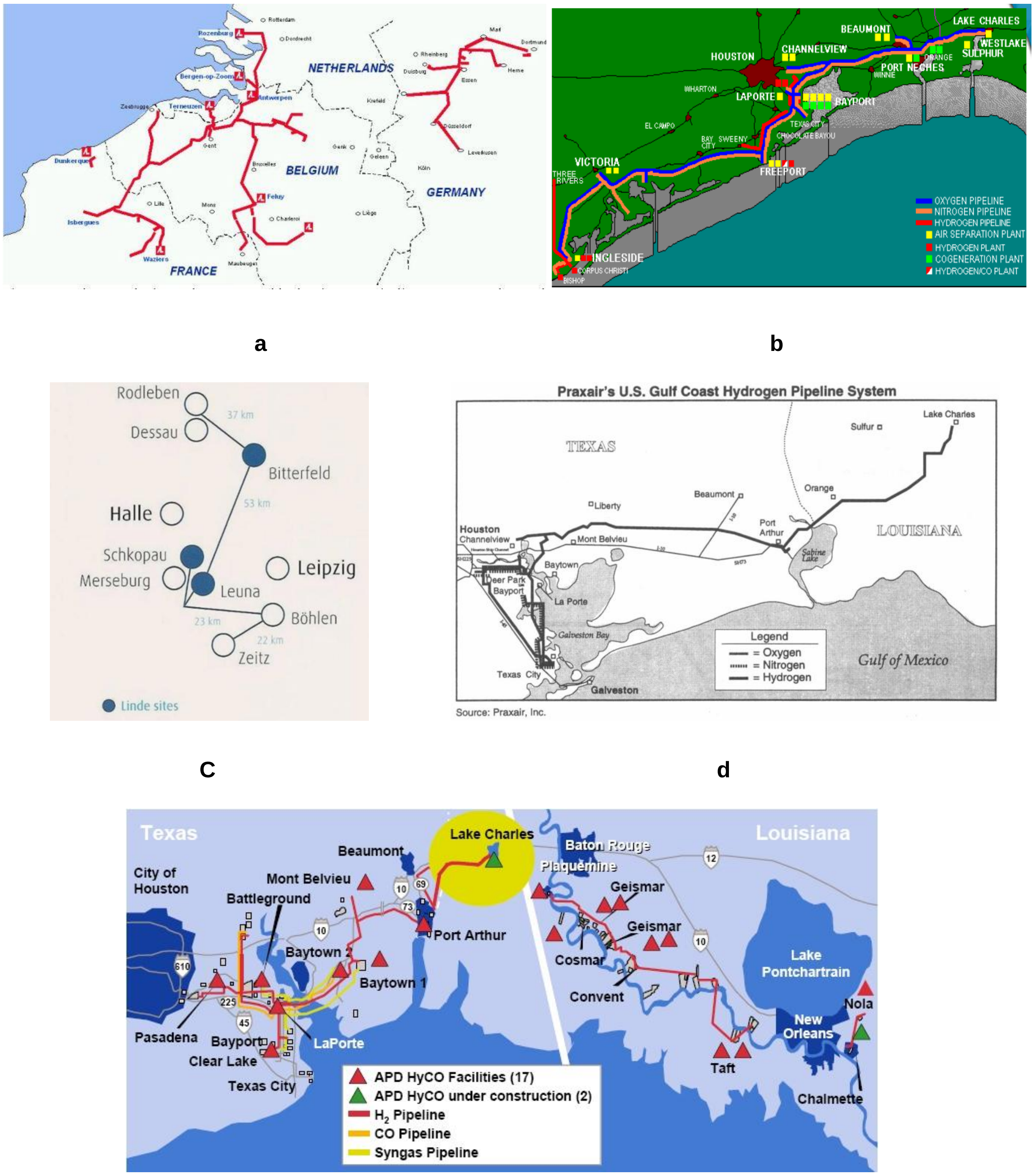


Figure 5-4: Main hydrogen pipelines in the world. (a) Air Liquide hydrogen pipelines in Benelux, France and Germany (Ruhr area). (b) Air Liquide hydrogen pipelines in the Gulf Coast (USA). (c) Linde hydrogen pipelines in Germany. (d) Praxair hydrogen pipelines in the Gulf coast (USA). (e) Air Product hydrogen pipelines in the Gulf Coast (USA)

Within the "Zero Regio" European project for hydrogen energy applications, Linde has installed a 900 bar hydrogen pipeline (of 1" diameter) over a distance of 1.7 km in the Frankfurt-Hoechst industrial park to supply fuel cell passenger vehicles.

Pipeline characteristics

Pipelines require adequate design, installation and maintenance procedures. The operating pressure of hydrogen pipelines is generally lower than 100 bar (most commonly between 40 and 70 bar) and the diameter of the pipelines (D) usually ranges from 10 to 300 mm. Current pipelines are made of steels. A technical concern is hydrogen embrittlement of metallic pipelines and welds, characterized by a loss of ductility and rupture when subjected to stress. The steels used for H_2 pipelines are thus low-carbon, low-alloy and low strength steels to reduce the risk of embrittlement (e.g., API X42 steel with C < 0.2, Mn < 1.3 wt%). These steels combine economical affordability with an adequate range of physical properties such as strength, toughness, ductility and weldability. For safety reasons, most pipelines are buried so steels are protected by coatings or cathodic protection to prevent corrosion issues.

Pipeline construction involves extensive welding for joining, with a minimum of inspections before operation for safety considerations. The exploitation of a pipeline network also requires compressor stations as hydrogen is generally available at low pressure. Hydrogen compressors feeding the pipeline system are usually found at locations where hydrogen is produced. The compressors are expensive and require a high maintenance so they are actually not installed if another alternative is possible. For instance, when hydrogen is produced using natural gas (steam methane reforming), the natural gas feedstock can be compressed and the production plant operated at a higher pressure. Friction losses in pipelines with hydrogen are much lower than for those in natural gas as the viscosity of hydrogen is smaller (the energy loss during transportation of hydrogen is about 4 % of the energy content).

Perspectives of evolution for H_2 pipelines

A hydrogen pipeline carries about 30% less energy compared to natural gas pipeline due to the lower heating value of hydrogen. The distribution of larger energy quantities in hydrogen pipelines requires a flow pressure increase (> 100 bar). This increase in pressure may have implications for the material which could be used in the pipeline construction.

Furthermore, the operating conditions of a hydrogen pipeline for energy applications would be different from an industrial pipeline which today operates at nearly constant pressures, without significant pressure cycles or swings. Hydrogen energy pipelines would have to bear variations of pressure. This may be a concern due to the susceptibility of steels to hydrogen embrittlement which affects their mechanical properties and decreases their resistance to fatigue crack.

To address these challenges, there is a renewed interest in the research for new pipelines materials compatible with hydrogen and their use at higher operating pressure, and to reduce capital costs.

New steels are explored to develop a better understanding of hydrogen embrittlement and to identify steel compositions and processes suitable for construction of a new pipeline infrastructure or potential use of the existing steel pipeline infrastructure.

Research also concentrates on alternative to metallic pipelines to achieve cost and performance targets for hydrogen transmission and distribution. Polymeric and fiber-reinforced polymer pipelines

(FRP) which present the advantages of being light compared to steels, easier to handle, join and weld, non-sensitive to corrosion, and non-sensitive to hydrogen embrittlement are investigated.

Polymeric pipes currently used in the natural gas distribution network are made of polyethylene and have a pressure rating limited to 10 bar. Polymers such as polyamide (and more particularly polyamide-12) present more interest as the permeability of hydrogen is significantly reduced and its thermo-mechanical properties allow pipes to sustain a 20 bar operating pressure and a 80°C operating temperature. Therefore, plastic pipes can be an alternative to steel thanks to savings in installation and maintenance costs. However, material supply can represent a high ratio of the total cost.

Figure 5-5: Composite pipeline (FRP) instrumented for testing

Pipes in composite materials (FRP) are composed of a thermoplastic liner (mainly polyethylene) wrapped with high strength fibers (most commonly aramid fibers) then coated with a thermoplastic layer. This last layer protects from environmental attacks and helps to retain the wrapping mainly responsible for the mechanical properties. Compared to simple plastic pipes, wrapping with aramid fibers allows getting pressure up to 100 bar. These reinforced plastic pipes are already used for natural gas or crude oil distribution in the middle-east and their development for H_2 delivery is currently part of DOE Hydrogen program (Figure 5-5). According to literature, Fibre Reinforced Plastic (FRP) pipes could be a cost-effective option compared to metallic pipes when long lengths can be installed (200 to 300 meters). However the manufacturing process does not allow getting plastic pipes with diameters as high as steel pipes (100 and 150 mm are most common diameter). Further developments are still needed to evaluate the feasibility of large-scale manufacturing operations, assess joining technology, and develop codes & standards for hydrogen-service FRP pipelines.

5.2.2. Safety features and concepts

This technology is not addressed within HyResponse because it is dedicated to industrial technology and not to hydrogen energy applications. Pipelines are specific assets with their own safety management system. Periodic inspections were performed following internal specifications: from aboveground to detect coating defects or directly inside the pipeline to measure the steel metal loss. Once a year all instrumentation and valves are checked which included corrosion protection, painting, lubrication of gear drive, cleaning filters and strainers

5.3. FC cars

Most of the following information on Fuel Cell Hydrogen (FCH) cars is taken from the draft of GTR document prepared by the Economic and Social Council, United Nations [1].

5.3.1. Description

Fuel cell hydrogen (FCH) cars have an electric drive train powered by a fuel cell that generates electric power electrochemically using hydrogen. In general, FCH cars are equipped with other advanced technologies that increase efficiency, such as regenerative braking systems that capture the kinetic energy lost during braking and store it in a battery or ultra-capacitors. While the various FCH cars are likely to differ in the details of the systems and hardware/software implementations, the following major systems are common to most FCH cars:

(A) Hydrogen fuelling system;

(B) Hydrogen storage system;

(C) Hydrogen fuel delivery system;

(D) Fuel cell system;

(E) Electric propulsion and power management system.

The functional interactions of the major systems in a FCH car are shown in Figure 6.1. During fuelling, hydrogen is supplied to the car through the fuelling receptacle and flows to the hydrogen storage system. The hydrogen supplied to and stored within the hydrogen storage system are usually compressed gaseous hydrogen. When the car is started, hydrogen gas is released from the hydrogen storage system. Pressure regulators and other equipment within the hydrogen delivery system reduce the pressure to the appropriate level for operation of the fuel cell system. The hydrogen is electro-chemically combined with oxygen within the fuel cell system to produce high-voltage electric power. That electric power is supplied to the electric propulsion power management system where it is used to power electric drive motors or charge batteries and ultra-capacitors.

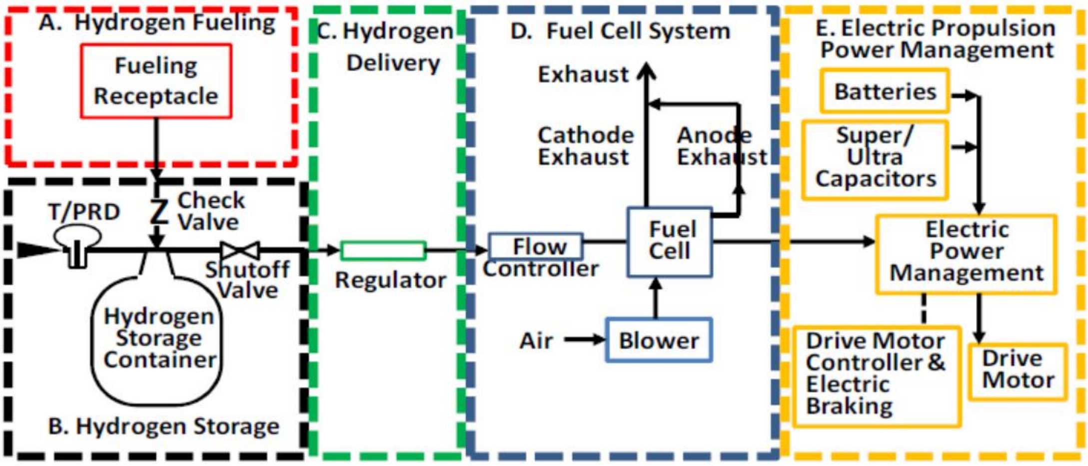


Figure 6.1: A scheme of key systems in FCH car [1].

Figure 6.2 illustrates a typical layout of key components in the major systems of a typical FCH car. The fuelling receptacle is shown in a typical position on the rear quarter panel of the car. As with gasoline containers, hydrogen storage containers are usually mounted transversely in the rear of the car, but could also be mounted differently, such as lengthwise in the middle tunnel of the car. Fuel cells and ancillaries are usually located under the passenger compartment or in the traditional "engine compartment," along with the power management, drive motor controller, and drive motors. Given the size and weight of traction batteries and ultra-capacitors, these components are usually located in the car to retain the desired weight balance for proper handling of the car.

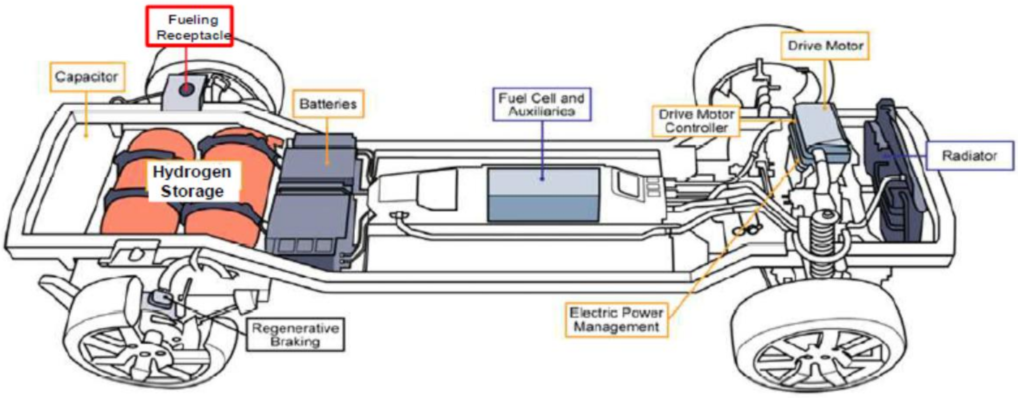


Figure 6.2: An example of a FCH car [1].

(A) Hydrogen fuelling system

Compressed gaseous hydrogen may be supplied to the car at a fuelling station. At present, hydrogen is most commonly dispensed to cars as a compressed gas that is dispensed at pressures up to 125 per cent of the nominal working pressure (NWP) of the car to compensate for transient heating from adiabatic compression during fuelling.

(B) Hydrogen storage system

The hydrogen storage system consists of all components that form the primary high pressure boundary for containment of stored hydrogen. The key functions of the hydrogen storage system are to receive hydrogen during fuelling, contain the hydrogen until needed, and then release the hydrogen to the fuel cell system for use in powering the car. At present, the most common method of storing and delivering hydrogen fuel on-board is in compressed gas form.

Lightweight compressed gas cylinders at 700 bar are also developed to increase storage capacity. They consist of a metallic (Type III) or polymeric (Type IV) liner in a fiber reinforced composite structure. An improvement in the gravimetric system storage density (around 5 wt %) is achieved with this high pressure technology (Figure 6.3,). Developments are on-going to reduce cost.

a **b**

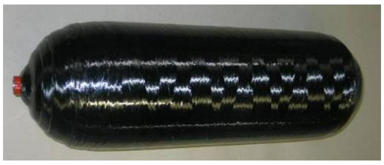
 

Figure 5.3: 700 bar cylinder prototype developed and tested within the STORHY European project: (a) Type III technology, (b) Type IV technology

(C) Hydrogen fuel delivery system

The hydrogen fuel delivery system transfers hydrogen from the storage system to the propulsion system at the proper pressure and temperature for the fuel cell to operate. This is accomplished via a series of flow control valves, pressure regulators, filters, piping, and heat exchangers. In vehicles with compressed hydrogen storage systems, thermal conditioning of the gaseous hydrogen may also be required, particularly in extremely cold, sub-freezing weather.

(D) Fuel cell system

The fuel cell system generates the electricity needed to operate the drive motors and charge vehicle batteries and/or capacitors. There are several kinds of fuel cells, but Proton Exchange Membrane (PEM) fuel cells are the common type used in automobiles because their lower temperature of operation allows shorter start up times. The PEM fuel cells electro-chemically combine hydrogen and oxygen to generate electrical DC power. Fuel cells are capable of continuous electrical generation when supplied with hydrogen and oxygen, simultaneously generating electricity and water without producing carbon dioxide (CO2) or other harmful emissions typical of gasoline-fuelled internal combustion engines.

(E) Electric propulsion and power management system

The electric power generated by the fuel cell system is used to drive electric motors that propel the vehicle. As illustrated in Figure 6.2, many passenger fuel cell cars are front wheel drive with the electric drive motor and drive-train located in the "engine compartment" mounted transversely over the front axle; however, other configurations and rear-wheel drive are also viable options. Larger Sport Utility Vehicle-type fuel cell cars may be all-wheel drive with electric motors on the front and rear axles or with compact motors at each wheel.

5.3.2. Safety features and concepts

(A) Safety devices in hydrogen fuelling system

The FCH cars are fuelled through a special fuelling nozzle on the fuel dispenser at the fuelling station that connects with the fuelling receptacle on the car to provide a "closed system" transfer of hydrogen to the car. The fuelling receptacle on the FCH car contains a check valve or other device that prevents leakage of hydrogen out of the car when the fuelling nozzle is disconnected.

(B) Safety devices in hydrogen storage system

Components of a typical compressed hydrogen storage system are shown in Figure 6.4. The system includes the container and all other components that form the "primary pressure boundary" that prevents hydrogen from escaping the system. There are three safety devices as parts of the compressed hydrogen storage system:

(1) The check valve;

(2) The shut-off valve;

(3) The thermally-activated pressure relief device (TPRD).

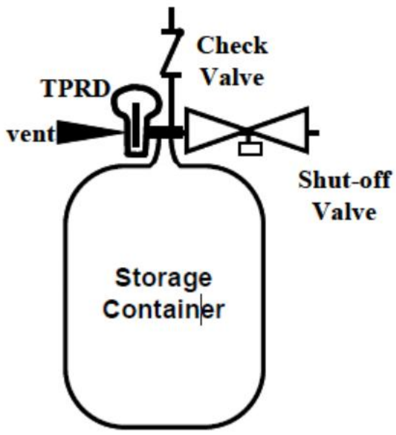


Figure 6.4: Typical compressed hydrogen storage system [1].

(1) The check valve

During fuelling, hydrogen enters the storage system through a check valve. The check valve prevents back-flow of hydrogen into the fuelling line.

(2) The shut-off value

An automated hydrogen shut-off valve prevents the out-flow of stored hydrogen when the car is not operating or when a fault is detected that requires isolation of the hydrogen storage system.

(3) The thermally-activated pressure relief devices (TPRDs)

In the event of a fire, thermally activated pressure relief devices (TPRDs) provide a controlled release of the gas from the compressed hydrogen storage containers before the high temperatures in the fire weaken the containers and cause a hazardous rupture. TPRDs are designed to vent the entire contents of the container rapidly. They do not reseat or allow re-pressurization of the container. Storage containers and TPRDs that have been subjected to a fire are expected to be removed from service and destroyed.

(C) Safety devices in hydrogen fuel delivery system

The fuel delivery system shall reduce the pressure from levels in the hydrogen storage system to values required by the fuel cell system. In the case of a 70 MPa NWP compressed hydrogen storage system, for example, the pressure may have to be reduced from as high as 87.5 MPa to less than 1 MPa at the inlet of the fuel cell system. This may require multiple stages of pressure regulation to achieve accurate and stable control and over-pressure protection of down-stream equipment in the event that a pressure regulator fails. Over-pressure protection of the fuel delivery system may be accomplished by venting excess hydrogen gas through pressure relief valves or by isolating the hydrogen gas supply (by closing the shutoff valve in the hydrogen storage system) when a down-stream over-pressure condition is detected.

5.4. FC Buses

5.4.1. Description

FC buses use the same technology as FCH cars described in the section 6.1. Hydrogen, which is stored in tanks (usually located on the roof of the bus) mixes with oxygen from the air creating electricity to drive the electric motors [2]. The main advantages of FC buses compared to the conventional ones are reduced pollution; lower concentration of greenhouse gases; increased energy efficiency and a quieter operation [2].

There is a range of European projects associated with a hydrogen-based transport. For example, Clean Energy Partnership (CEP) (http://www.cleanenergypartnership.de) is the project that aims to test and to demonstrate the use of FCH technologies in transport applications. CEP, established in 2002, is an international cooperation of 18 partners including leading car manufacturers such as BMW Group, Honda, Daimler, Ford, Hyundai, GM/Opel, Toyota and Volkswagen. In 2011 CEP moved to its third phase 'Market preparation'. Another project is HyFleet: Cute (http://www.global-hydrogen-bus-platform.com/Home), which seeks to develop and operate the world's largest fleet of FC buses. There are between 40 and 45 FC and Internal Combustion Engine (ICE) buses in operation around the world, most of which are in regular public service [3]. These buses have been successful in providing valuable data to developers and operators as they are operated under harsh conditions, through uninterrupted operation and extreme climatic conditions. Another important aspect of this project has been to familiarize the public with this new technology and to thereby gain public acceptance of its introduction [3]. London now has a fleet of 8 FC buses running on route RV1 between Covent Garden and Tower Gateway (Figure 6.5).

Figure 6.5: Wright Pulsar 2 hydrogen-powered bus on route RV1.

“FC-buses have evolved substantially in the last decades. A number of different design configurations have been used, including hydrogen in ICE, and various fuel cell technologies. In addition, companies have used direct drive systems and hybrid drive systems, where an energy storage device (battery or ultra-capacitor) is included within the drivetrain to reduce peak loads and allow regenerative braking” [4]. A brief comparison between the main hydrogen bus technologies is presented in the review curried out within NextHyLights project [4].

Figure 6.6 shows the layout of SunLine’s “All American” FC bus [2].

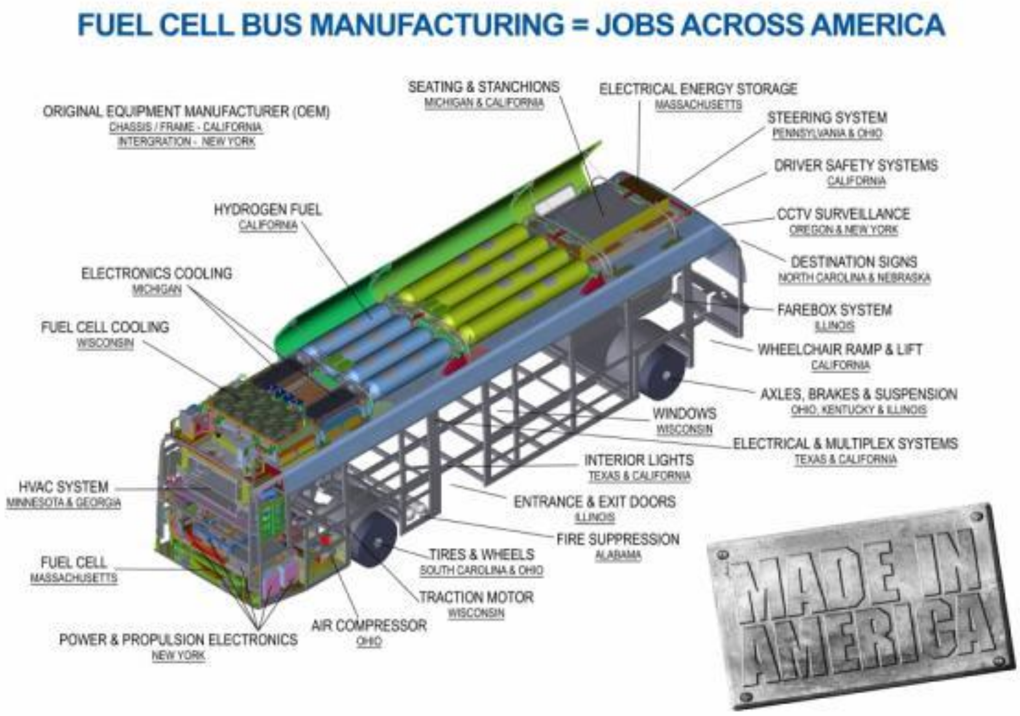


Figure 6.6: Typical layout of the main components of a FC bus [2]

In this example hydrogen is stored as compressed gas (CGH2). Adams [5] carried out a research looking into the optimum on-board storage pressure that would be required for buses equipped with CGH2 tanks [5]. This it was concluded that a standardised on-board storage pressure restricting device is required in order to ensure that a vehicle is not refilled to a pressure greater than the storage pressure to which it was designed. This standardisation would also be necessary to reduce unnecessary system development costs for vehicles and the associated refilling infrastructure as well as reducing the risk of damaging refilling interfaces due to incompatibility. The compression energy within the gas in a container increases for a given mass of hydrogen with increasing storage pressure; therefore sudden expansion of the gas due to the container rupturing could have severe consequences that would increase with higher pressures. Therefore when considering storage systems for buses, where volume is not as critical a constraint as in cars, optimum pressures for non-articulated single deck city buses were found to be between 20 and 35MPa [5].

5.4.2. Safety features and concepts

Safety devices used in FC buses are similar to those used in FCH cars (see section 6.1 of this document). PRD is a non-reclosing thermally activated device that is designed to protect a pressurised hydrogen tank from a catastrophic failure should an emergency situation such as a fire occur. It is used to ensure that the thermal impact caused by flames does not increase the pressure in the storage vessel beyond its structural capacity. It should be noted however that fires that cause a PRD to open may not result in the hydrogen's immediate ignition on release. The importance of a PRD being installed and working correctly in case of emergency was underpinned by research carried out by Zalosh [6]. In his study a cylinder, containing gaseous hydrogen pressurised at 35 MPa and not equipped with a PRD, was exposed to a fire and eventually ruptured. When rupture occurred the heat release rate was measured to be 370 kW, with the blast-wave reaching a peak pressure of 310 kPa at a distance of 1.9 m. The amount of energy released during the rupture was highlighted by a 14 kg fragment of the tank being found 82 m away from its original location.

5.5. Forklift

5.5.1. Description

The forklift truck and the fuel cell (see figure 6.7) are CE marked and meet the requirements of the applicable European directives[2].

	
Forklift truck	Focus on the fuel cell unit

Figure 5.7: Photograph of the forklift truck

Figure 6.8 shows an exploded view of the fuel cell. Its principal components are:

- the fuel cell (or PAC),
- the fuel cell auxiliaries,
- a hydrogen storage area, the volume of which varies between 20 and 70 L in water and fitted with a regulator system,
- a lithium ion battery. This passes the tests required by the United Nations (UNO), specified in the United Nations Manual of Tests and Criteria, Section 38.3
- a water collection tank

[2] Pressure Equipment Directive (97/23/EC), Machinery Directive, Electromagnetic Compatibility Directive, EC79/2009: Type Approval of hydrogen-powered motor vehicles, ISO 15500-6-2001(E) Road Vehicles-Compressed Natural Gas (CNG) fuel, Components-Part 9:Automotive Tank valves, NGV3.1-Fuel System Components for Natural Powered Vehicles, EIHP European Integrated Hydrogen Project

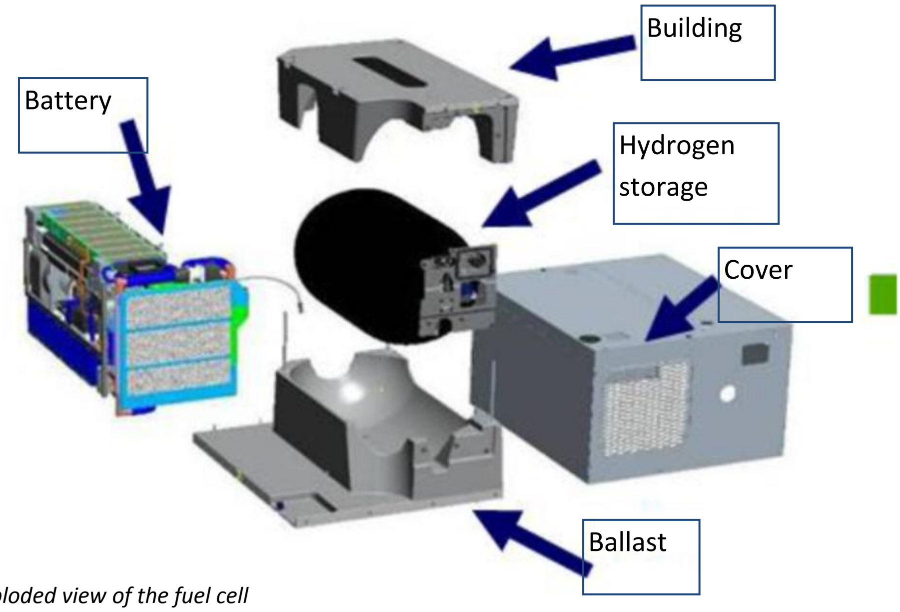


Figure 5.8: Exploded view of the fuel cell

5.5.2. Safety features and concepts

From a safety point of view, the hydrogen storage is protected by a thermal fuse (F1 in Figure 6-1) situated between the forklift's isolation valve (V6) and the cylinder itself. This fuse opens at 109°C and allows the rapid release of pressurised hydrogen. There is also a non-return valve on the filling port to prevent gas present in the storage from escaping. Also, all the components of the fuel cell are built into a cast iron casing, itself protected by a cover. There are two advantages to this cast iron casing: it provides strength against external mechanical attack and allows the flow received to be evened out in the event of an external thermal attack.

6. Hydrogen refueling stations

6.1. Description

6.1.1. Operating principle

The main function of the installation is to fill the tanks of vehicles (forklift truck, bus, car) powered by fuel cells (PAC) with gaseous hydrogen. A block diagram of the installation is shown in Figure 6-1. The gaseous hydrogen, contained initially in a semi-trailer at a pressure of 200 bar, is compressed in the HP storage. During the filling, the tank is filled by a balancing of the pressure. The pressure in HP storage is between 450 bar for forklift truck and bus and 1000 bar for car. The pressure in vehicle tank is between 350 bar for forklift truck and bus and 700 bar for car. To fill as fast as possible a car, hydrogen could be cool during filling by cryogenic liquid nitrogen storage or a cold unit.

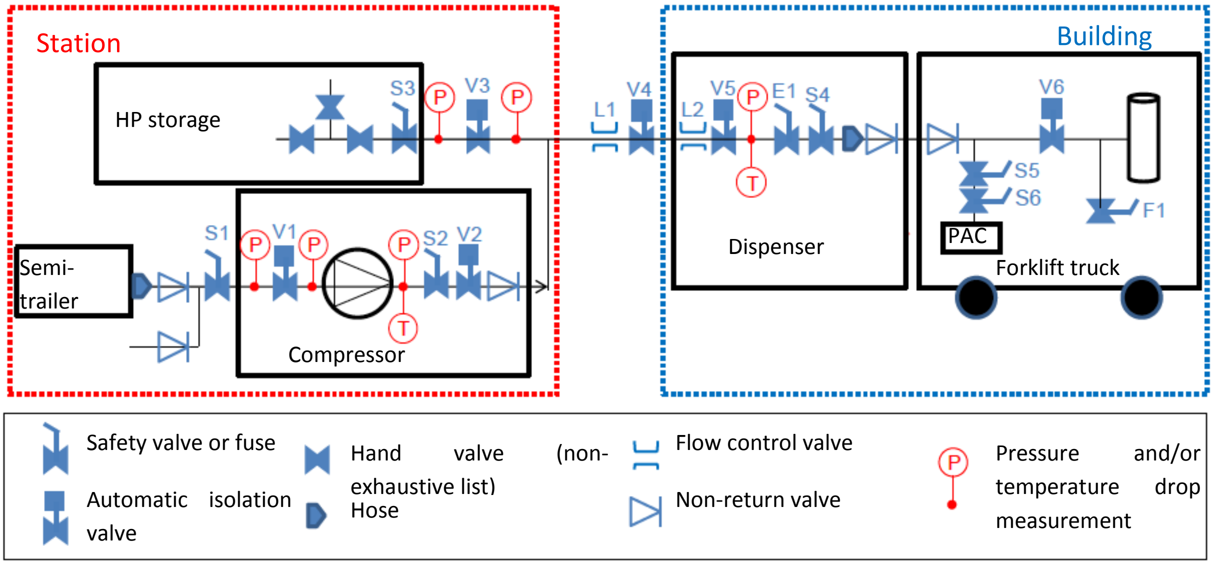


Figure 6-1: Block diagram of the installation

The semi-trailer, compressor and HP storage are located outside in an area subsequently called the "outdoor area" (see Figure 6-2).

The dispenser could be located in the dedicated building and/or in a logistics warehouse cell and/or outside depending on the applications. These premises have volumes that could vary between a hundred or so cubic metres to some 10,000 cubic metres. Standard MF58-003 requires forced extraction for low volume premises[3].

A connecting pipe runs between the filling area and the dispenser.

Each of these items of equipment is described in detail in the following paragraphs.

The entire installation is CE certified.

[3] The notion of low volume is defined in paragraph **Erreur ! Source du renvoi introuvable.**.

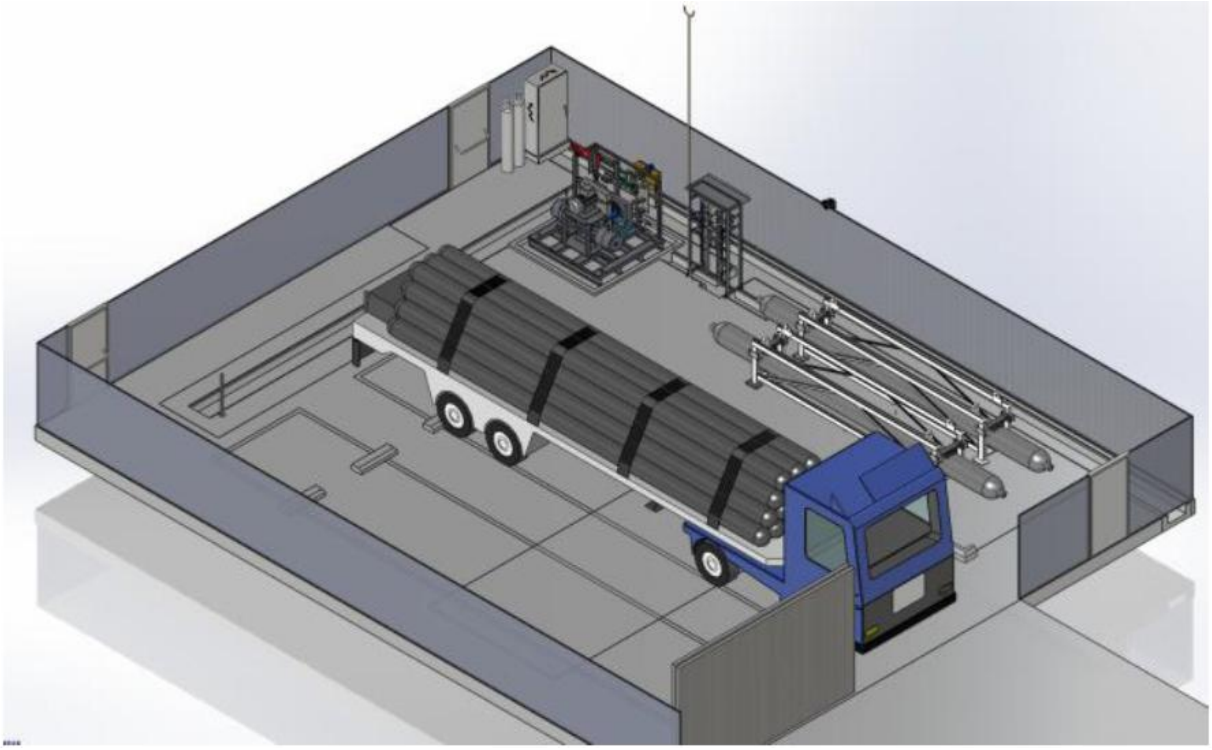


Figure 6-2: Typical layout plan of an outdoor area

6.1.2. Compressor

The compressor system is installed on a concrete slab and is protected by a shed. It comprises (seeFigure 6-3) or in a container:

- a diaphragm or hydraulic compressor for the hydrogen,
- a compressor cooling system,
- miscellaneous equipment (valves, relief valves, etc.).

Figure 6-3: Photograph of the compressor

6.1.3. HP Storage (or "buffer")

The HP storage is a buffer capacity and meets the Pressurised Equipment Directive (DESP) (Figure 6-4).

Its total volume varies between 1,000 and 3,000 L in water. It may be designed from several storages whose unit volume varies between 50 and 1,500 L. The pressure in HP storage is between 450 bar for forklift truck and bus and 1000 bar for car. The storage is protected by a relief valve (S3). The discharge from this relief valve is evacuated through the same vent stack as that used for the compressor system (see previous paragraph).

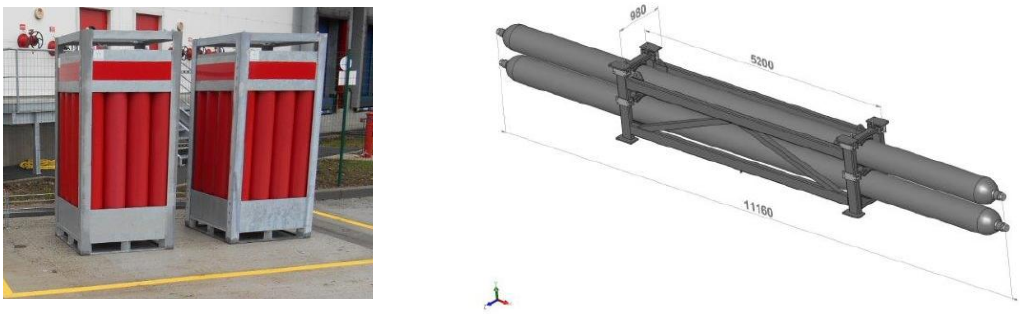


Figure 6-4: Image of the HP storage

6.1.4. Connecting pipework

This pipework connects the HP storage to the dispenser. Depending on the site concerned, its total length can vary between several tens and several hundreds of metres. So far as is possible, an outdoor routing is preferable, in order to avoid the risk of a leak indoors. Parts crossing access roads are contained in a channel or supported on a gantry or buried and exposed parts are protected (possibly physical protection on vertical sections, passing through walls or on a roof). Pipework enters the building at the last possible moment for connection to the dispenser.

The characteristics of the pipework are:

- Material: compatible with the use of hydrogen (example: 316L stainless steel).
- Outside diameter: less than 1" depending on the length of the pipework.

6.1.5. The dispenser

The dispenser may be installed in one of three different places:

- in a storage cell
- in a dedicated room,
- outside

The dispenser comprises (see Figure 6-5):

- a mast, itself equipped with;
  - a hose fitted with an anti-tear-out system and connected to a filling gun
  - a cabinet containing the pipework connection and the system of valves
- station-vehicule communication and vehicule earthing cable (when it is needed),

- a pipe for draining water from the truck's water tank
- a remote interface allowing the operator to remotely control the filling of the forklift.


Figure 6-5: Configuration example for a dispenser

6.1.6. Description of the different operating modes

The installation has three distinct operating modes:

- the HP storage filling phase
- the forklift filling phase
- the forklift filling phase in impaired mode

Each of these situations is illustrated very diagrammatically in

Figure 6-6. After each filling the connection pipework is isolated from the outside by closing valves V3 and V4. The dispenser is then de-pressurised by opening vent valve E1 and isolated by valve V5.

- A daily test is done in the following stages.
  - Isolation valves V3 and V4 opened (while valves V2 and V5 are kept closed),
  - Waiting for the pressure to balance upstream and downstream of V3,
  - Once that pressure is balanced, valve V3 is closed,
  - Monitoring of pressure changes downstream of V3. This monitoring time is defined depending on the acceptable rate leakage from the installation.

Any leak noted during the daily test results in valves V3, V4 and V5 being closed, vent E1 being opened and the station being closed until it has been dealt with by the maintenance department. This test is automatic. It is recommended that it is carried out before use.

- A leak tightness test before every filling operation. This is done according to the following steps:
  - Vent valve E1 is closed, valves V3, V4 and V5 are opened.

- ○ Valve V5 closed and comparison of the pressure measured at the dispenser with that at the exit from the HP storage.
- ○ Monitoring of pressure changes measured in the dispenser. This monitoring time is defined depending on the acceptable rate leakage from the installation.

Any leak noted during the daily test results in valves V3, V4 and V5 being closed, vent E1 being opened and the station being closed until it has been dealt with by the maintenance department. This test is automatic.

- A leak tightness test during filling. It consists of controlling the changes in the pressure measured during filling. This test is automatic.

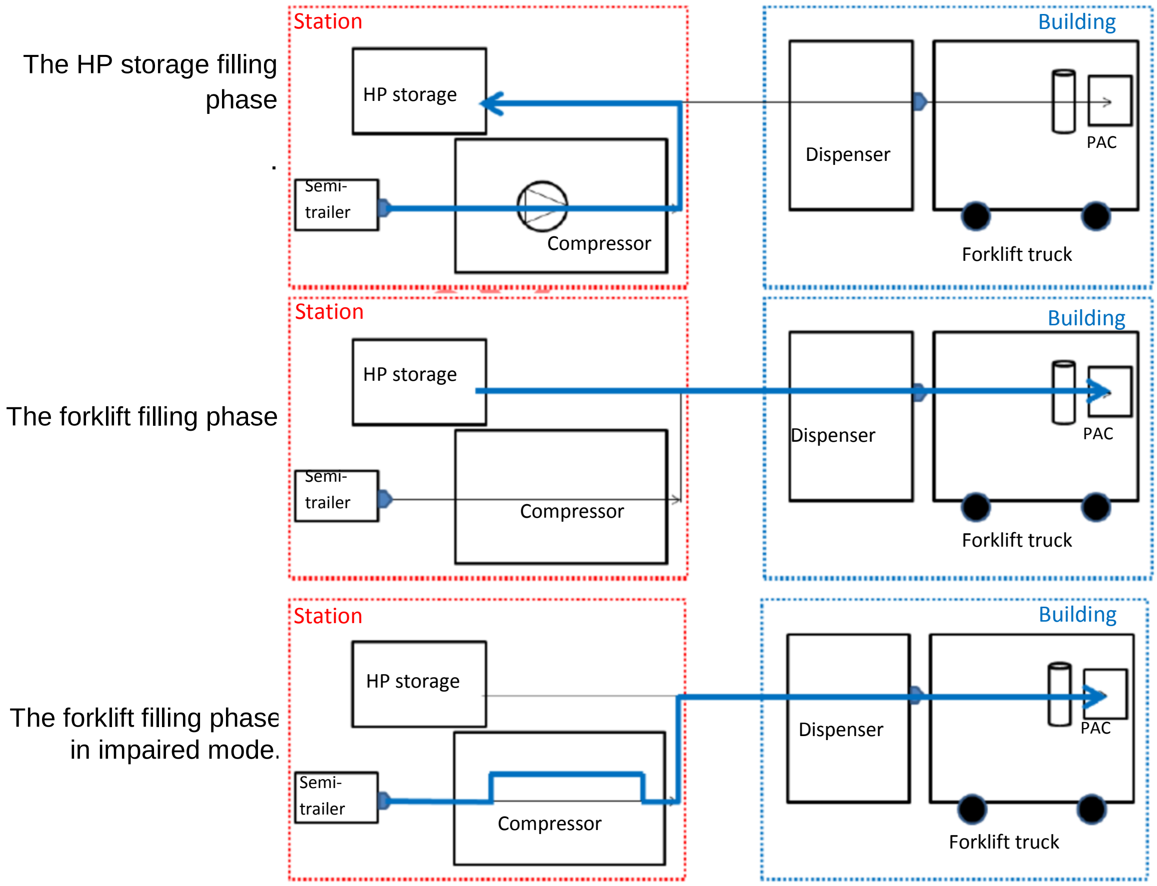


Figure 6-6: Presentation of the installation's three different operating modes

6.2. Safety features and concepts

6.2.1. Outdoor area

The "outdoor area" is identified, marked out, physically protected and has controlled access. It complies with "industrial" hydrogen installation rules. Among the main rules, we should cite access not possible to unauthorised personnel, compliance with a minimum distance from a building, or alternatively the presence of an REI120 wall.

From a safety point of view, the hydrogen compressor is equipped with two automatic isolation valves at the intake and exit (V1 and V2 in Figure 6-1), a safety relief valve (S2) and a non-return

valve. Discharges from relief valves are collected and evacuated through a vent stack which is sized according to the maximum permitted flow rate, the noise on exiting the vent; the heat flow caused by the hydrogen flame and expected overpressures in the event of the discharged hydrogen cloud igniting. Also, the compression system includes a retention tank, sized according to the quantity of oil used.

6.2.2. Connecting pipework

The pipework includes an automatic isolation valve (V3 in Figure 6-1), normally closed and located in the outdoor area.

6.2.3. Dispenser

The items contributing to safety are as follows:

- The dispenser is located away from roadways. If it is needed, protective barriers are put in place around it to prevent any collision with a vehicle approaching to be filled or with another one manoeuvring in the area. The dispenser is also on a raised platform.
- Combustible things are kept at least 4 m away from the dispenser. Markings on the floor make the perimeter clearly visible.
- The vehicule's speed is limited. An area is marked on the floor to indicate the position of the vehicle during filling.
- When the operator handles the hose (connection to or disconnection from the vehicule), the hose is no longer under pressure.
- The filling control interface is 2 m away from the hydrogen mast (ATEX zoning).
- An anti-tear-out system is fitted to the hose. If the hose is torn out, the device quickly closes two valves to isolate the leak on the station side and the truck side. It is therefore a weak point in the line.
- The dispenser is fitted with a regulator/ flow limiter (L2 in Figure 6-1), with a normally closed isolation valve (V5), with a safety reducing valve (S4) and a normally open vent valve (E1). During normal operation of the installation, flow limiter L2 is used to regulate the downstream flow rate, such that a rise in pressure in the vehicle’s storage is limited. In the event of an accidental rupture occurring downstream of this item, it is expected that it will limit the rate of leakage. Discharges from S4 and E1 are collected in a second vent stack which is sized according to the maximum permitted flow rate, the noise on exiting the vent, the heat flow caused by the hydrogen flame and expected overpressures in the event of the released hydrogen cloud igniting. It is situated on the building.
- If the dispenser is located in a building, a naked flame detector (UV/IR sensor appropriate to the radiation characteristics of a hydrogen flame) could be positioned above the dispenser.
- Hydrogen detection is installed in the dispenser at the top of the mast. During the filling stages, a concentration greater than 25% of the LEL or the detection of a flame will result in all isolation valves (V3, V4 and V5) closing and vent valve (E1) opening. Other than during the filling phase, the isolation valves are closed and the vent valve is open.
- If the dispenser is located in a building of relatively modest, hydrogen detection is also installed in the upper part of the building (ambient detection). In actual fact, the low volume inside the building may not allow sufficient dilution of the hydrogen discharge to prevent it

from forming an explosive atmosphere. An air extractor is also installed, as required by standard M58-003.

7. FC stationary applications

7.1. Combined production of Heat and Power (CHP) system

This application is exactly the same that Hydrogen based energy storage see section 8.1

7.2. Stationary back-up power generation

7.2.1. Principle and functioning of the fuel cell

The fuel cell is an electrochemical generator which produces electricity, heat and water (pure), from a fuel (hydrogen) and a combustive (oxygen which can be pure or resulting from the ambient air).

Several technologies of fuel cell exist, AREVA Stockage d'Energie focuses exclusively on fuel Cells of the PEM type (Proton Exchange Membrane), operating with hydrogen and oxygen gases. With these gases, fuel cell has a better efficiency and to be independent of the ambient air (anaerobic operation), which allows operation in a hostile or vitiated environment, even confined.

- The principle of operation of a fuel cell of the PEM type is the following:

- At the anode, the hydrogen H_2 molecules are dissociated in H^+ protons and electrons e- under the effect of a catalyst: $H_2 \rightarrow 2H^+ + 2\ e^-$,

These protons are led to cathode through the membranes and the electrons pass through the external electrical circuit.

- At the cathode, the oxygen O_2 molecules are recombined with the protons and the electrons to form water: ½ $O_2 + 2H^+ + 2e^- \rightarrow H_2O$.

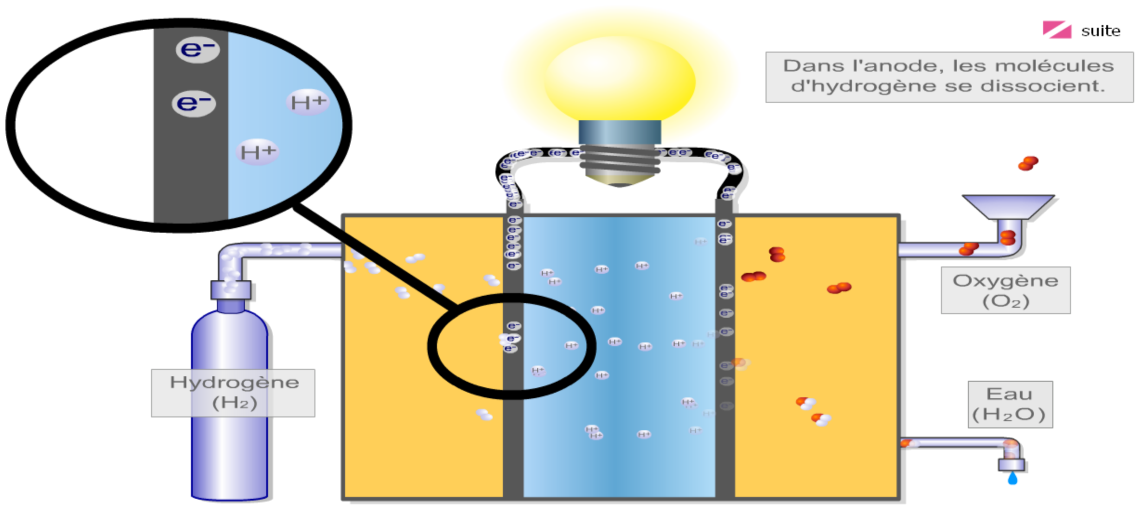


Figure 7-1: Schematic principle of fuel cell functioning

In a practical way, the electrodes (anode and cathode) and the membrane are associated to form a Membrane Electrode Assembly called MEA.

It should be noted that water is in vapor and liquid forms, and that a part is transferred to the anode (hydrogen side) by electroosmosis.

This reaction generates a differential of terminal voltage at the electrochemical cell, function of the generated current (about 0.7 V with the rated current). A stacking of fuel cell (called stack) allows obtaining the desired power.

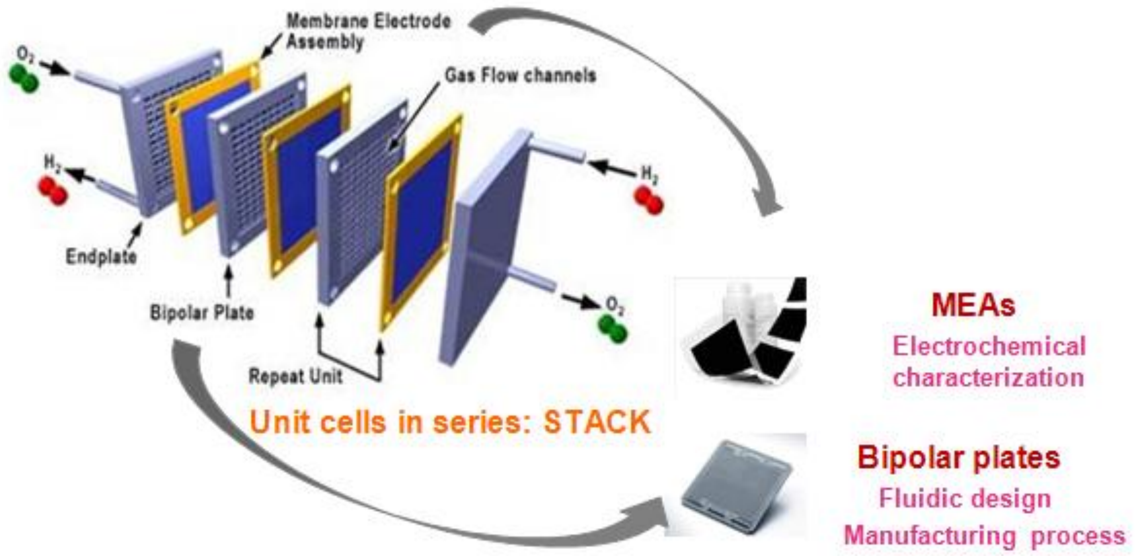


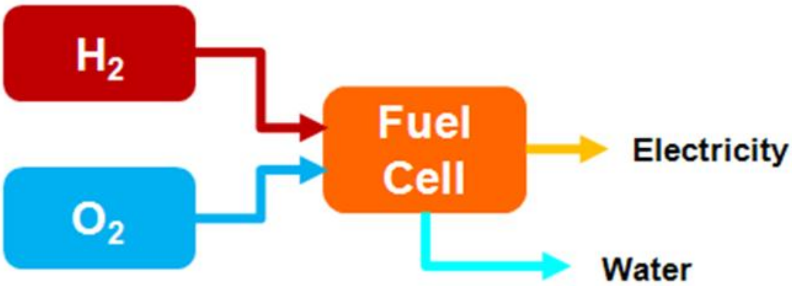
Figure 7-2: Illustration of a MEA

7.2.2. Example of FC stationary application: Backup system connected to a datacenter

The main objective of such a technology is to provide instantaneous power in time in case of blackout

Figure 7-3: Back up system on AREVA Stockage d'Energie-Aix en Provence

- Overview of the process



- Technical specifications

Power capacity	16 - 80 kW (20 -100 kVA) up to 6 systems in parallel
Startup time	Instantaneous
Autonomy (example)	80 kW at full load with 9 standard H2 cylinders: 1 hour 25 min

- Main advantages
  - High reliability and fast startup
  - Scalable autonomy only depending on gas storage volume
  - Low maintenance
  - Clean and silent

- USERS
  - Telecom, Datacenters
  - Hospitals, Military
  - Industries

- Luxury hotels

- Reference project: IP Project

Figure 7-4: Fuel cell backup power coupled to the IP Energy data center

- Key facts & figures
  - Market segment: Backup Power
  - Customer: IP Energy
  - Location: Aix-en-Provence, France
  - Power supply: 30 kW
  - Schedule: Installed in 2008

- Results of the IP Energy project:
  - 30 kVA backup power system installed in 2008, 1st containerized solution
  - Internal gas storage allowing a 4-hour operating capacity
  - 3-year experience feedback as backup power supply to AREVA Energy Storage's test benches, until 2011
  - In late 2011, it provides backup power to a modular and containerized data center

7.2.3. Safety features and concepts

- *Gas Venting*

The fuel cell system has two separated vent lines, one for oxygen and one for hydrogen, that discharges the gas on the roof of the container at a separation distance to avoid mixing of oxygen and hydrogen during discharge. After a discharge, a residual amount of hydrogen subsists within the system.

- *H2 detection*

The process compartment is equipped with two hydrogen sensors that triggers an emergency stop if the hydrogen concentration is above 0.4% H_2 (vol.) in the containers.

If an abnormal hydrogen concentration is detected, a safety stop is triggered and the following actions will take place:

- Stop of the process of the system
- Activation of the mechanical ventilations
- Insulation of gas storages (closing of the solenoid valves)

Detection H_2 is insured permanently even if the system is on standby. In the event of loss of detection, the system triggers a safety stop.

- *Fire detection*

The container is equipped with fire detector sets fire which can provoke an emergency stop of the system:

- Stop of the process of the system
- Insulation of gas storages (closing of the solenoid valves)
- Cutting off ventilations

- *Prevention of hydrogen accumulation and ATEX formation*

Hazardous explosive atmospheres resulting from anticipated hydrogen leaks or releases shall be prevented in the Fuel Cell enclosure.

Passive prevention methods include but are not limited to:

- use of joints that are permanently secured and so constructed so that they limit the maximum release rate to a predictable value;
- natural ventilation.

Active prevention methods include but are not limited to:

- active ventilation;
- a flammable gas detection system;
- other means of leak detection (e.g. through pressure measurements relative to control settings).

- *To reduce ignition sources*

The inside of the container where hydrogen may leak or diffuse into is not classified since safety barriers ensure no dangerous hydrogen ATEX at the leaking point or by accumulation. Nonetheless, all equipment installed just below the container ceiling and susceptible ignite a flammable hydrogen-air mixture is certified for ATEX zone 2. In particular, it concerns the fire, hydrogen, sensors and the ventilation system.

Besides, the electrical compartment is systematically separated from the process compartment.

- Prevention of the risk related to the use of oxygen

Oxygen is not flammable in the air but it maintains combustion (it constitutes the combustive). An oxygen leak can be at the origin of a fire hazard. The fire risk is increased when the atmosphere is enriched out of oxygen:

- At 23%; combustion is accelerated.
- At 30%; combustion is intense.
- At 50%; combustion is instantaneous.

Any contact must be avoided between oxygen and the organic matters because of the fire risk.

General measures of risk prevention are taken with the design and in exploitation:

- Choice of the materials (degreased stainless), protected pipes and without abrupt elbows, tight connections and as much as possible welded
- Limitation of the oxygen flows according to the pressure
- Protection of the oxygen lines by filters in order to trap dust that is likely to ignite
- Natural and forced ventilation in the process compartment
- Reduction of lengths of the pipe under high pressure, sufficient separation of the pipes with the electric components
- Regrouping of the bodies containing oxygen in a delimited zone (compartment)
- Respect of the procedures of control and maintenance (periodic tests) of the facilities defined in addition

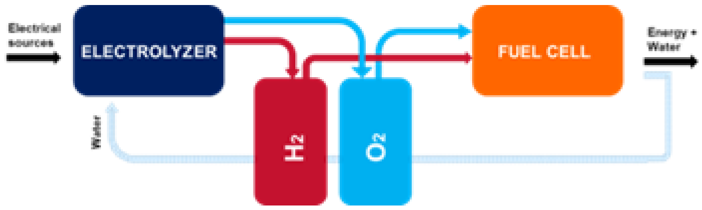
8. Decentralized hydrogen production

8.1. Hydrogen-based energy storage system (Greenergy Box)

8.1.1. Description

The Greenergy Box™ is a containerized hydrogen chain comprising an electrolyser, a fuel cell, a water and heat management, and electrical converter systems coupled with a hydrogen and oxygen storages installed aside of the container. The Greenergy Box™ is an integrated modular system that can offer a power from 50 to 500 kW with a storage capacity from 0.2 to 2 MWh. Several systems can be coupled to increase the power and the energetic capacity. Coupled with RES, such a solution allows not only ensuring a partial building autonomy from 45 to 85 % but also providing the function of backup system for few hours at high power.

Overview of the process



Technical specifications

Maximum charge power	75 kW
Discharge power	20 - 100 kW up to 5 systems in parallel
Round trip efficiency **Electrical efficiency**	70-80 % (heat included) 30-35%

The photovoltaic panels provide electricity to the electrical network and the surplus is used by the electrolyser to generate gaseous hydrogen and oxygen. Once produced, gaseous hydrogen and oxygen are stored within separated tanks installed aside of the Greenergy Box™. It is thanks to the fuel cell system that the stored hydrogen and oxygen can be used to produce electricity to ensure partial energetic autonomy of the buildings as well as the backup system in case of power cut. The Greenergy Box™ manages itself the electricity received by the photovoltaic panels to electrolyze water or to provide electricity to the network. Furthermore, heat, which is also produced by the system during both electrolysis and fuel cell processes, is also managed and valorised for the adjacent buildings.

The water-proof and wind-resistant Greenergy Box™ is separated into three different compartments, including in particular an electrical, a fuel cell compartment and an electrolyser compartment as shown in Figure 8-1 below.

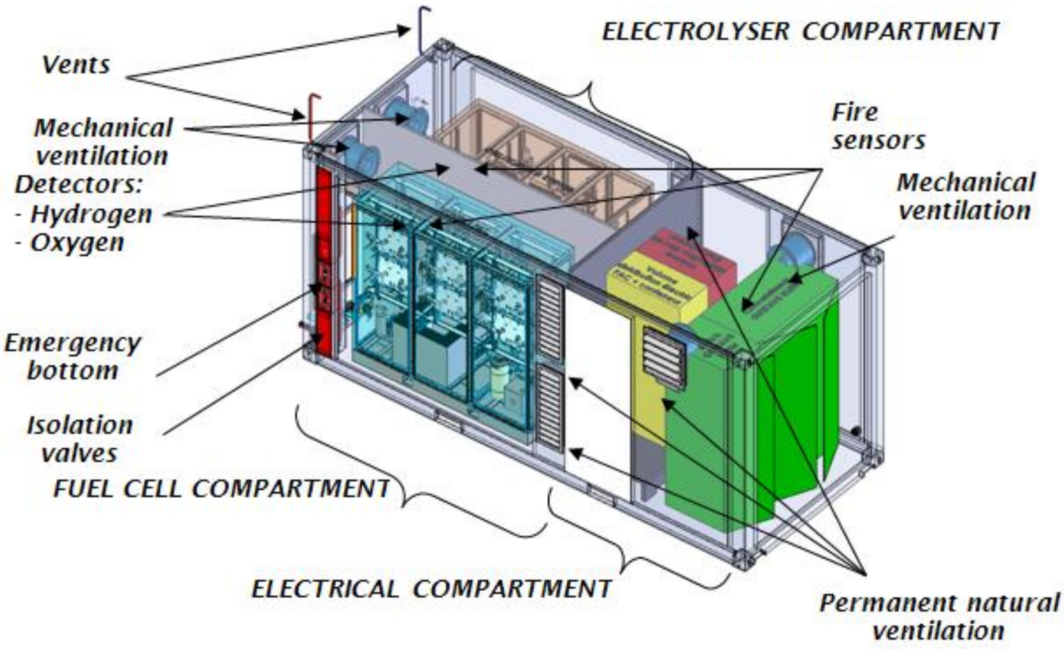


Figure 8-1: Compartments of the Greenergy Box™

8.1.2. Safety features and concepts

- <u>Safety strategy of the Hydrogen Chain</u>

AREVA Energy Storage is designing and building hydrogen systems for more than 10 years. Safety is always a key consideration. A good knowledge of hydrogen behaviour, designing and building our system in conformity with European and French codes, standards and best practices allows maintaining a high safety performance.

The Greenergy Box™ is certified CE by following the Low Voltage Directive, LVD 73/23/EEC, the Electromagnetic Compatibility Directive, EMC 89/336/EEC, Machinery Directive, MD 98/37/EC, Pressure Equipment Directive, PED 97/23/EC.

The risk assessment of the complete hydrogen chain is realized in three steps. First, a document "Basic safety considerations" that describes the main safety requirements to be followed for the architecture and conception stages of the hydrogen chain is written. Once the architecture of the system is sufficiently detailed, a HAZOP revue of each subsystem (HAZard and OPerability Study) is realized to define the potential causes of each process deviation, associated potential consequences and assess the existing barriers. As a third stage, a fault tree analysis completes the HAZOP revue so as to highlight the conception failure, inappropriate system configuration and external sources of danger. All the safety study is centralized in a same document "Synthesis of the safety studies of the Greenergy Box™".

The overall safety strategy of the hydrogen chain is detailed below into six different parts.

- Leak suppression and control

Equipment and piping materials are chosen to be compatible for hydrogen and oxygen use. In particular, hydrogen material embrittlement and oxygen corrosion are selected from the IGC15/06, ISO/TR 15916 and ISO 11114-4. Steel cylinders are commonly used to store pressurized hydrogen and oxygen. The maximum carbon equivalent (CE) for hydrogen is 0.43 as described in the IGC 121/04, § 3.

Welded connections are preferred and are used in a practical way to minimize potential leak sources. The number of joints and fitted connections are minimized.

Both electrolyser and fuel cell compartments of the Greenergy Box™ are equipped with two hydrogen sensors and an oxygen sensor. A safety shutoff triggers at 10 % of the lower Flammability Level (0.4% H_2 in air) and an emergency shut-off occurs at 25 % of the Lower Flammability limits (1% H_2 in air). Oxygen detection triggers whenever the oxygen concentration reaches more than 23% in volume air.

Furthermore, hydrogen and oxygen leaks are also detected by difference of pressure during standby phases. If a tank or a portion of pipe losses pressure during a standby stage, it potentially means that there is leak. If there is a minor loss of pressure during the standby stage, an alarm triggers and if the pressure loss is too significant the system will not be able to restart.

Before commissioning, hydraulic and leak tests are performed as required by the Pressure Equipment Directive.

Regular inspections and preventive maintenance program are organized to ensure the maximum safety level. In particular, leak tests on pressure regulators, valves, pipes, joints and connections etc. are realized regularly. Regular visual inspections are organized to check the level of corrosion. Information regarding inspection and maintenance frequency is in the Appendices F of the IGC 121/04 and IGC 13/02.

- Prevention of formation of flammable or over-oxygenated atmospheres

The three compartments of the Greenergy Box™ are naturally ventilated thanks to lateral vents located on both sides of the container as shown in Figure 2.

The fuel cell and electrolyser compartments are both equipped with an ATEX type ventilation that triggers for hydrogen and oxygen concentration above respectively 0.4% hydrogen or 23% oxygen in air. The maxima flow rate are sized for the thermal dissipation i.e. 2,500 m^3/h for the Fuel Cell compartment and 2,700 m^3/h for the electrolyser compartment.

Modeling of an accidental hydrogen leak of 750 Nl/min flow rate using the LES (Large Eddy Simulation) approach developed at the University of Ulster highlights that it takes about 10 s for the hydrogen sensor to detect a hydrogen concentration greater than 0.4 % in the naturally ventilated electrolyser compartment. Considering the conservative hypothesis of 30 s for a response time of the hydrogen sensor, it can be observed that after 40 s of continuous constant release the hydrogen-air concentration formed below the ceiling is still below the Lower Flammable Limit (LFL) of

hydrogen in air i.e. 4 % by air volume. From this moment, the hydrogen sensor sends a signal to the control command that triggers the air intake fan to its maximal speed. It can be observed that the hydrogen air cloud is entirely diluted in less than 2 s.

- Suppression/Reducing of ignition sources

The inside of the Greenergy Box™ where hydrogen may leak or diffuse into is not classified since safety barriers ensure no dangerous hydrogen ATEX at the leaking point or by accumulation. Nonetheless, all equipment installed just below the container ceiling and susceptible ignite a flammable hydrogen-air mixture is certified for ATEX zone 2. In particular, it concerns the fire, hydrogen, oxygen sensors and the ventilation system.

The Greenergy Box™ and reservoirs are earthed and bonded to give protection against the hazards of stray electrical currents and static electricity.

- Protection against overpressures

Each reservoir and piping lines from the Greenergy Box™ to the storage tanks are equipped with a pressure relief valve. The tare pressure of the pressure relief valve is set so that the PRV actuates when the pressure within the reservoir reaches 1.15 of the maximal operating pressure.

The storage tank vents are mounted vertically at a minimum high of 3 m. They are equipped with a hat for which the weight is calibrated to lift under pressure in order to avoid the introduction of water within the vent.

The Greenergy Box™ is equipped with two distinct hydrogen and oxygen vents located at a minimum height of 1 m above the roof of the container and well separated to avoid oxygen-enriched hydrogen-air mixture. Each distinct venting line is common to the electrolyser and the fuel cell and allows the depressurization of the totality of the system in less than 2 minutes in case of emergency shut-down.

- Emergency and safety shutdown

The control command that is used for piloting automatically the system is also used to trigger the safety functions. About 70 safety functions are recorded into the control command to detect any process deviation or gaseous leak or fire within the system. Depending on the amplitude of the deviation compared to the safety threshold of the parameter, an emergency or and safety shutdown is triggered and is followed by power shutdown, system depressurization, inerting and ventilation activation (except for fires).

The main safety functions i.e. H_2, O_2 and fire detections, emergency shutdown bottom and watchdog of the control command are realized by logic cable and respect a SIL 1 level (Safety Integrity Level).

8.2. Example of existing project: MYRTE platform

8.2.1. Description of the platform

MYRTE (Mission hYdrogen – Renewable for the inTegration on the Electrical grid) is a project which concerns among various other tasks the supply of the grid connected by a photovoltaic plant and hydrogen hybrid system acting as an energy storage system. The project is coordinated and monitored by the University of Corsica in the site of Vignola (Ajaccio, Corsica – France) from where researches are led. The project is supported by the Corsican Regional Authority, the French Government and the European Union (European regional development fund ERDF). This high performance technological platform will contribute to enhance knowledge and strengthen the control of the global energy system, as well as develop the technology based bricks.

The hydrogen platform has to fulfill two main objectives:

- Daily peak load shaving of the electrical demand of the Corsican electrical grid (Corsica Island, France) by using a PV/FC/EL renewable energy system.
- Use of hydrogen for the PV production smoothing to prevent the strong energy variations to the load.

The whole platform is illustrated in the Figure 8-2.

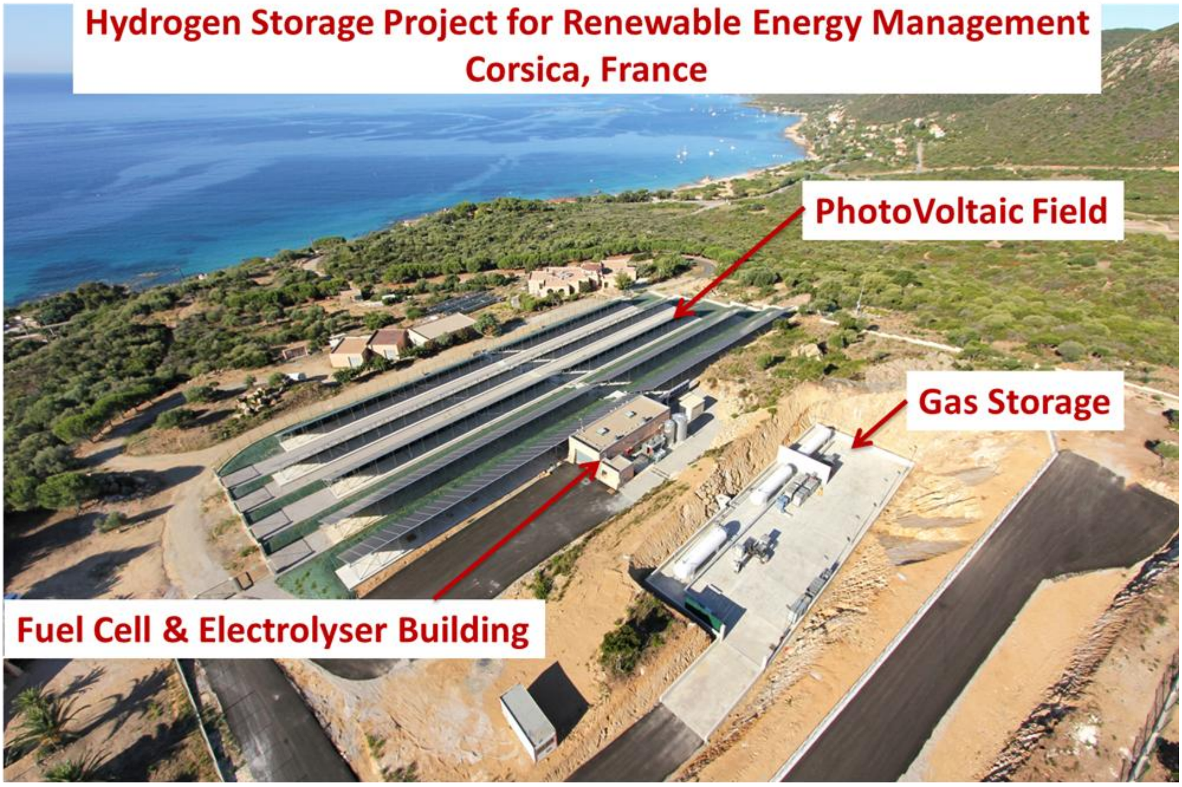
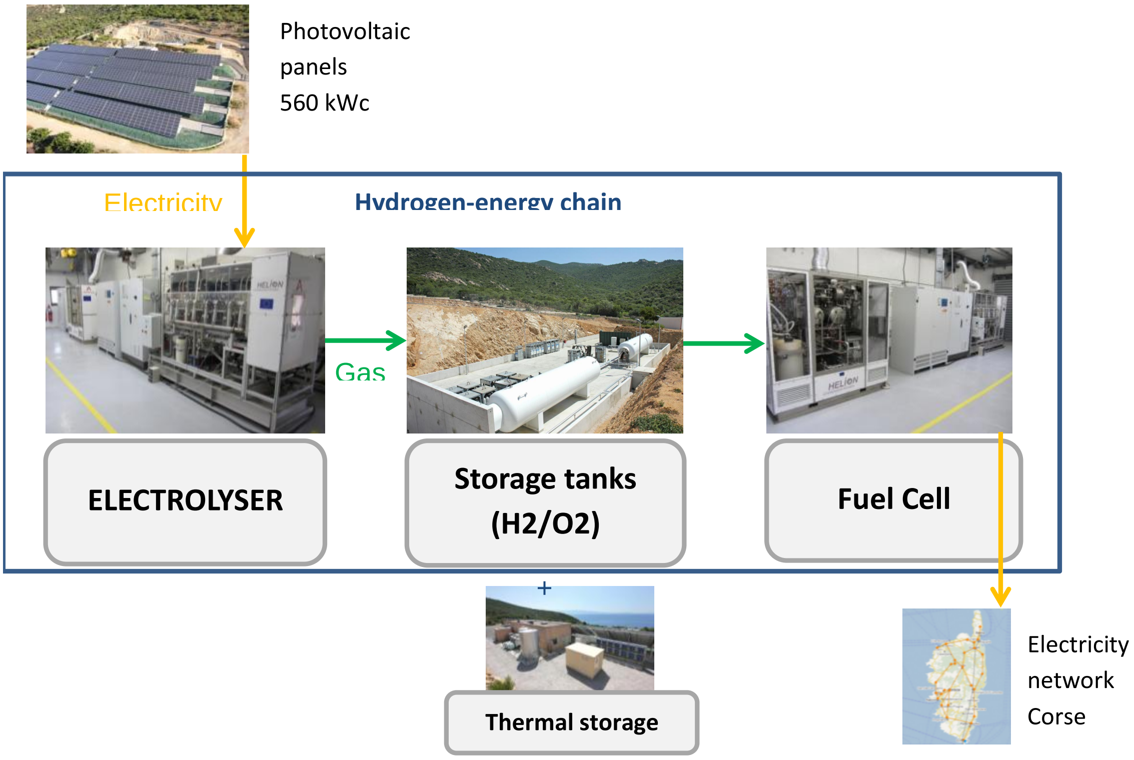


Figure 8-2: Overall view of the MYRTE platform.

The overall functioning principles is described the Figure below. The photovoltaic panels provide electricity to the electrical network and the surplus is used by the electrolyser to generate gaseous hydrogen and oxygen, as shown in Figure 1. Once produced, gaseous hydrogen and oxygen are stored within separated reservoirs. It is thanks to the fuel cell system that the stored hydrogen and oxygen can be used to inject electricity to electrical grid network. The overall chain manages itself the electricity received by the photovoltaic panels to electrolyze water or to provide electricity to the network. Furthermore, heat, which is also produced by the system during both electrolysis and hydrolysis processes, is also managed and valorized.



The platform is composed of several sub-systems that include in particular:

- A photovoltaic farm that aims at providing electrical energy to the electrical network but also to the electrolyser;
- A hydrogen building that includes:
    - an electrolyser that generates gaseous hydrogen and oxygen using the electricity surplus;
    - A H_2/O_2 fuel cell that provides electricity using the gas stored in the reservoirs to deliver electricity to the network;
    - The electric management that ensures the conditioning of the electrical energy to provide the electrical network
    - The control command room to pilot the whole system;

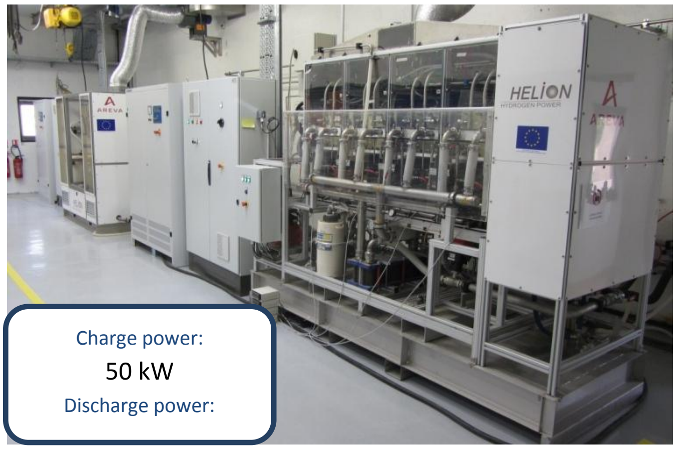


Figure 8-3: Hydrogen building containing the fuel cell System and the electrolyser.

– Hydrogen and oxygen storages;

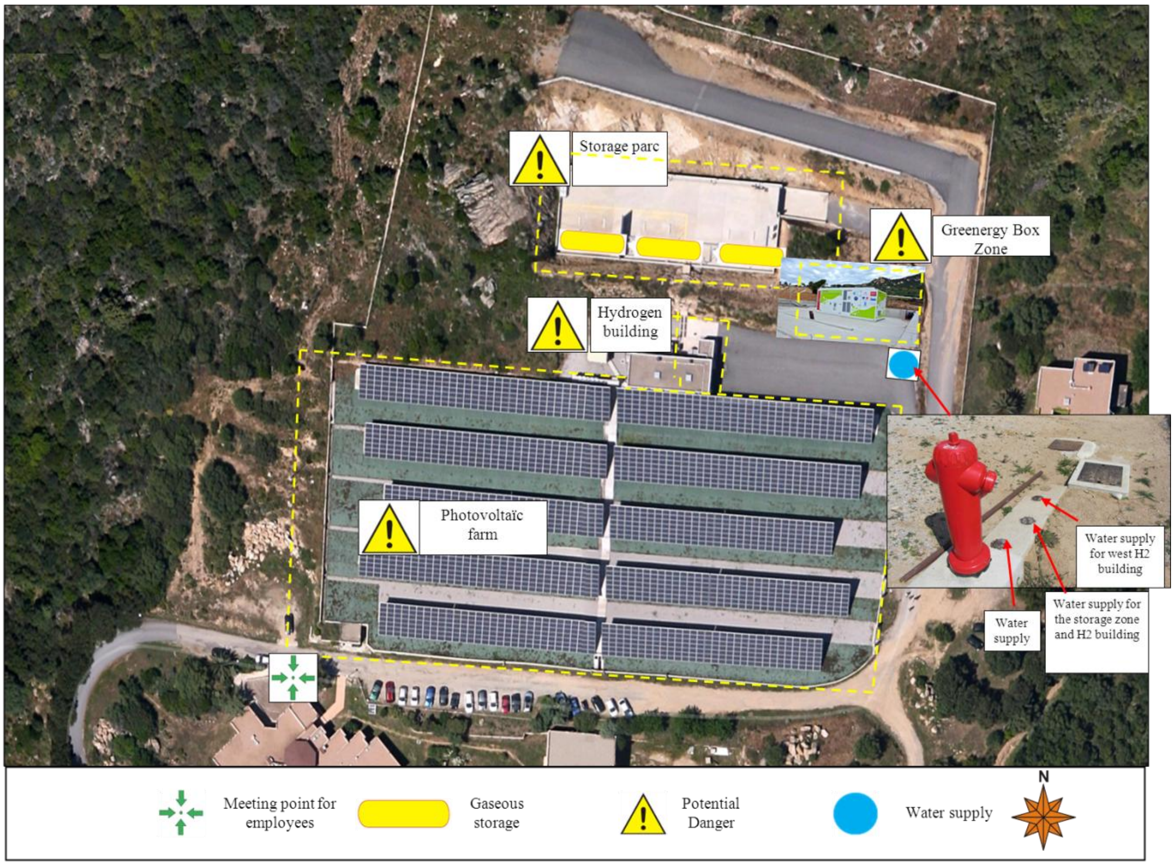
Figure 8-4: Storage zone.

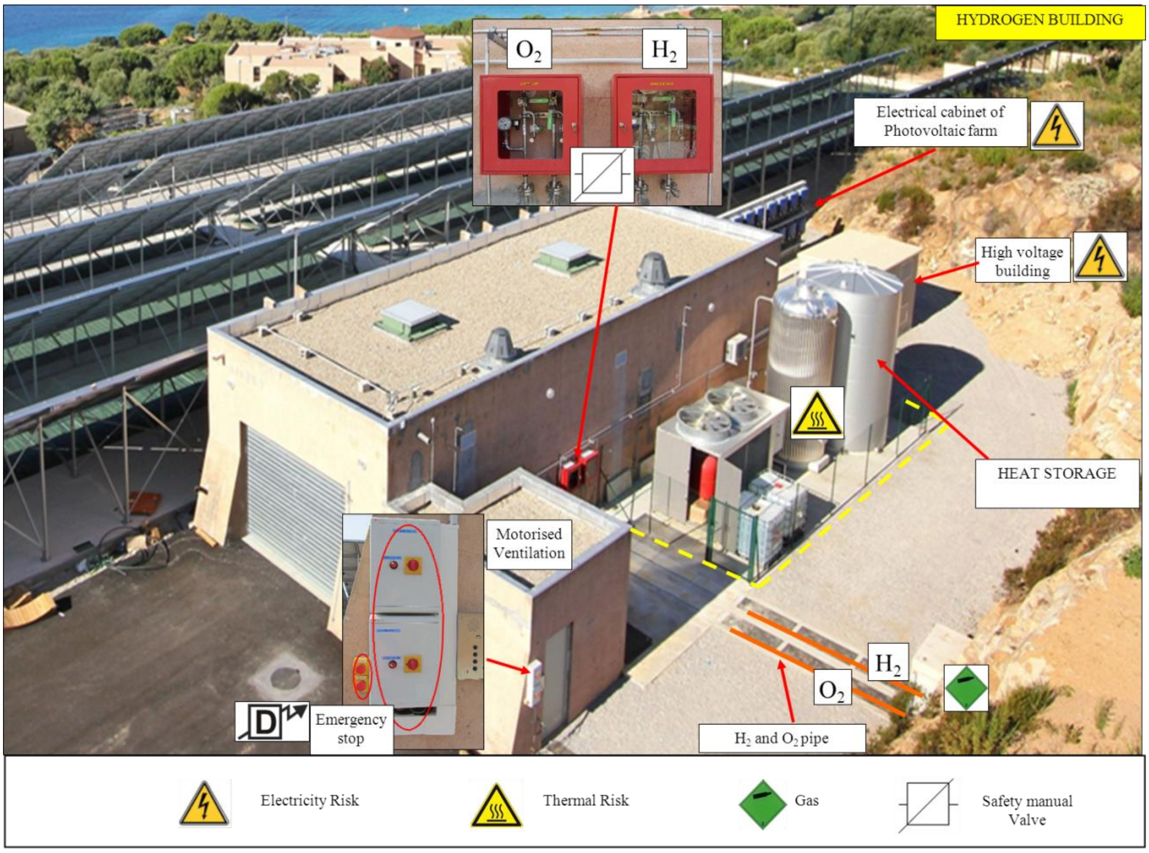
– Heating managing system that ensures the storage and the management of the heat produced by the system;

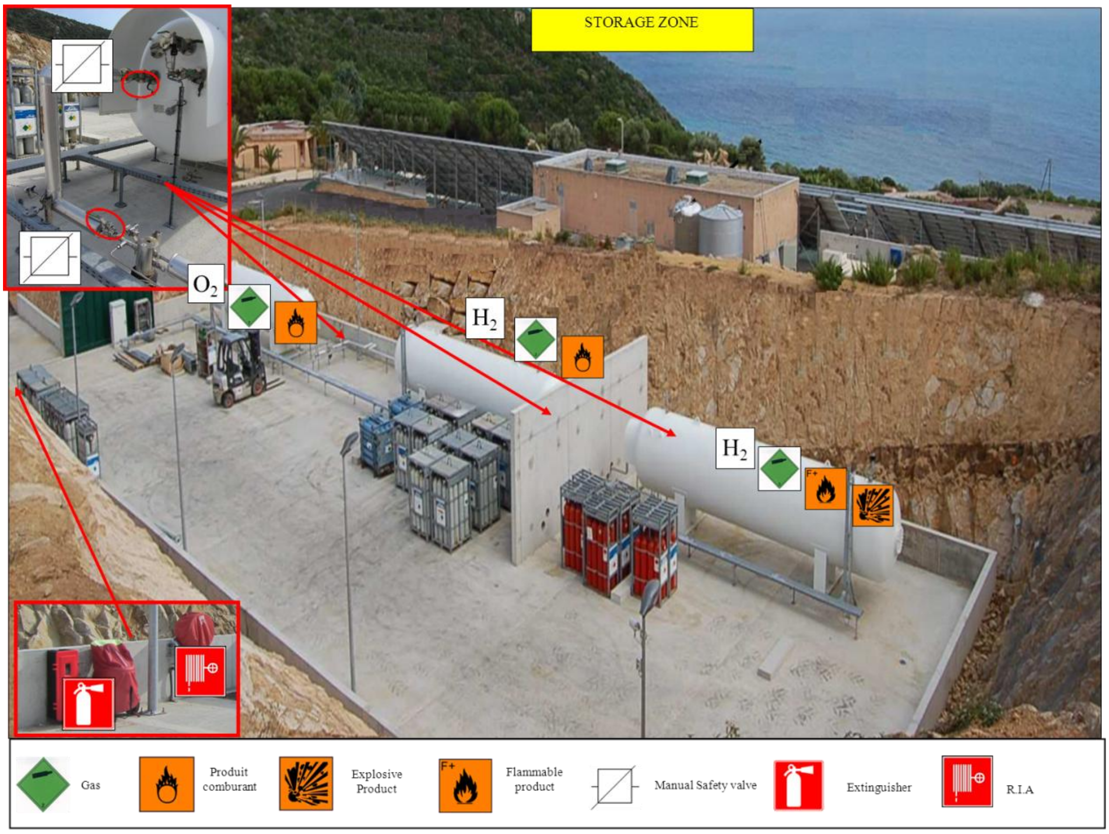
The MYRTE Project is organised in two main phases. For the first phase of the project that was launched in June 2011, a 100 kW fuel cell of and a 10 Nm3/h (50 kW) electrolyser were installed in the Hydrogen building. The net electrical energy stored is equivalent to 1.75 MWh using two hydrogen reservoirs of 28 geometrical cubic meters each.

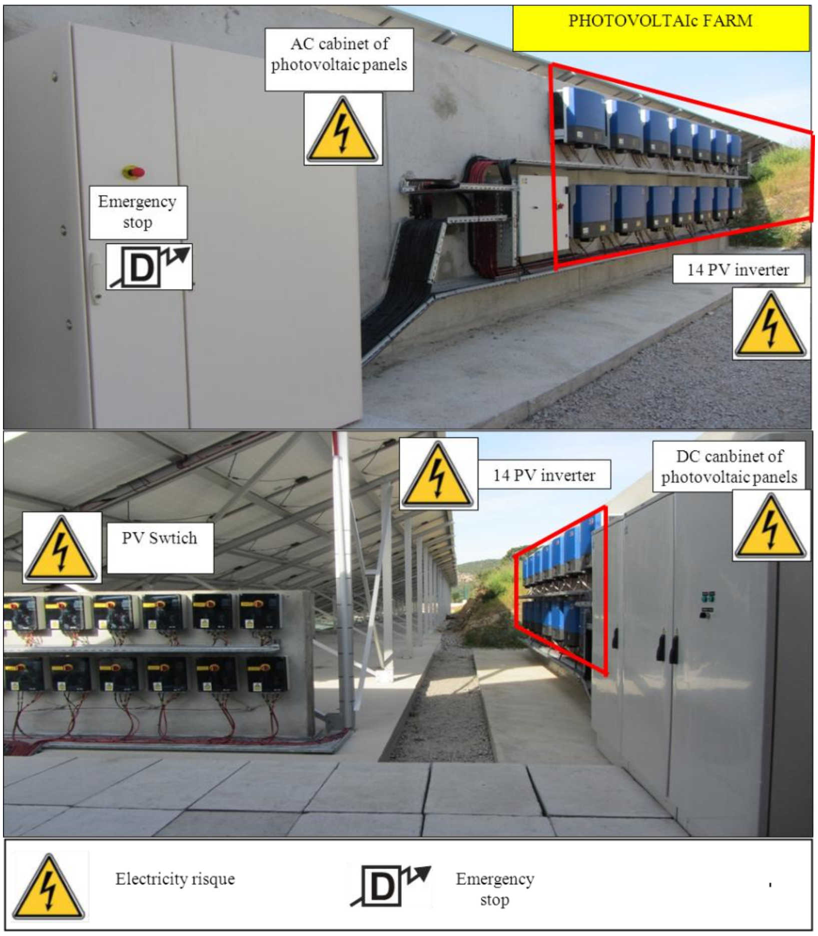
For the second phase of the project that was launched in February 2014, the discharge power was extended to 150 kW by adding a fuel cell of 50 kW and the charge power was extended to 125 kW by adding a 15 Nm3/h PEM electrolyser. The electrolyser and FC systems were installed into an integrated solution i.e. the Greenergy Box™.

8.2.2. Example of intervention map for Fire and Rescue services




HYDROGEN BUILDING
O_2
H_2
Electrical cabinet of Photovoltaic farm
High voltage building
HEAT STORAGE
Motorised Ventilation
Emergency stop
H_2
O_2
H_2 and O_2 pipe
Electricity Risk
Thermal Risk
Gas
Safety manual Valve


STORAGE ZONE
O_2
H_2
H_2
Gas
Produit comburant
Explosive Product
Flammable product
Manual Safety valve
Extinguisher
R.I.A


PHOTOVOLTAIc FARM
AC cabinet of photovoltaic panels
Emergency stop
14 PV inverter
PV Swtich
14 PV inverter
DC canbinet of photovoltaic panels
Electricity risque
Emergency stop

8.3. JANUS

8.3.1. Description of the project

The city of La Croix Valmer, located in the Golf of Saint Tropez, faces the problematic increase of population by a factor 10 in summer. Furthermore, the city of La Croix Valmer is often exposed to repeated power cut on account of the end line location on the electrical network. In this context, the city of La Croix Valmer has fixed the objective to be more electrically independent from the network.

JANUS is the name given to the project which the aim is to install a hydrogen-based energy storage system and production i.e. the Greenergy Box™ the Kid Leisure Centre at La Croix-Valmer (Var, department in south of France).

Figure 8-5: Pictures of the Kid Leisure Centre at La Croix-Valmer

The purpose of the system is to act like a storage system of energy. Indeed, it stores energy (resulting from production by photovoltaic panels) and restores it at the convenient periods in electric and thermal form to feed the Childhood Pole of the commune of La Croix-Valmer.

In order to ensure this, energy resulting from the photovoltaic panels installed on the building, is stored in a module Greenergy Box in Hydrogen form and Oxygen form by means of an electrolyser. This energy is then restored via the fuel cell of the module Greenergy Box™.

The entire system enables the building to increase its autonomy in energy as well as to adapt the energy production with the periods of consumption. In the long term, this kind of installation must also stabilize the local area electrical network.

Furthermore, heat, which is also produced by the system during both electrolysis and hydrolysis processes, is also managed and valorised for the adjacent buildings.

The hydrogen-based energy storage system includes:

- the Greenergy Box™ that includes:
  - A fuel Cell system
  - An electrolyser system
  - An electrical converter management systems
- A storage tank of hydrogen
- A storage tank of oxygen
- A heat management system (integrating an air cooler) used to ensure the thermal regulation of Greenergy Box.
- A water management system of water and treatment system allowing the good performance in mode electrolysis.

Some Features

PERFORMANCE	
Maximum generated Power (mode PAC) Maximum absorbed Power (mode ELY) Maximum instantaneous flow of hydrogen Maximum instantaneous flow of oxygen Pressure of production (without compressor)	40 kW @ cosφ=1 30 kW @ cosφ=1 < 5 Nm^3 H_2 / h @30 kW < 2.5 Nm3 O2 / h @30 kW 35 bar(g)
Input/Output Voltage	400 V tri +N/ 50 Hz

ENVIRONMENTAL IMPACT	
Greenhouse gas emissions	None

SAFETY	
Conformity	CE certified

OPERATION	
Outside temperature	From -10°C to +40°C
Ambient air	The technology is insensitive to air quality - sea salt, sand, dust, moisture
Altitude	Insensitive to the temperature
Localisation	Outside

SUPERVISION/ CONTROL

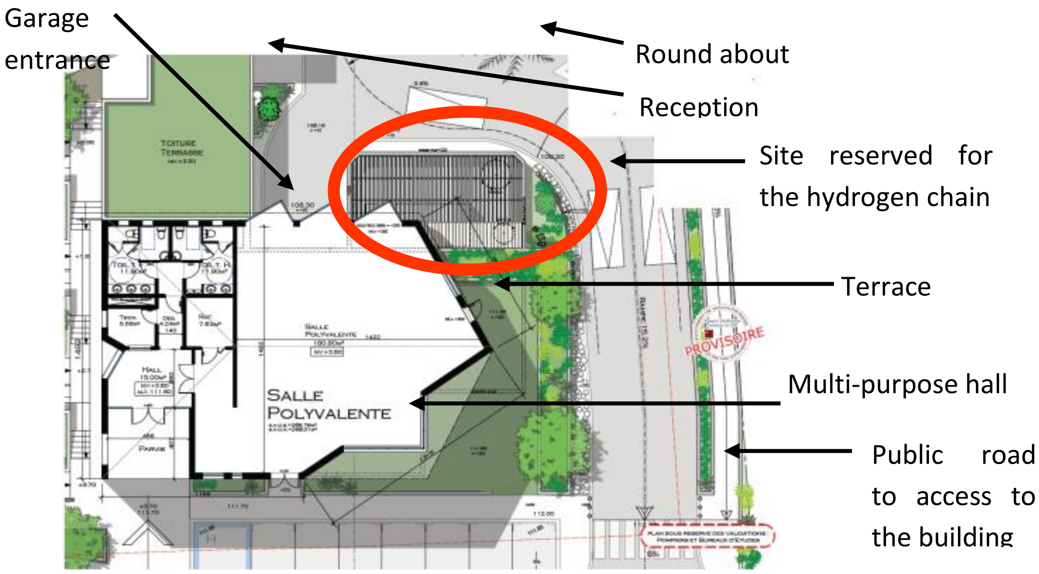
Supervision at distance	Configuration and state of the system Logging of the operational data
Communications	Ethernet and dry contact Supervision via connection ADSL Reference of information towards possible GTC

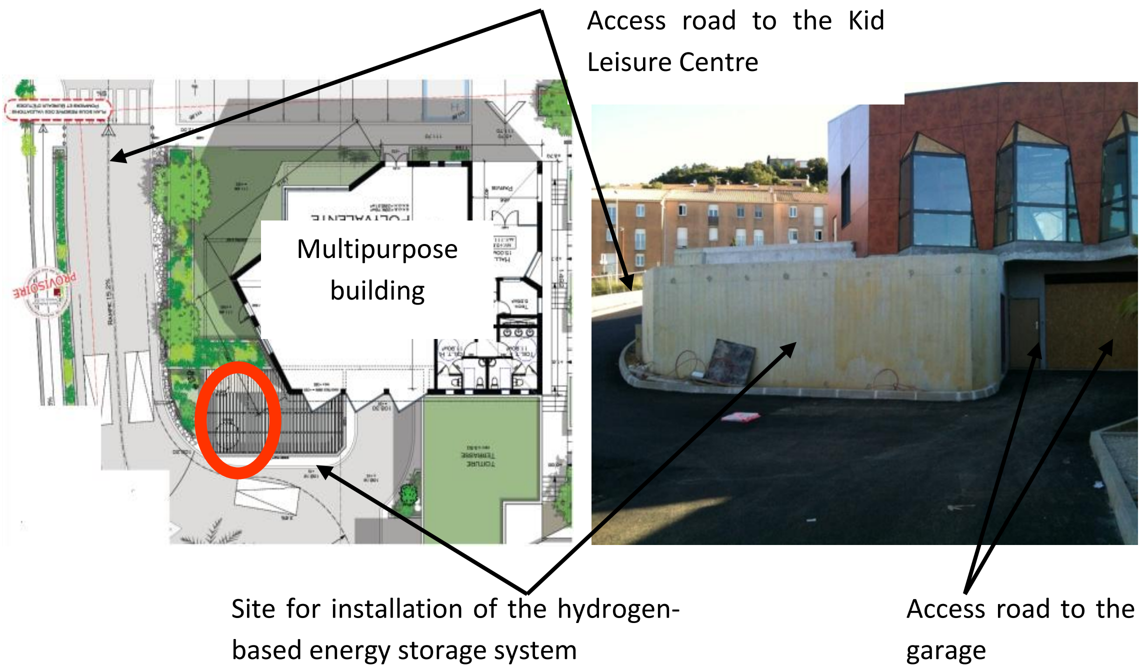
STORAGE		
Nature of the gas	Hydrogen	Oxygen
Capacity of the tanks (active Gas)	< 150 Nm^3	<75 Nm^3
Pressure of storage	35 bar(g)	
Maximum autonomy (mode FC)	210 kWh For a power generated between 20 et 40 kW with cosφ=1	
Time of load for the maximum capacity (mode ELY)	30 h For an absorbed power equal to 30 kW with cosφ=1	
Dimensions	∅ = 1.7 m; L = 3 m which represent 6 m3	∅ = 1.2 m; L = 3 m Which represent 3 m3
Mass	~9t (filled of water)	~ 5t (filled of water)
Facility	Vertical	
Conformity	CE Certified	

Table 8-1: Technical specification of the Greenergy Box for La Croix-Valmer

The Greenergy BoxTM is installed in the new Kid Leisure Center building of the city. Regarding the French regulation, this type of building occupation is considered as a public building that has to follow precisely the building codes requirements. In France, such regulation is not adapted to the installation of hydrogen-energy applications since the word ‘hydrogen’ is even not mentioned anywhere in the texts. Therefore, one major challenge was to define the rules for the first installation of a hydrogen-energy storage system in adequacy to the existing safety strategy in public building regulations.

On account of a late involvement, the space attributed for the settlement of the Greenergy BoxTM system and the hydrogen and oxygen reservoirs, is quite restricted and located in the proximity of the reception area of the building, close to the building access road and a garage entrance, as shown in Figure below. Above the garage is found a multi-purpose hall and its terrace that gets a direct view of the hydrogen chain settlement.





8.3.2. Key safety devices and concept of the overall installation

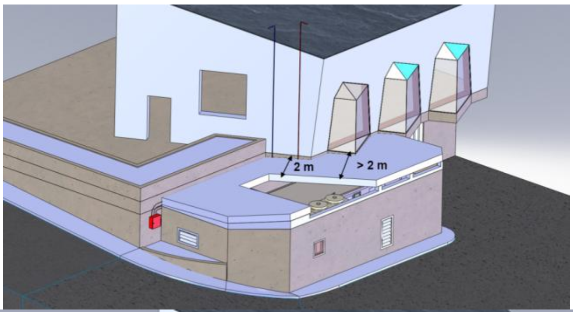
- <u>Greenergy Box:</u>

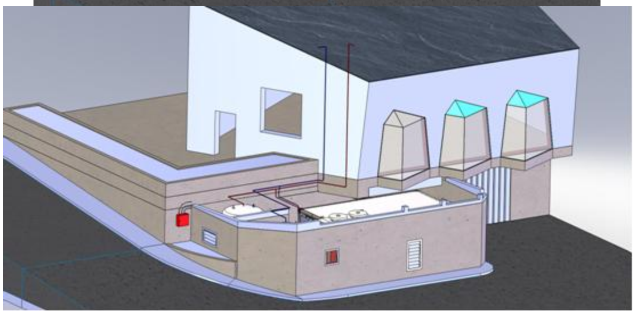
The overall safety devices and strategy of the Greenergy Box™ are presented in §9.2.

- <u>Key safety elements regarding the installation:</u>

    - Zone inaccessible to public or made inaccessible by the use of a 2 m high and 2h fire resistant wall or a fence of at least 2 m height

- Zone is protected by a 2h fire resistant canopy to protect the system and the storage and/or the façade of the multi-purpose from thermal effects in case of fire





- <u>Storage:</u>

The quantities of hydrogen gas and oxygen stored are the following ones:

Hydrogen = 17 kg
Oxygen = 142 kg

Storages of oxygen and hydrogen are installed in a protected area by two-hour firewall protection, and are overhung by a hood built out of two-hour fireproof and firebreak materials, including the storage section completely.

Storages of hydrogen and oxygen are separated by two-hour firebreak wall. Storage capacities are certified CE under the directive on pressure equipment (DESP) - 97/23/CE. The materials used are compatible with hydrogen and oxygen.

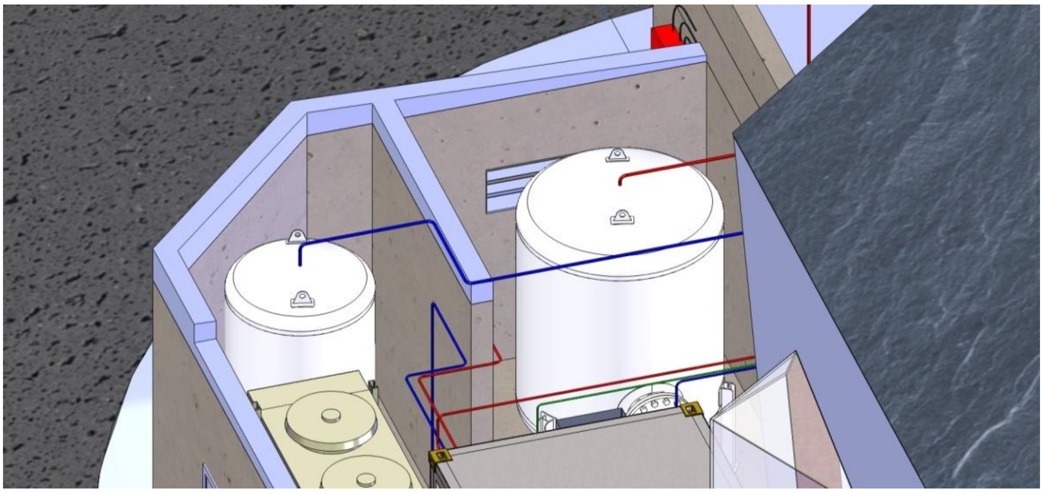


Figure 8-6: Sight on the two hydrogen and oxygen tanks storage (except roof, not represented)

For maintenance reasons, two nitrogen bottles (standard B50 at 200bar) are installed near the access door of the zone. These nitrogen bottles are positioned near the entry in order to facilitate their handling.

- Isolation valves

Each tank i.e. H_2 and O_2 is equipped with a manual safety valve and an electro-valve in order to isolate storage from the installation. Safety manual valves and electro-valves are also positioned at the entrance of the Greenergy Box. Therefore, in case of power cut or activation of a safety function, both the storage tank and the Greenergy Box are isolated by the electro-valves.

- Emergency safety devices

In case of emergency, two additional safety devices may be used on the installation:

- ❖ An "Emergency Discharge Device" (DDU-*Dispositif de Décharge d'Urgence*) of the tanks, positioned outside of the technical premise with a protected access, enables to discharge the storage tanks in less than 8 minutes through the vent.

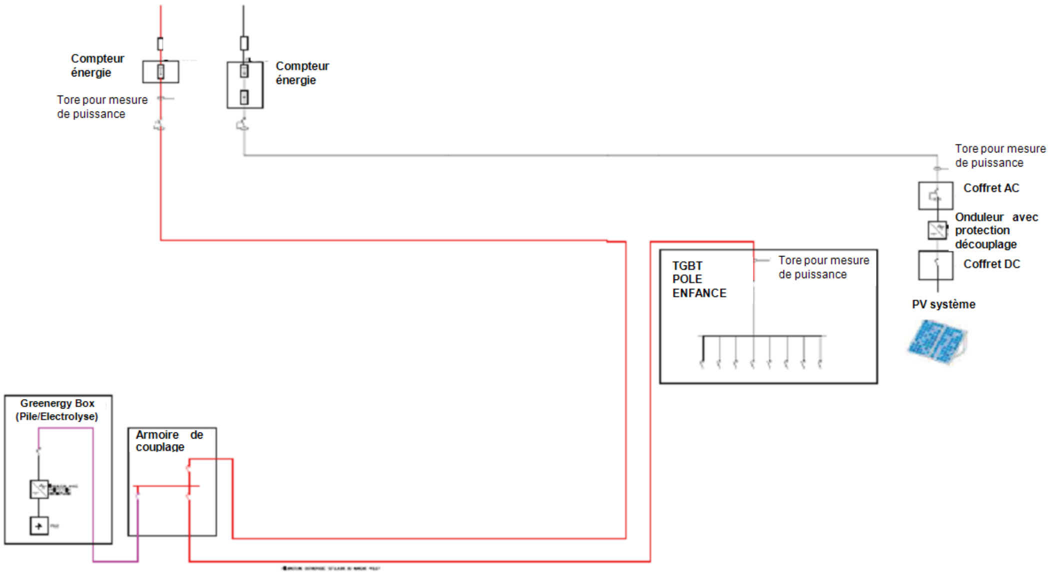
- ❖ An emergency Stopping bottom (CPAU-*Coup de Poing d'Arrêt d'Urgence*) enables to isolate the gas supply at the tank and the container, disconnect the Greenergy Box™ from the electrical grid up to the electrical Voltage , which will imply the depressurization of the system through the vents installed on the roof of the building. Residual amount of hydrogen will subsist in the process.

- Connection to electrical installations of the building

The Greenergy Box is connected to the building via a specific electric control panel "Cupboard of coupling", shielded from the rest of the facilities of the building.

The electric control panels of connection are situated in inaccessible places to public (TGBT-*Tableau Général Basse Tension* or Main Low-Voltage Board).

Electric wiring is fixed and walks on cable shelves not propagator of the flame, in accordance with regulation EL 10. The cables used to connect the module Greenergy Box to the building, are part of C2 category. The cross section of the cables through the two-hour firebreak partition of the building is done by means of stuffing box respecting the two-hour firebreak degree.



- *Gas Venting*

The Greenergy Box™ and storages have two vents of evacuation, including one for hydrogen and the other for oxygen. The lines of vent coming from storage and Greenergy Box™ are inter-connected and channeled vertically along the versatile room. The end of the vents leave to 1 m above roof the building and are bent with a 90° angle. The oxygen and hydrogen vents are directed with 90° one compared to the other in order to discharge gases out of the building's room in different directions. The external pipes are protected mechanically.

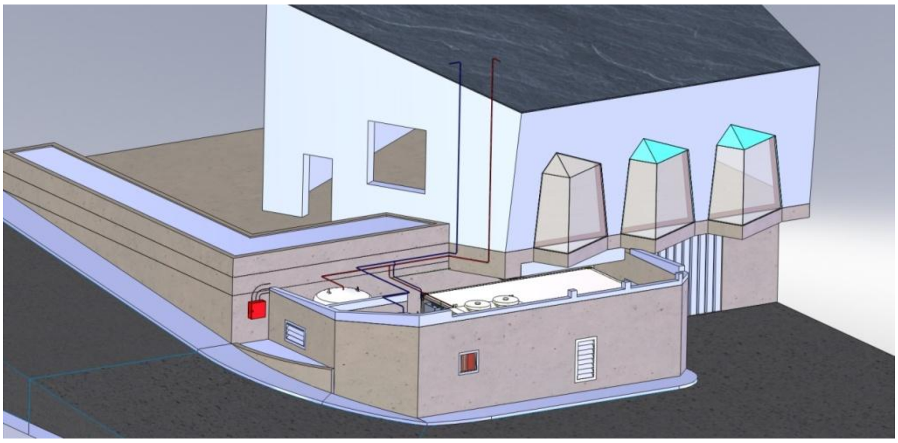


Figure 8-7: Sight on the vents of evacuation of hydrogen and oxygen.

9. References

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