Guidance

Injection of Hydrogen/natural gas admixtures in Underground Gas Storage (UGS)

1. OBJECTIVES

With the implementation of measures to mitigate climate change, renewable gas and especially Hydrogen is expected to take growing place in the energy mix in the next decades. Underground Gas Storage (UGS) operators are keen to support this evolution. However, as the Underground Gas Storage facilities are predominantly built for the storage of natural gas, a certain number of technical issues have to be investigated and dealt with before confirming the feasibility of Hydrogen/natural gas admixtures injection. The purpose of this paper is to present an overview of all these technical issues and how they have been already addressed in literature. Another objective is to promote research programs and experimentations to complete our knowledge on the impact of storing natural gas blended with Hydrogen.

Pure Hydrogen storage is also a topic of interest for gas industry but even if research programs or experiments of H_2 storage are considered in this paper, this is not topic addressed in this paper.

2. EXECUTIVE SUMMARY

The overall analysis of storage facilities shows that pure Hydrogen cavern storage dedicated facilities are already in operation and under development. The challenge consists in storage of mixtures of Hydrogen in natural gas in existing UGS facilities.

UGS are usually connected to the gas grid and that is the reason why the consequences of the injection and storage of Hydrogen/natural gas admixtures for all UGS types have to be assessed.

Considering adding Hydrogen into Underground Gas Storages, an important point not to forget is that, for the same volume, Hydrogen gas carries three time less energy than natural gas, resulting in reduced marketable storage capacities.

The review of research programs and experiments with Hydrogen storage, allow to conclude that salt caverns are by nature more compatible with Hydrogen storage.

Concerning storage in porous rock, such as aquifers or former gas or oil fields, phenomena of dissolution in water, fingering and confinement under caprock are mostly similar to the ones obtained with Methane (CH_4) and should need only little additional research.

A major issue remains the possible chemical/biological reaction in porous reservoirs, which has already been observed in some of former manufactured gas storages. Potential risks are linked to the consumption of Hydrogen by microorganisms, implying H_2S generation, development of biofilms in the vicinity of wells, and even pore clogging in the worst case.

A special attention should be paid to well integrity regarding risks of steel corrosion, elastomers fractures in the sealing elements and reaction to the cement.

Expected impact on surface facilities is similar to gas transmission lines and compression stations, but the specific storage conditions, especially the significantly higher pressures, have to be taken into account. Furthermore, some specific aspects as consequences on the storage performance by lowering of compression power, corrosion of steel under carbon dioxide (CO_2), impact on desulfurization and dehydration processes have to be assessed.

In order to complete our knowledge on the impacts generated by Hydrogen/natural gas admixture injection into underground natural gas storages, we recommend the following working axes:

- Reinterpretation of previous observations on the former manufactured gas storages.
- Laboratories tests and monitoring on microbiological reactivity of subsurface Hydrogen with different water/gas compositions and at reservoir conditions.
- Laboratories tests on material.
- Pilot storage in a porous reservoir which formation water contains sulfates.
- Pilot storage in a salt cavern to get technological information about operating issues.
- Check list for each facility to review the compatibility of wells and surface facility equipment with a given H_2 content.

The conclusion is that research programs are needed before standardization on H_2 content in natural gas before injection in underground storage facilities. Marcogaz will promote these programs and recommend that they are based on a wide European cooperation among stakeholders.

3. BACKGROUND

3.1. GENERAL BACKGROUND

Directive 2009/28/EC [1] on the promotion of the use renewables establishes mandatory and differentiate targets to be achieved by 2020 by Member States; so that, the share of renewable energy in the EU gross final energy consumption is at least 20% in 2020. With the development of electricity from renewables (wind or solar), experience showed that in Europe, when production exceeded local requirements and without available storage capacity for electricity, plants have been shut down. This issue should occur more and more frequently with the growing part of electricity produced from renewable sources and without additional storage facilities.

The concept of Power-to-Gas is a way to use this surplus of electricity by conversion to Hydrogen through electrolysis, which is an important energy carrier. Hydrogen could be directly blended and injected into the natural gas stream of the existing natural gas network. Methanation (combination between H2 and CO2) is a second option of Power to Gas but it is not considered in the scope of this paper. The natural gas infrastructure could store these gases and, thanks to the Power-to-Gas conversion, the surplus of electricity.

Power-to-Gas is a way of managing the energy grid and coping with intermittence of renewable energy (*Figure 1*, page 3).
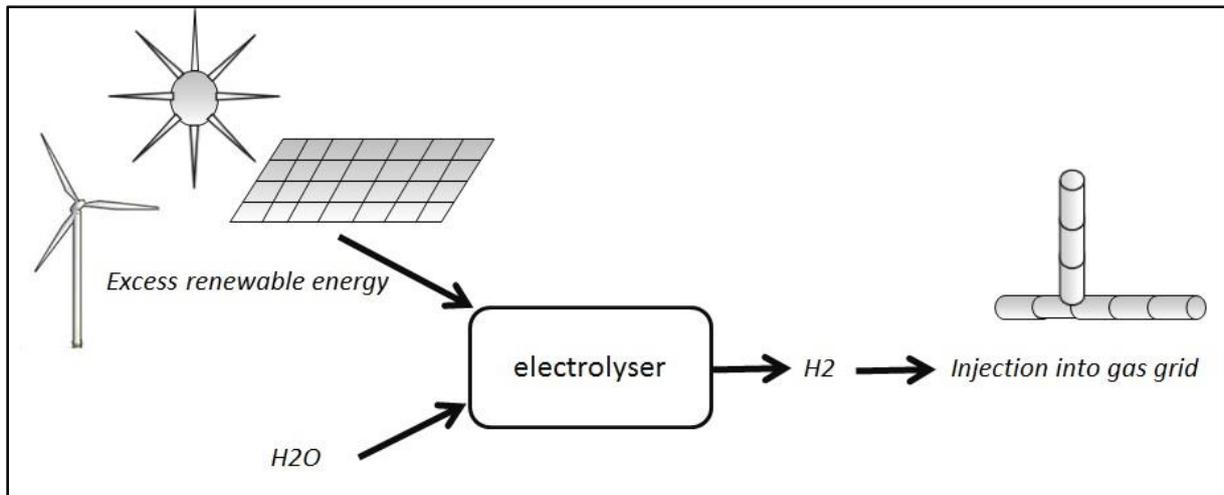

Figure 1: Power-to-Gas for Hydrogen injection into the gas grid

Generic studies on Hydrogen have also been made in the past years:

- *NaturalHy* GERG project, funded by the European Commission, ended in 2009 [2]. It identified no major stoppers for up to 20 % of Hydrogen in the natural gas network, in terms of pipeline durability, pipeline integrity, safety, and gas quality for end users. Conclusions showed that some adaptations are needed but Underground Gas Storages were not part of the study.
- The *Hydrogen In Pipeline System (HIPS)* project, coordinated by the GERG (European Gas Research Group), ended in 2013 [3]. It exposed that a blend of up to 10 % of Hydrogen in the natural gas system is possible, but with remaining issues in gas turbines, gas engines, gas chromatography, some steel tanks, and underground storages in porous reservoir.

The *HyUnder* project started in 2012 is the first European-wide assessment of the potential for Hydrogen storage in underground salt caverns to renewable electricity over the long term. The project concluded that further research was required to consider the potential of Hydrogen storage in porous formations such as aquifers and depleted gas fields [4]. For more information on the different types of storage, one can refer to [4], [5] and [6].

An important point not to forget when considering adding Hydrogen into Underground Gas Storages is that, for the same volume Hydrogen, gas carries three time less energy than natural gas [6]. Thus, replacing 20% of natural gas by Hydrogen could represent a 13% loss of energy and therefore revenue for Underground Storages operators, as far as they sell their capacities as energy capacities (and not volume capacities).

3.2. EXISTING PROJECTS ON NATURAL GAS GRID

In Europe, several Power-to-Gas projects experiment Hydrogen production from renewable sources through electrolysis coupled to gas grid injection, mixed with natural gas.

Project name	Place	Sponsors	Type of grid injection	Years of development/ status	Quantity of H$_2$ injected
ITM Hydrogen injection into the German distribution network[1]	Frankfurt am Main, Germany	ITM Power, Mainova, and NRM Netzdienste Rhein-Main	Distribution grid	2013 – 2017 in service since May 2014	3000m3/h Pressure 3,5 bar. Percentage of Hydrogen in the mix is less than 2 %.
Falkenhagen Power to gas pilot unit[2]	Falkenhagen, Germany	Uniper, Swissgas	injecting more than two million kilowatt-hours of Hydrogen into the regional gas transmission system	2013-2015, injection since 2014	Production of 360m3 of H2 per hour
Reitbrook power to gas unit	Hamburg / Reitbrook, Germany	E. ON/Uniper	Distribution grid	2015	
WIND-Hydrogen[3]	Grapzow, Mecklenburg-Vorpommern state, Germany	E. ON/Uniper	Distribution grid	In operation since 2013	
Ibbenbüren	Ibbenbüren, Germany	RWE, CERAM HYD	Distribution grid	2015	
EnergyPark[4]	Mainz, Germany	Siemens, Linde, RheinMain University	Distribution grid	2012 – 2016 In operation	
GRHYD[5]	Dunkerque, France	Engie	Distribution grid	2014-2019 First injection scheduled for March 2017	Up to 20% of H$_2$ blended into natural gas
Jupiter 1000[6]	Fos-sur-mer, France	GRTgaz, TIGF, McPhy…	Transmission grid	2015-2020	Engineering studies and permitting
INGRID	Puglia, Italy	McPhy, Enel, Hydrogenics	Distribution grid	2013	
BioCat[7]	Denmark	HMN Gashandel, Hydrogenics, NEAS Energy	Distribution grid	2015	Pilot under construction

[1] http://www.itm-power.com/news-item/injection-of-Hydrogen-into-the-german-gas-distribution-grid

[2] http://www.eon.com/en/media/news/press-releases/2014/9/1/eon-power-to-gas-pilot-unit-falkenhagen.html

[3] http://www.Hydrogenics.com/about-the-company/news-updates/2013/10/01/140-mw-wind-park-officially-opens-in-germany-with-energy-storage-facility-using-1-mw-power-to-gas-system-from-Hydrogenics

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[6] http://www.jupiter1000.com/en/projet.html

[7] http://biocat-project.com/about-the-project/scope-objectives/

Project name	Place	Sponsors	Type of grid injection	Years of development/ status	Quantity of H_2 injected
HyBalance	Hobro, Denmark	Air Liquide, Hydrogenics, Neas Energy…	Refuelling station network	2016	

Table 1 : Existing Power-to-Gas projects on natural gas grid

These projects have tested or will test H_2 contents up to 20%, mainly in the distribution grid.

The questions related to metering and the compatibility with Wobbe index as thus to existing combustion devices has to be checked [3].

3.3.   PAST AND EXISTING STUDIES AND PROJECTS OF HYDROGEN STORAGE

Past and existing projects and studies on underground Hydrogen storages are summarized in the following table, including former underground storages of manufactured gas and pure H_2 storage. Historically, manufactured gas was produced in the 19th Century and the first half of the 20th Century. It is also referred to as town gas or water gas. It typically contained 30%–50% Hydrogen and was used for heating and cooking until its replacement by natural gas.

Name	Type of project	Type of storage	Stakeholders	Progress
Engelbostel (Germany)	Former manufactured gas storage	Porous reservoir (aquifer)	Formerly Ruhrgas	Decommissioned
Bad Lauchstadt (Germany)	Former manufactured gas storage	Salt Cavern and pore storage	VNG	Now used as a natural gas storage
Hähnlein	Former manufactured gas storage	Porous reservoir (aquifer)	MND Storage	Now used as a natural gas storage
Eschenfelden	Former manufactured gas storage	Porous reservoir (aquifer)	Uniper	Now used as a natural gas storage
Kiel (Germany)	Former manufactured gas storage	Salt Cavern	Uniper/Stadtwerke Kiel	Now used as a natural gas storage
Kirchheiligen (Germany)	Former manufactured gas storage	Porous reservoir (depleted field)	VNG	Now used as a natural gas storage
Ketzin (Germany)	Former manufactured gas storage	Porous reservoir (aquifer)	Formerly VNG	Decommissioned
Lobodice (Czechia)	Former manufactured gas storage	Porous reservoir (aquifer)	RWE	Now used as a natural gas storage
Beynes (France)	Former manufactured gas storage, aquifer	Porous reservoir (aquifer)	Storengy (formerly Gaz de France)	Now used as a natural gas storage

Name	Type of project	Type of storage	Stakeholders	Progress
HyUnder	Economical study on pure Hydrogen storage	Mainly salt cavern	European Commission, E. ON, Shell, CEA, …	Ended in 2014 [4]
Moss Bluff (USA)	Pure Hydrogen storage	Salt cavern	Praxair	Operated
Clemens dome (USA)	Pure Hydrogen storage	Salt cavern	ConocoPhillips	Operated
Splindletop (USA)	Pure Hydrogen storage	Salt cavern	Air Liquide	Under development
Teesside (UK)	Pure Hydrogen storage	Salt cavern	Imperial Chemical Industries	Operated
HYPOS (Germany)	Integrated pilot project of production and transport of Hydrogen, including a project of pure Hydrogen storage in Bad Lauchstadt	Salt cavern	Numerous industrial companies (including VNG for the salt cavern, and Storengy)	Launching
ETI project (UK)	Study of salt cavern appraisal for Hydrogen and gas storage	Salt cavern	Energy Technologies Institute	Request for proposals
Underground Sun Storage (Austria)	Academic studies and pilot site, blend of natural gas and Hydrogen	Porous sandstone reservoir (depleted field)	RAG, Nafta, DVGW, Etogas, Hychico, Verbund, academic partners (MUL, Boku)	On-going, no formal publications yet [11]
H2STORE (Germany)	Academic studies, blend of natural gas and Hydrogen	Porous sandstone reservoir (depleted fields)	German federal government, academic partners (GFZ, FSU, TUC, CNRS)	On-going, early publications ([9], [10], [22], [23], [25])
Hychico (Argentina)	Pilot site, blend of natural gas and Hydrogen	Porous reservoir	Hychico	Unknown [12]
Large scale energy storage (Slovakia)	Study of feasibility of a blend of natural gas and Hydrogen storage	Porous reservoir (aquifer)	Nafta, academic partners	Launching
SFEM -Sector Forum Energy Management/Working Group Hydrogen	Study on analysis of state of art of technology, gap analysis, collaborative framework and recommendations and further actions	Total gas infrastructure incl. natural gas storages	CEN-CENELEC/EU	Final report [28]

TABLE 2 : Past and existing studies and projects of Hydrogen storage

3.4. EXPECTED IMPACTS OF HYDROGEN/NATURAL GAS ADMIXTURE INJECTION INTO STORAGE FACILITIES

The expected impacts are listed here below, thanks to extensive literature studies [13] [17], results from past and existing projects, or other specific quoted studies. The impact is different regarding the type of storage and is presented from the reservoirs, wells and surface facilities to the grid.

3.4.1. CONFINEMENT IN SALT LAYER

Laboratory measurements confirm the integrity of salt layer to Hydrogen [13]. No operating issues have been reported on pure Hydrogen storages or manufactured gas storages in salt caverns. Moreover, Helium, whose atom structure is very similar to that of Hydrogen, has been stored in salt caverns in Orenburg (Russia) since the 1980's [16].

Confinement in salt layer is not considered as problematic.

3.4.2. DISSOLUTION

In porous reservoir, due to the increasing part of Hydrogen in the blend of stored gas, gaseous Hydrogen will be dissolve until reaching equilibria between water (and oil) and gas phases. So dissolution will be more important in the beginning of the operating period, especially for aquifer storages.

Experimental data of Hydrogen dissolution in water and equation of state models can be found in the literature for various conditions. Complementary measures are acquired in the *H2STORE* project [23]. This could not be considered as a major phenomenon because of the theoretical factor of Hydrogen dissolution is close to the Methane one: in pure water at 100 bar and 50°C, around 0.07 mol/kg water for pure H_2 [23] and around 0.08 mol/kg water for pure CH_4 [24] (which is 1,6g H2/kg water and 13 g CH_4/kg water).

3.4.3. FINGERING IN POROUS RESERVOIR

Hydrogen has a lower viscosity than natural gas (app. 0.009 mPa.s for H_2 and 0.018 mPa.s for CH_4 at 200 bar and 50°C). Fingering of gaseous Hydrogen could happen during the operation of storage in an active aquifer formation. This should be investigated through numerical simulations when developing or converting a new storage, but should not be considered as an obstacle. It is also investigated in the *H2STORE* project. The simulation results have to be included in the feasibility study.

3.4.4. CONTAINMENT

Containment of Hydrogen in a porous reservoir has to be provided by an overlaying caprock:

- Diffusion of dissolved Hydrogen through water-saturated caprock is expected to be very slow and limited, of the same order of magnitude as natural gas [18]. Moreover, an underground storage of 1×10^9 m$^3_{(n)}$ Helium (which is very diffusive) has been exploited in depleted Cliffside gas field (USA) since 1963 without published problems of losses.

- No capillary threshold pressure of gaseous Hydrogen versus water or brine has been measured. But superficial tensions of Hydrogen/water are in the same order of magnitude as Helium and Argon [19] (and thus as natural gas [20]). As a first step, capillary threshold pressure of Hydrogen and natural gas can be considered as close.

On the former manufactured gas storage Lobodice, observed gas losses were explained by several mechanisms including dispersion, structural trap [28], partial H_2 leakage [26] and mainly change in gas composition ([21] and [28]). No other issues related to H_2 were published for other former town gas storages and in the *Underground Sun Storage* project (intermediate results: laboratory tests indicate that H_2 permeability is in the same range as natural gas).

The monitoring of containment may be complicated because of hydrogen produced by cathodic protection/corrosion phenomenon in wells or in soils.

In conclusion containment of Hydrogen under existing caprock should not be considered as a general blocking point but has to be confirmed for each site.

3.4.5. WELL INTEGRITY AND CONTAINMENT

The influence of Hydrogen on the materials of well completions might create integrity defaults, especially on existing wells of pore and cavern storages: corrosion of steel, fractures in the elastomer of sealing elements, reaction with the cement. Study [13] recommends to examine the parts of the existing operational subsurface equipment before injection of Hydrogen for the envisaged storage operating conditions. The influence of other gas components (CO_2, H_2O, O_2) has to be taken into account.

No special issues were published for former town gas storages and in the *Underground Sun Storage* project (intermediate results: laboratory tests indicate that H_2 permeability in cementing is in the same range as natural gas, and no influence of H_2 on well completion materials).

3.4.6. SURFACE FACILITIES AND STORAGE CAPACITIES

Surface facilities of Underground Gas Storage are very similar to gas transmission lines and compression stations but at different operation conditions; i.e. higher pressures and wet systems. There could be specific storage impacts that require further investigation, even if anticipated effects should be limited:

- Impact on compression power. Due to a less calorific fuel gas, flow capacity can slightly deteriorate and should be estimated considering proportion of H_2 in the blend.
- Allowable H_2-percentages for the existing gas turbines should be checked in order to avoid damage to the turbine blades.
- Impact of H_2-percentages on the storage capacities (working gas volume, injection/withdrawal rates) due to the lower calorific energy content and to the changed PVT-properties (pressure, volume and temperature) and expected pressure changes in reservoir.
- Modifications on gas measurements and process gas chromatographs are required as well for accounting purpose.
- Corrosion of steel under CO_2, H_2O vapor and H_2 at storage operating conditions.

- Impact on desulfurization and dehydration units, especially with air injection or dehydration unit based on Joule-Thomson expansion gas cooling effect.

3.4.7. REACTION IN POROUS RESERVOIRS

Hydrogen reactivity in porous reservoirs is expected to have an important impact, as observed in some of the former manufactured gas storages:

- in Lobodice, a loss of 10 to 20 % of total gas volume was observed [27]. H_2, CO and CO_2 from the town gas were supposed to be consumed by methanogenic bacteria to create Methane (CH_4) [27] ;
- in Ketzin, 61 % of H_2 volume has been lost (8 million m^3/year) according to [14] and [15], as well as important modifications on gas composition and H_2S generation and pressure losses/temperature changes;
- in Beynes, the impact was real but limited (Storengy unpublished information).

Hydrogen is an easy source of energy for microorganisms (bacteria and archaea). Hydrogenotrophic microorganisms could theoretically catalyze reactions such as:

Sulfate reduction to H_2S	$5\ H_2 + SO_4^{2-} = H_2S + 4\ H_2O$
Iron reduction	$H_2 + Fe_2O_3 = 2\ FeO + H_2O$
Acetogenesis	$4\ H_2 + 2\ CO_2 = CH_3COOH + 2\ H_2O$
Methanogenesis	$4\ H_2 + CO_2 = CH_4 + 2\ H_2O$ ***or*** $3\ H_2 + CO = CH_4 + H_2O$

Table 3 : Reactions

This would lead to H_2S generation, bio corrosion of the well equipment, Hydrogen consumption, biofilm detachment, transport and pore clogging in a worst-case scenario.

Microorganisms initially able to biodegrade minor compounds of natural gas could also switch to hydrogen consumption.

Abiotic reactions are also thermodynamically possible, such as reduction of dissolved sulfates, nitrates or ferrous ions or reactions on minerals. But, they are usually too slow in the reservoir temperatures without catalyzers.

So, H_2 behavior is expected to be very different from a storage site to another, depending on the lithology of the reservoir, water chemistry, pressure, temperature, microorganisms' population, and gas quality (presence of CO and CO_2 for example). Published data on depleted reservoir from the *H2STORE* project and *Underground Sun Storage* project will be of great interest.

4. WHAT IS LEFT TO INVESTIGATE

Some further research, laboratories studies and pilot experimentation are necessary to retrofit existing Underground Gas Storages for H_2 - natural gas mixtures.

This paragraph presents the type of research projects or pilot projects needed to improve the knowledge on storage of natural gas blended with H_2 and be able to define standards and concrete consequences for storage operators.

4.1. FEEDBACK OF FORMER MANUFACTURED GAS STORAGES AND EXISTING H_2-STORAGE FACILITIES

Feedback from former manufactured gas storages operation is hard to find in the literature. In order to share good practices, companies which operated these storages may do an internal research for data on expected impacts mentioned above. This bibliographic research could also be done on old industry publications or in house data.

Publications, data and experiences from the existing 100% H_2-storage facilities should be analyzed concerning applied materials, cements and operational experience.

4.2. LABORATORY STUDIES ON REACTIVITY OF HYDROGEN IN RESERVOIRS

More laboratory studies are needed to assess the reactivity of Hydrogen in specific porous reservoirs, such as storages in aquifer with different water compositions. These investigations should be made at reservoir conditions (pressure and temperature) with formation water, rocks samples and microorganisms population from the studied reservoirs. The effect of gaseous Hydrogen injection at various pressures and associated with various gases (CO_2, CH_4) should then be monitored: evolution of the composition of liquid and gas phases, and observation of the solid phase at the end of the experiment, microorganisms' ability to biodegrade minor compounds of natural gas in presence of Hydrogen should also be checked. A more detailed program has to be developed for these studies considering all relevant different storage conditions.

4.3. LABORATORY STUDIES ON MATERIALS

For a dedicated pure hydrogen dedicated new storage facility materials must be designed to be compatible with hydrogen for most representative operating conditions.

More generally, specific studies must be led to test the impact of H_2 on the materials of existing storage facilities equipment. Steels and elastomers are the most sensitive materials.

4.4. PILOT PROJECTS

The final step would be a pilot storage in aquifer reservoir hosting sulfates with seasonal injection and withdrawal.

A pilot storage in salt cavern, as planned in the *HYPOS* project with pure H_2 will not provide new scientific knowledge but will provide technological information about operating issues. It would allow to acquire data and to be a last step before extended commercial operation.

It's worth noticing that only low concentrations of Hydrogen in the blend with natural gas would be investigated if the hydrogen is produced by Power-to-Gas. A 1 MW_e electrolyser roughly produces 200 $m^3_{(n)}$/h of Hydrogen, which is only 480 000 $m^3_{(n)}$ for a nonstop 100 days' operation.

4.5.   FURTHER ASPECTS TO BE REVIEWED FOR EXISTING FACILITIES

Usually UGS are designed and constructed for the storage of natural gas. In case the admixture of Hydrogen into the injected natural gas is foreseen all consequences of the Hydrogen admixture especially on the integrity of the UGS have to be investigated before any Hydrogen injection.

In addition to the general need for research and further studies the following topics have to be analyzed and concluded positively for an existing UGS in order to proceed with any Hydrogen admixture injection:

- Inventory of all materials, seals and components installed.
- Ensure compatibility of identified materials (subsurface/surface) with anticipated maximum H_2-concentration, which should not be exceeded by temporary peaks.
- Maximum allowable H_2-concentration for gas turbines.
- Assess consequences on dehydration processes by Joule-Thompson expansion.
- Check of the containment
- Need for retrofitting as e.g. well completion, gas measurement.
- Run reservoir simulations.
- Evaluate operating characteristics and energetic storage capacities (working gas volume, withdrawal/injection rate profile).
- Grid connection agreements, including gas quality requirements (e.g.: % H_2, O_2–impurities from H_2).
- Approval by authorities for the operation of the storage for the anticipated H2 concentration.

Marcogaz will promote research and pilot programs investigating these issues and recommend that they are based on a large European cooperation among operators, searchers and Research and Development organizations.

Once the knowledge increased, based on that type of research/pilot programs, storage operators will be able to assess the consequences of Hydrogen injection in their facilities and standardization could define a maximum content of H2 acceptable in the grid connected to storage facilities.

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