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# Hydrogen storage for the energy transition: an overview

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“Ma ricordate bene, tutto quello che farete nella vita non sarà così leggendario, se non avrete con voi degli amici”

Barney Stinson

## Summary

# 1. INTRODUCTION

Resources such as solar, wind, geothermal and ocean could reduce the greenhouse gasses emissions playing a main role in the goal to reach the carbon neutrality by the 2050.

The only way the production can meet the demand is through energy storage or energy carriers, like hydrogen. In fact, with the renewable energy the pollution can be cut significantly, but it exposes the user to the risk of fluctuations in the production in the moments in which these resources are not present. The trends seem to indicate the future dependency on energy storage or energy carriers. With the surplus of the production it can be produced green hydrogen which can be burnt when the energy is needed, in a reaction that doesn't pollute and has in the water its main product. The hydrogen itself, in this pathway is not considered a source of energy but and energy carrier, since the energy obtained by its combustion is less than the one used to produce it.

In this panorama there is a large amount of hydrogen that needs to be stored and much storage capacity, that was used for storing natural gas, that will be unutilized, as far as the gas production will be cut to meet the climate goals.

The aim of this work is to investigate the possibility to use the same storage facilities used for the natural gas to store hydrogen, reducing the cost of building or invent new solutions. To study the feasibility of this process is important to understand how men have stored the natural gas so far, analyzing the different kinds of facilities, the physics and the chemistry that stand behind this process and the real storage capacity suitable for this solution. In this research is given an overview who aims to lead to a complete knowledge of the main parameters and solutions available for this purpose, along with a detailed background of the natural gas storage and an analysis of the challenges that must be overtaken to store safely and correctly hydrogen. In the process will be performed also an economic analysis, that together with the aspects indicated before can give a complete overview of these solutions.

# 2. OVERVIEW OF EUROPEAN GAS STORAGE FACILITIES

## 2.1 WHY DO WE NEED THEM?

Gas storage in Europe is used mostly to ensure the security of its gas supply since Europe consumes more gas than it produces and so it is heavily dependent on imported gas. This leads to the vulnerability of supply disruption in relation to political tensions, conflicts, and natural disasters. For example, looking at the effect of the Ukraine war on Europe, one of the consequences of the conflict the gas supplied from Russia to the European Union decreased to 60 billion cubic meters in 2022 from 140 billion cubic meters in 2021 [1]. Having a reliable source of gas available in storage allows Europe to minimize the impact of such disruptions and maintain a stable energy supply.

Besides supply security, gas storages are also helpful to give flexibility to the system that can manage gas supply and demand fluctuations. This is possible by injecting gas into the storage, when there is an excess in the production or in the supply, and then withdrawing it during periods of high demand, responding quickly to the changes in the demand or production. This feature of gas storage is interesting to ensure the gas supply and stabilize its price fluctuations. In fact, the price of TTF gas in August 2022 reached its all-time price record closing the market day in Amsterdam at 340 euros/Megawatt hour. After this peak, thanks to the high levels of gas stored and a winter warmer than expected, the gas price decreased significantly, being exchanged today for roughly 40 euros/ Megawatt hour, as is seen in the following diagram [2].

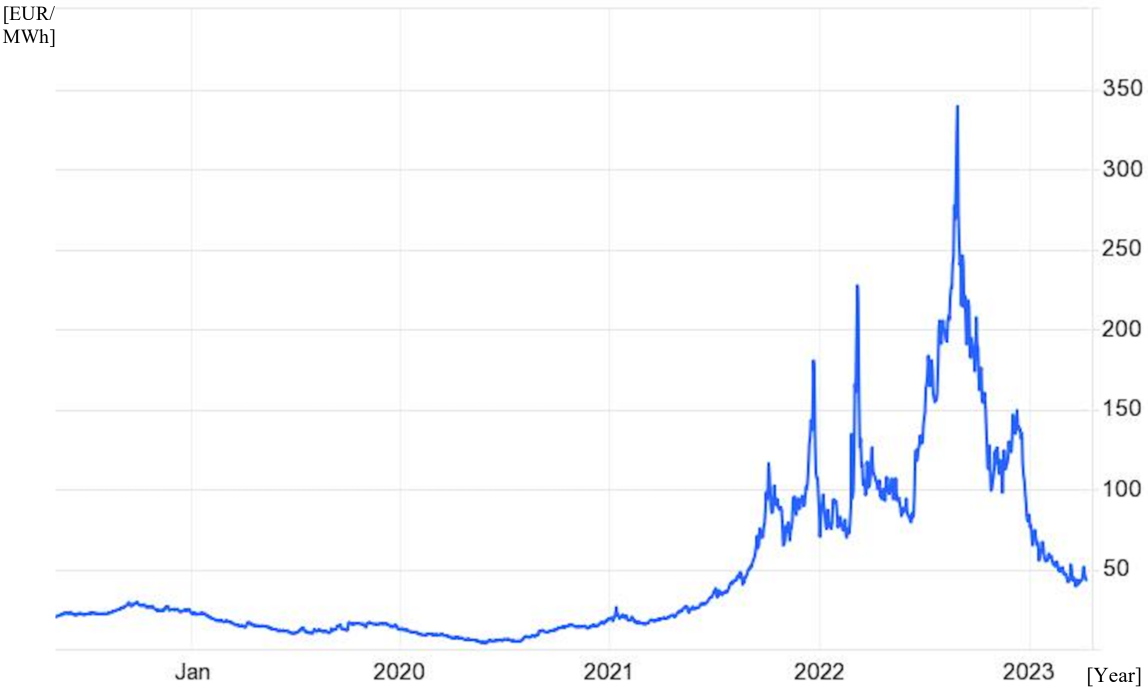

**Figure 2.1** Natural Gas EU Dutch TTF price (EUR/MWh) [3].

Gas storage helps to reduce Europe’s reliance on imported gas, which is important considering the risk of geopolitical tensions and supply disruption that can impact the gas supply system and improves its energy security. Just storing gas domestically already reduces European exposure to such risks and assures a secure and stable energy supply for its citizens.

Another important advantage of gas storage is the possibility to be used for seasonal storage. The fluctuations in demand or supply are not just related to unexpected events or within a small amount of time, but they can be related to the different needs that are present in the different seasons of the year or different sectors. Demand for district heating and so for gas tends to be higher in winter and lower in summer, for instance. This is an example of seasonal storage, it’s possible to store gas during the summer months to meet the higher demand in winter without solely on imports. The fluctuations in the demand of different sectors have been driven not only by seasonal needs but also by the increased price of gas, and its consequent behavioral response, fuel switching, and efficiency gains [1].

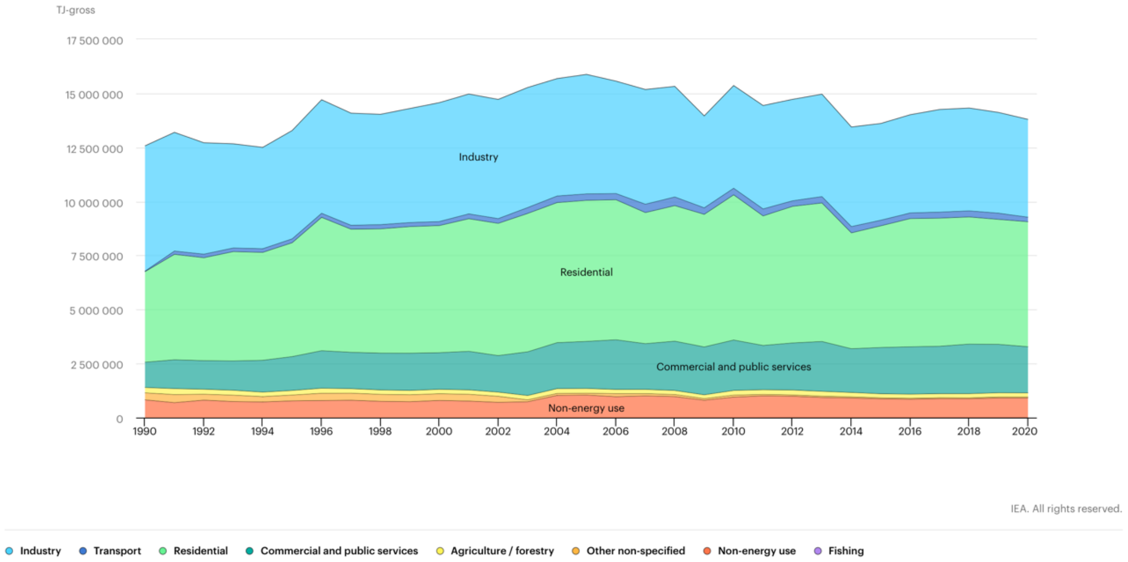

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**Figure 2.2** Natural gas final consumption by sector, Europe 1990-2020 [4].

Finally, gas storage has played a key role in ensuring the stability and security of the energy supply, since it provides a flexible and reliable way to store gas that can manage the fluctuations in demand and supply while it reduces the reliance on importing gas from other countries. However, nowadays the European Union and the rest of the world seem to be interested in covering as much as possible of the energy supplied by gas and other fossil fuels with renewable energies and other environment-friendly solutions.

## 2.2 HISTORY OF GAS STORAGE

The presence of natural gas in Europe was unknown until 1659 when it was found in England. During the 19th century, the use of natural gas has not been developed widely because of the issues related to the transport of large quantities for long distances [5]. Nevertheless, the need for gas storage facilities became apparent in the mid-20th century due to the increasing importance of gas as a source of energy. The first gas storage facilities were primarily designed to balance seasonal changes in demand, especially for winter when it’s important to have sufficient gas for peak demand. Among the earliest underground gas storage facilities in Europe, according to Gas Infrastructure Europe, we can find the aquifer storage facilities located in Beynes in France. This aquifer storage, which takes place twenty kilometers from Versailles and has been built in 1956, is still the biggest underground storage site in France. It continues to be operative but between 2007 and 2015 the facility underwent some renovation and development works for safety and efficiency reasons [6]. From that moment the storage facilities in Europe started to be developed and increased in number. In the following 30 years, almost 80 new storage sites took place and spread across Europe under different types of storage. Cortomaggiore and Sergnano are the first case in Europe of exploitation of a depleted field. They operate from 1964 and 1965 respectively. Just a few years later, in 1970, in Germany, at Bruggraf-Bernsdorf the first salt cavern storage began its operations.

Nowadays, gas storage is a main component of the EU energy system that provides flexibility and security of supply to gas consumers, with an operational storage capacity on the 21st of July 2021 equal to roughly 1,148 TWh which corresponds to 102 billion cubic meters of natural gas [7], or one-fourth of the total EU-yearly gas demand [8]. If Europe as a continent is considered, instead of the European Union, this value increase to 1,572 TWh or roughly 140bcm [7].

The capacity of gas storage in Europe has increased steadily over the past few decades as the demand for natural gas has grown. Today the largest gas storage country in the European continent is Ukraine, with 325 TWh, followed by Germany with 246 TWh, and Italy with 193 TWh [9].

Recently, there have been efforts to increase the gas storage capacity in Europe, particularly in response to concerns about energy security and supply disruption. The number of storage sites is increasing, and this trend doesn’t seem to stop soon, as we can see from the 23 sites that are planned or already under construction and expected to be ready before 2026 [10].

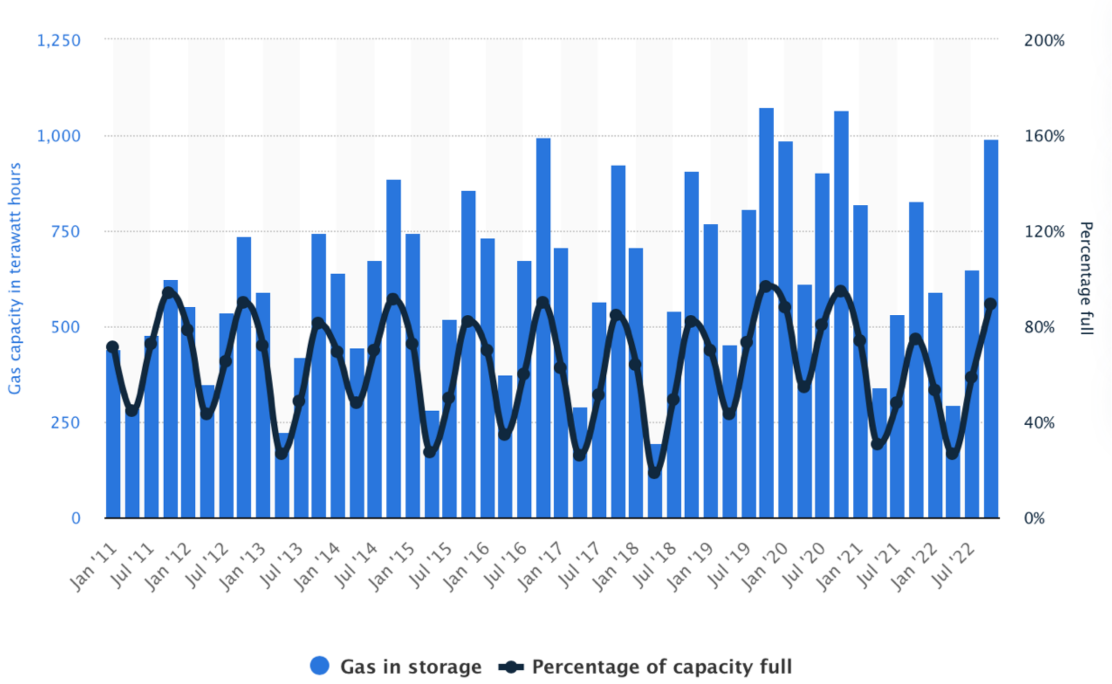


**Figure 2.3** Natural gas in storage in the European Union in select months from 2011 to 2022 [11].

The rise in the number of gas storage facilities in Europe has been driven by several factors, including the need to ensure the security of the gas supply, the growing importance of natural gas as an energy source, and the need to balance seasonal variations in demand. Moreover, the liberalization of the gas market in Europe led to an increase in the number of gas storage facilities as companies seek to profit from the arbitrage opportunities created by the fluctuation in gas prices.

Europe has always relied on other countries to import gas since it consumes more gas than it produces. One of the main gas suppliers was Russia, considering that in 2021 Europe imported 83% of its natural gas and almost 50% of it came from Russian reservoirs. After February 2022, Europe started to look for new gas suppliers or alternative ways to meet European's energy demand.

The first change is represented by the prohibition to import coal and other fossil fuels from Russia on the 8th of April, followed by the same measure for crude oil and refined petroleum products, although with some exceptions, on the 3rd of June.

In response, Russia cut the supply of natural gas by 80% and this forced a trade-off to other market players for Europe [12].

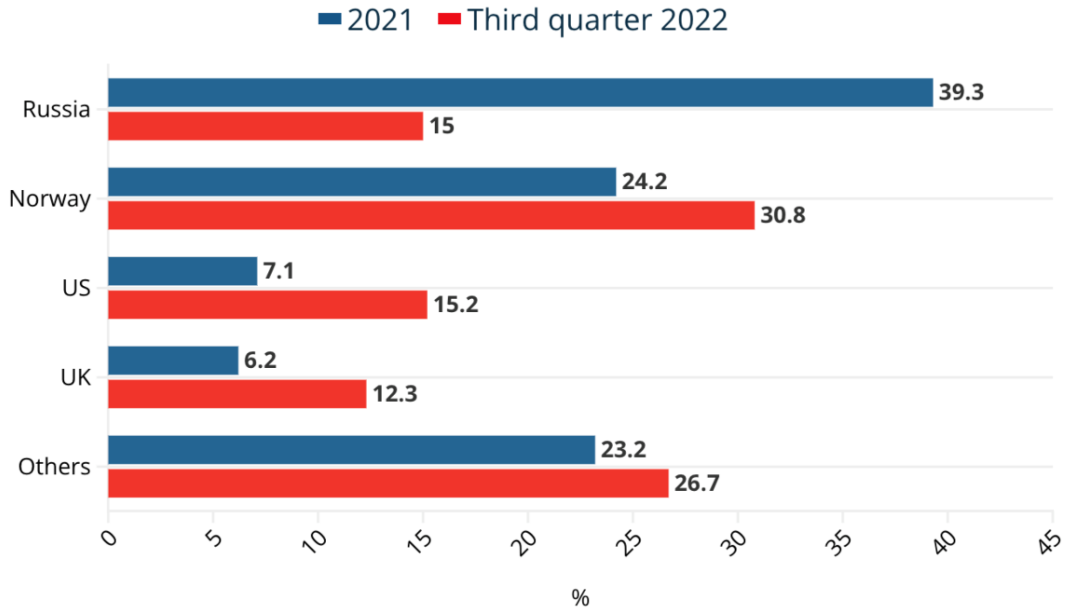


**Figure 2.4** The source of imported gas in Europe during 2021 and the third quarter of 2022 by countries [12].

Norway has significantly increased its supply of gas to Europe, implementing its LNG (Liquified Natural Gas) structures. The LNG imports by the United States, Nigeria, and Qatar reached 25.7% of the total, playing a critical role to avoid gas shortages. This pathway helped the LNG network to develop dramatically and ends out with an amount of LNG imports from the USA between January and November 2022 that was more than double the volume exchanged in the whole of 2021 [11]. According to the Gas Market Report of the first quarter of 2023 redacted from IEA, the value of global LNG trade raised to an all-time high in 2022. This is not supported by an incredible increment in volumetric terms like someone may think, in fact, it was just 5.5% higher than the past year, otherwise, the global energy and gas crisis guides the value of the global LNG trade up to 450 billions of American dollars, more than double of 2021 [13], with Australia, the leader in the market, with revenues from the export worth more than 90 billion dollars [14].

This market is growing rapidly, especially if it is considered that in 1970 its global trade was negligible, with roughly 3 billion cubic meters traded, and in 2022 it is essential to avoid shortages in gas supply. The first European countries to buy this commodity were the UK and France, which bought it from Algeria in 1964. At the end of 2017, there were 19 exporting countries and 40 importing countries [15]. According to the International Group of Liquified Natural Gas Importers, the import capacity, which is based on the regasification capacity, will expand by 34% in the EU and the UK by the end of 2024 compared to the capacity of the end of 2021, which was equal to 20.2 billion cubic feet/day, reaching a regasification capacity of roughly 27 billion cubic feet/day or 0.76 billion cubic meters/day [16]. This added capacity can be built on-shore in a regasification plant, off-shore in a plant that is located in the sea or it's possible to buy an FSRU, which stands for Floating Storage and Regasification Unit, so a boat that is able to develop the regasification of the natural gas. The FRSUs are cost-effective, time-efficient, and cleaner solutions with a minimal footprint, that exploit the same process of a land-based terminal, having onboard the capacity to vaporize the LNG and deliver it through special receiving facilities at the pipeline network with the desired pressure and a flow rate that ranges from 14,6 kWh to more than 220 kWh [17]. Several counties in Europe are purchasing or constructing FRSU terminals, and among them, there are Germany, France, Italy, Greece, Finland, and Estonia [16].

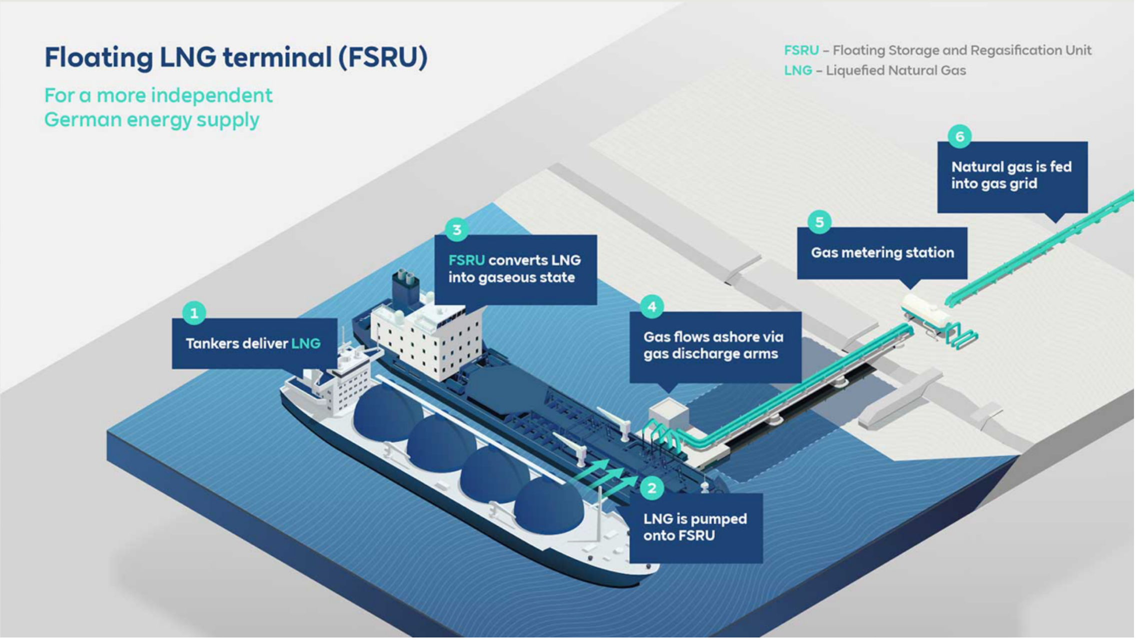


**Figure 2.5** How a floating LNG terminal works [18].

LNG terminals are also used for storing natural gas that has been liquified by cooling it to the liquid state. Some European countries, like Spain and France, use liquified natural gas as a storage medium. The liquified gas is produced by cooling natural gas to around -162 degrees Celsius, which reduces its volume by a factor of 600. The same process can be exploited for hydrogen or other gases, at different temperatures. The LNG is then stored in large tanks until it is needed, at that point, it is re-gasified and injected into the pipeline network. LNG terminals have higher energy densities than the above-ground tanks, this means they can store more energy in a smaller space. However, they are expensive to build and maintain since they require specialized equipment and expertise to operate.

## 2.3 TECHNICAL PERSPECTIVE OF UGS

Concerning another problem related to the use of gas, oil can be stored in tanks and can be transported inside them, but natural gas must be transported through pipelines. This implies that the gas supply can be disrupted if there are problems with the pipeline infrastructure or political conflicts.

In 1890 the leakproof pipeline coupling was invented and this allowed an increase of up to 160 km of transported distance from the supply source.
With the further advances in pipeline technology, in the late 1920s, long-distance transport became effective, especially in the US where between 1927 and 1931 many pipelines with a diameter of 50 cm and a length of over 320 km were built.
After the World War II the diameter of pipelines increased reaching 150 cm [5].
Nowadays, the share of natural gas in the European energy mix accounts for 21.5%, and 80% of the gas needs are imported by other countries outside Europe.
Today in Europe are present 200,000 kilometers of transmission pipelines and roughly 2 million kilometers of distribution pipelines, this means that the European gas network can be considered a gas storage facility itself due to the incredible amount of gas that passes through the network and considering the pressures present within the pipelines, that are reached exploiting over 20,000 compressors [19]. Through a process called ‘line packing’ gas can be stored in the short-term in the pipeline system. This is possible by compressing more gas into the pipeline and during periods of high demand a major amount of gas can be withdrawn directly into the market area requested. This method can be a temporary solution to substitute the underground storage and it is useful in off-peak times to meet the next day’s demand [20].

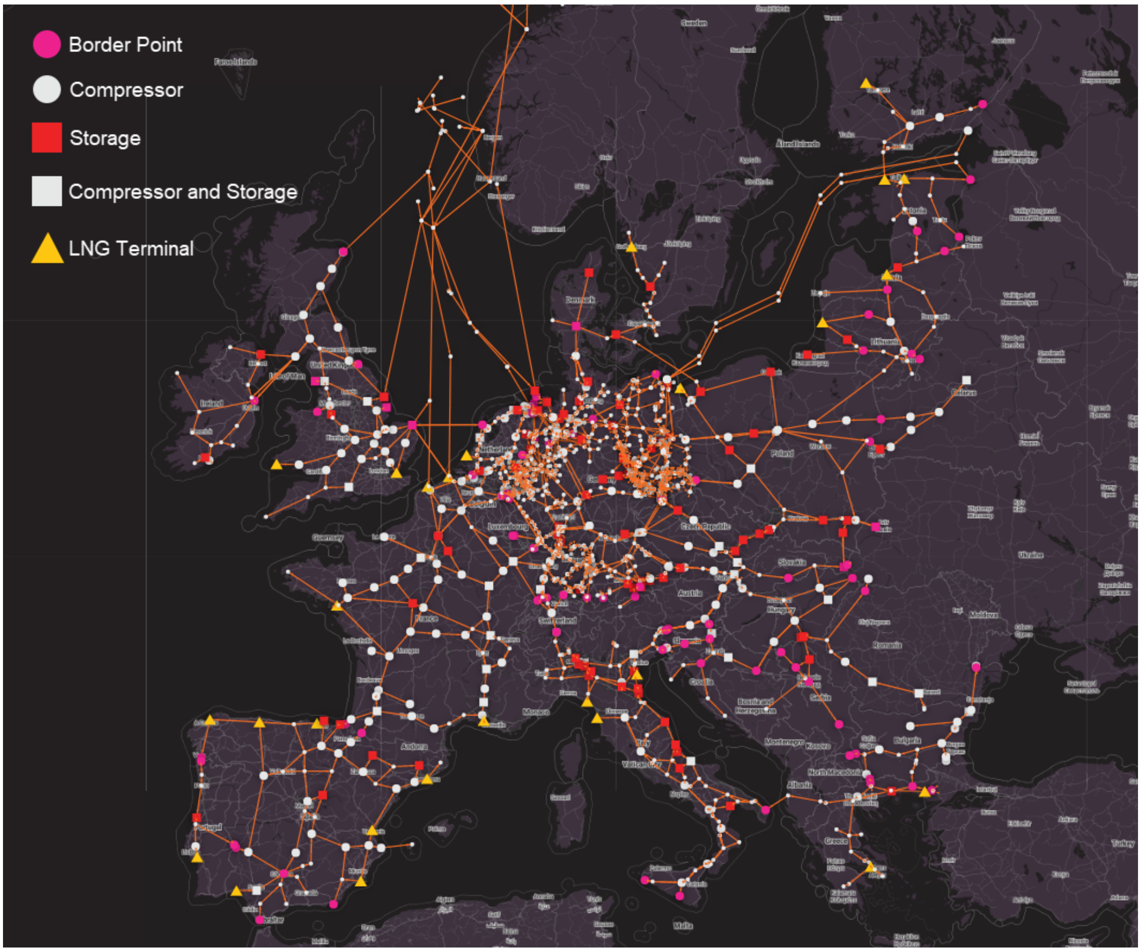


**Figure 2.6** EU Natural gas pipeline network [21].

The future of gas storage in Europe is still uncertain due to the increasing focus on renewable energy, the goal to achieve carbon net zero, and the recent shock in the supply system. However, as long as natural gas remains important, also gas storage will continue to be a critical component of the energy infrastructure in Europe, but the role of natural gas in the energy mix will depend on the continued focus on reducing methane emissions, the development of the hydrogen market and the employment of carbon capture systems. The future trends, according to the Technical Report of the European Commission, which analyzes part of the 67 possible scenarios publicized between 2017 and mid-2019, are represented by a 25% reduction in natural gas use by 2030, and in 2050 the reduction will be equal to 75%. In this scenario, renewable energy provides between 75% and 100% of the electricity, and an important trade-off between hydrogen and electricity as the final energy carrier in the energy industry will be needed, with a share of hydrogen equal to 5-20% in the energy consumption in addition to about 50% in electricity production [22]. In this case, the installed storage capacity of natural gas that there is in Europe nowadays would exceed the needs, but an increased interest in renewable energy sources along with the strong presence of hydrogen will lead to an increase in the demand for underground hydrogen storage facilities. Due to this trend is important to understand the feasibility of changing the natural gas storage facilities into hydrogen ones, to meet the demand and the goals of the European countries.

## 2.4 KEY PARAMETERS FOR GAS STORAGE

To ensure a secure and reliable supply of gas is important to have clear the characteristics of a gas storage facility. After the analysis of the gas network and the market is critical to understand how gas storage works and which one are the physical parameters behind its design to exploit it as well as possible. Nevertheless, it’s important to know that some characteristics are due to the facility, such as its capacity, and others are given by the gas within the facility, such as the energy density [23].

One of the factors that influence a storage facility is its capacity. This is important to evaluate when a site is taken into consideration, and it refers to the maximum amount of gas that can be stored in the reservoir at any given time. It is usually expressed in cubic meters/feet of gas volume or concerning the gas stored and its energy in Watt-hours and varies widely depending on the type of storage facility. For instance, underground storage facilities in depleted oil or gas fields can have capacities ranging from a few million to several billion cubic meters, while above-ground tanks may have a much smaller capacity.

It’s possible to distinguish two different types of capacity, such as the design capacity and the demonstrated peak capacity. The design capacity, or nameplate capacity, is a theoretical limit of this parameter, based on the physical characteristics of the reservoir, the operating procedure used, and the installed equipment, which must be certified by state regulators. Instead, the demonstrated peak capacity, or total demonstrated maximum working natural gas capacity, reports the actual facility usage and is typically less than the theoretical one. In a storage facility that has more than one individual storage field, it is the sum of the largest volume of working natural gas for each field registered anytime within the last five years [24]. Another type of capacity is named working gas capacity and stands for the working gas volume that can be stored, injected, or withdrawn within the normal operation of a gas storage facility. It is defined as the total storage volume minus the base or cushion gas, which is the minimum gas required to stay in the storage to prevent issues related to pressure, injection, or withdrawal rates [25].

The deliverability, or withdrawal rate, is the complement of the injection rate. They refer to the amount of gas that can be withdrawn/injected on a daily base and are usually expressed in terms of million cubic meters/day. These rates are not constant but vary over the year, in relation to several factors such as the production strategy, the wells placement, and the geological characterization, but they depend also on the amount of gas in the facility: the withdrawal rate of a full reservoir is higher than one that contains only the base gas, on the opposite, injecting gas in an empty one is faster than injecting gas in one that is close to its maximum gas volume stored. These rates vary also among different types of storage facilities aquifers and depleted fields are the slowest solutions, while the salt cavern is the fastest, having a fast response and allowing multi-cycle [26].

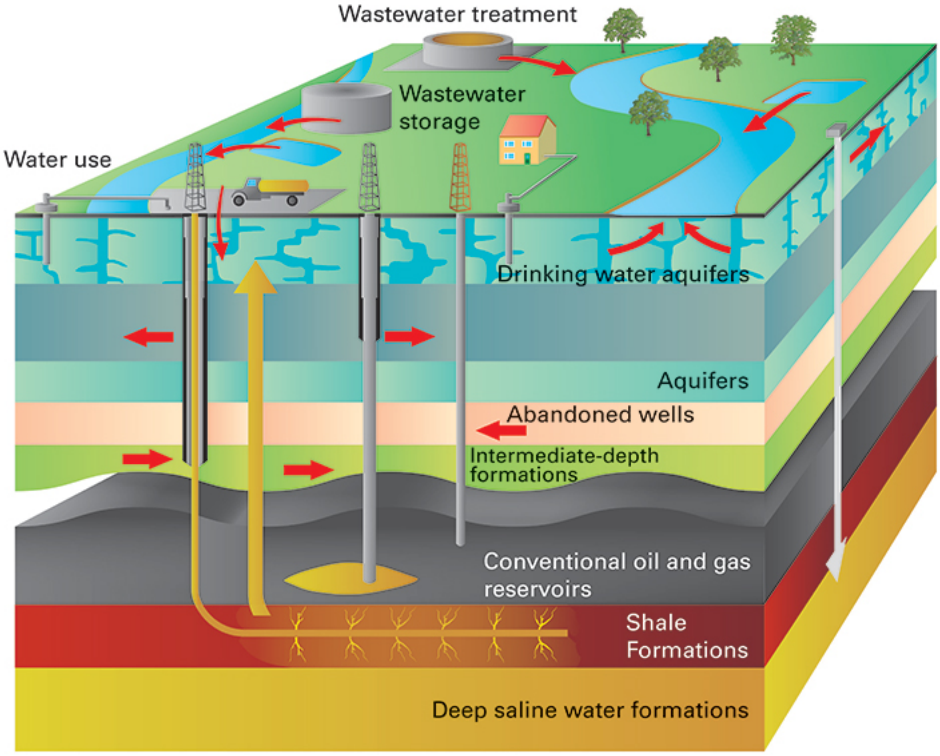


**Figure 2.7** Different underground storage facilities [27].

There are several types of gas storage facilities such as underground storage facilities (UGS), which are the most common type in Europe and can take place in depleted oil or gas fields, salt caverns, or aquifers. Each type of storage has different characteristics that affect its capacity, availability, and cost. Other types of gas storage are represented by liquified gas storage and above-ground gas storage.

The location of the gas storage facility is also important because it affects the cost of transporting gas to and from the facility, as well as the availability of infrastructure such as pipelines and storage tanks. For example, a storage facility located near a major gas pipeline can have lower transportation costs and greater availability of gas than one located in a remote area.

The energy density of a gas storage facility is another important factor to evaluate. Energy density refers to how much energy can be stored in a given volume and is mainly a characteristic of a gas instead of a facility. For instance, hydrogen has a much lower volumetric energy density than natural gas, which means that it requires more space to store the same amount of energy. This is important because it affects transporting and storing gas costs and efficiency.

Many other factors are important to consider when a gas storage facility is evaluated like the cost associated with construction, operation, and transportation. Regulatory compliance is also critical, as gas storage facilities are subjected to regulations from the government regarding their construction, operation, and safety.

Ensuring a secure and reliable supply of gas requires careful consideration of all these factors.

# 3. RESERVOIR ENGINEER BACKGROUND

## 3.1 GEOLOGICAL DESCRIPTION AND SEISMIC MONITORING

The techniques developed by the oil industry for the research and exploitation of hydrocarbons are now used to investigate the presence of underground gas storage and its structure. This R&D spin-off accounted for 600 billion USD of savings for the storage industry in the early 2000s, whose own R&D was just about 4 billion USD [28].

This sector is not particularly innovative, with drilling techniques used from the 19th century and seismic monitoring from the first half of the 20th century, which has had a significant improvement in the 1980s thanks to the development of computer technology. In fact, in the 1990s the 3D seismic monitoring tool enhanced the progress, leading to the 4D seismic in the 2000s.

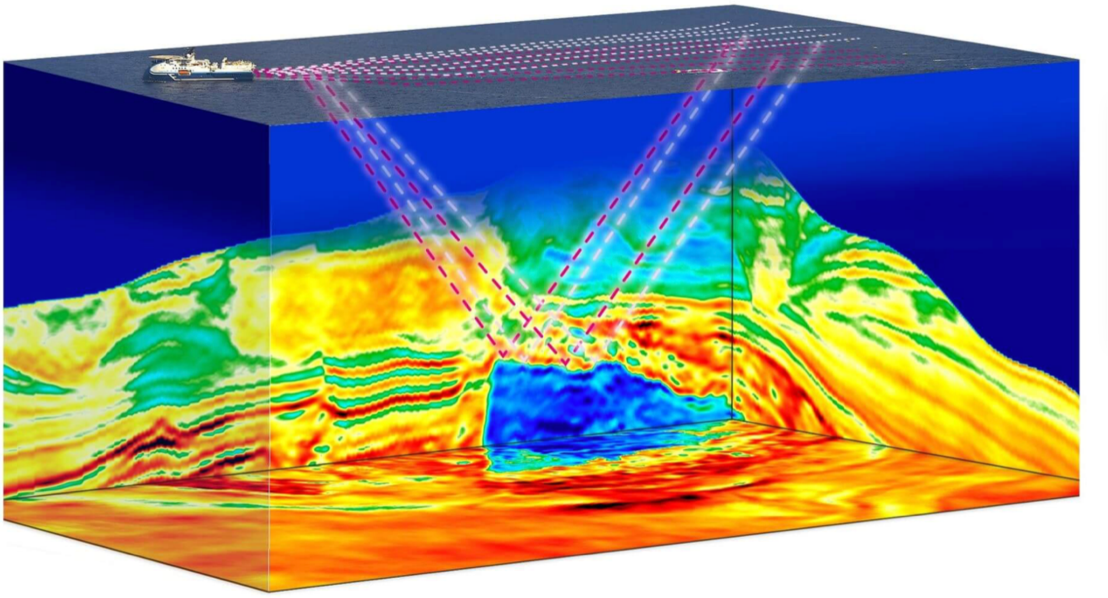


**Figure 3.1** Time-laps 4D seismic processing and imaging [29].

The feasibility study of a structure's suitability to be a storage facility is a complex and expensive process, that requires at least the use of a 3D seismic survey, drilling, and various measures and tests, e.g. the interference measurements between wells. Fortunately, the accuracy reached in the 3D tests reduces the uncertainties. It minimizes the number of wells to be drilled for the certification and gives a better allocation of them along the structure, lowering the development wells required. The geological and geometrical characteristics of a structure influence its performance, thus this knowledge helps to optimize the development and productivity of the site. The geological description has benefitted from advances in geostatistics, a science developed in the latest 1970s, related to the increased computational power [30].

The 4D seismic technology, or 3D repeatable seismic measures, is based on the use of seismic sensors placed at regular intervals in the wells or on the surface permanently [28]. The new technologies, such as the time-lapse 4D seismic technology, supply accurate reservoir characterization and seismic monitoring based on the utilization of expert data processing, imaging always more complex, and multi-vintage data acquired. The baseline survey and any 4D monitor repeat surveys must be considered together, in a method that optimizes the results, instead of using an individual 3D seismic dataset [29].

In the interpretation of the dataset is very important to consider seismic attributes such as frequency, amplitude, and phase because these parameters change over time since they are sensitive to reservoir parameters like pressure and fluid changes. This characteristic implies that nowadays these tools are not used just to investigate the presence or the features of a reservoir but also for its surveillance and monitoring the productivity over the long term [31]. These detailed techniques allow us to collect data on small structures, small-scale discrepancies, gas-liquid interfaces, and even stratigraphy. Due to these improvements, we are now able to develop better structures. Moreover, the seismic measures help to investigate the limit of the gas bubble in the facility and notice the difference between two measures, this improves the production prediction. The main advantage of this technology is the possibility to check the progression of the gas bubble between the critical spill points in several directions to maximize the filling of the reservoir and to recognize the area with the vastest presence of the gas to better organize the production wells system in that area. The fluid flow numerical simulation with the geostatistical model of the space of reservoir properties, such as porosity and permeability, helps to provide a prevision of the reservoir behavior in operational conditions, optimizing recovery and wells efficiency.

## 3.2 GEOLOGICAL CHARACTERISTICS

The development of a storage facility exploits the technology of the hydrocarbons industry but is also more complex since not every suitable reservoir is appropriated to be used as a storage facility without proving that the site can store gas that will not escape through the caprock, which must be analyzed to assure its continuity and closure of the structure. A caprock is defined as a relatively impermeable rock, that forms a barrier above and around reservoir rocks so that fluids cannot migrate beyond the reservoir. The permeability of a caprock capable of retaining fluids through geological times is usually considered from $10^{-6}$ to $10^{-8}$ Darcy [32].

The Darcy is recognized as the unit of permeability, equivalent to the passage of one cubic centimeter of fluid, having a viscosity of one centipoise (cP), per second through a sample one square centimeter in cross-sectional area under a pressure of one atmosphere per centimeter of thickness [33].

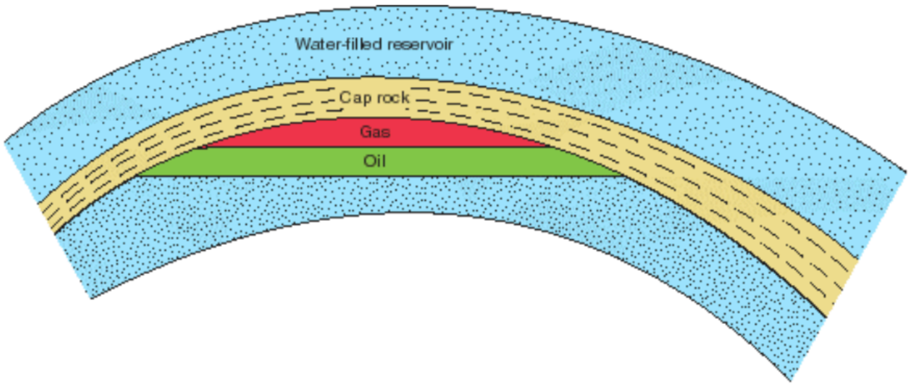


**Figure 3.2** Schematic diagram of a caprock over reservoir [32].

Concerning the geological characteristic is preferred that a depleted field has a high porosity and permeability the former is one of the main parameters that influence the amount of gas that the reservoir can hold, and the latter accounts for the calculation of the rate of the gas in the facility and so influence the injection and withdrawal rates, but this process is enhanced by the pressure, that is usually higher than the normal pressure of natural reservoirs, and when a certain amount of gas is needed it’s possible to extract it by an expansion process.

Depending on dimensions and geometry, the design of the original exploitation wells, and the properties of the storage facility, different values of the gas turnover rates can be obtained. To increase this parameter new wells must be drilled designing the lower section of the well to run horizontally with respect to the depleted field. By using this design is possible to reach a larger flow area that increases the availability of the formation.

Nevertheless, the computerized description reached so far is strictly needed to create the huge amount of data that must be evaluated for fluid flow simulation, such as geometric characteristics and petrophysical properties of a potential storage site.

## 3.3 DARCY'S LAW

The displacement of gas components requires a convective and dispersive transport mechanism. Darcy's law describes the convection phenomenon, which does not lead to mixing. The dispersive transport mechanism, instead, is led by diffusion and dispersion, where diffusion is the random motion of the molecules of gas, and the word dispersion is usually referred to various physical phenomena. Darcy's law is a phenomenologically derived equation that describes fluid flow through a porous medium. This important law came out from the experiments of Henry Darcy on the flow of water through the sand. One of the applications of this law is in geology, more precisely in the depleted fields, to investigate the behavior of gas in the reservoir.

In the case of constant elevation, it is reduced to a simple proportional relationship between the instantaneous discharge rate, the viscosity of the fluid, and the pressure difference over a certain length:

$$Q = \frac{-kA(P_b - P_a)}{\mu L}$$

Where Q, which represents the total discharge with a unit of volume per time [$m^3/s$], is obtained by the product of k, the intrinsic permeability of the medium [$m^2$], A, the cross-sectional area of the flow [$m^2$], and the pressure drop ($P_b$-$P_a$) [Pa] between the points A and B that are analyzed, all divided by the viscosity $\mu$ [Pa s], and the distance L [m] over the pressure drop is considered. The minus sign relates the formula with the real behavior of the flow, which goes from the high pressure to the low pressure as illustrated in Figure 2.3.

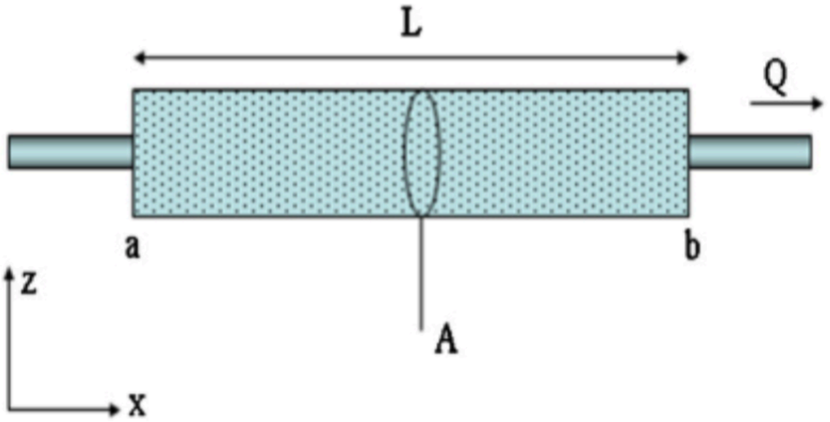


**Figure 3.3** Definitions and directions for Darcy's law [34].

If the inlet and the outlet are at different elevations, this must be considered. If the interest is focused on the evaluation of the fluid velocity, a further step is needed. The velocity of the fluid is related to the Darcy flux, which is obtained by dividing Darcy's law by the cross-sectional area of the flow.

$$q = \frac{-k}{\mu} \Delta p$$

In this case, regarding the parameters that have changed, q is the flux discharge per unit area [m/s], and $\Delta p$ is the pressure gradient vector [Pa/m]. This value is not the fluid velocity in a reservoir. Porosity ($\emptyset$) has to be considered in this evaluation because not all the volume of the reservoir allows the fluid to flow through it, so Darcy's flux (q) is divided by the porosity ($\emptyset$), obtaining the velocity of the fluid (v):

$$v = \frac{q}{\emptyset}$$

Darcy's law is important because it relates these quantities and summarizes different properties of a gas in a reservoir:

- if there is no pressure gradient over a distance there is no flow, this condition is called hydrostatic condition;

- the motion of a fluid is driven by a pressure gradient, from high-pressure zones to low-pressure ones;
- the velocity of the fluid is directly proportional to the pressure gradient, and so do the discharge rate;
- the discharge rate of a fluid has different values through different materials, or even through the same material but in different directions, considering the same pressure gradient.

Darcy’s law is valid only for a slow and viscous flow, but almost all the underground gas and the groundwater respect this condition, which is respected for a laminar flow with a Reynolds number minor than one unit, even if experimental tests have shown that fluids with a Reynold number up to 10 units can still be considered Darcian [34].

Although this law is very important in the evaluation of the deliverability rates of a reservoir, is important to remember that these are influenced by many different parameters not only by Darcy’s law, which consents to have a better explanation of a fluid motion in a porous medium, but alone is not enough to develop a production strategy of a reservoir.

## 3.4 NUMERICAL SIMULATION

The always increasing computational power in calculation and the reduced prices of the technology allowed the simulations to be more accurate, rapid, and cost-effective. Thanks to the fluid flow simulation is now possible to have a clear scheme of how the gas is distributed inside the facility at any moment and place, assuming that the rock properties are known. This is very important for the operational parameters of a UGS because it permits the assessment of the working volume, the peak withdrawal rate, the number and location of new wells required, and eventually the minimum cushion gas to be used to assure an optimal performance [35].

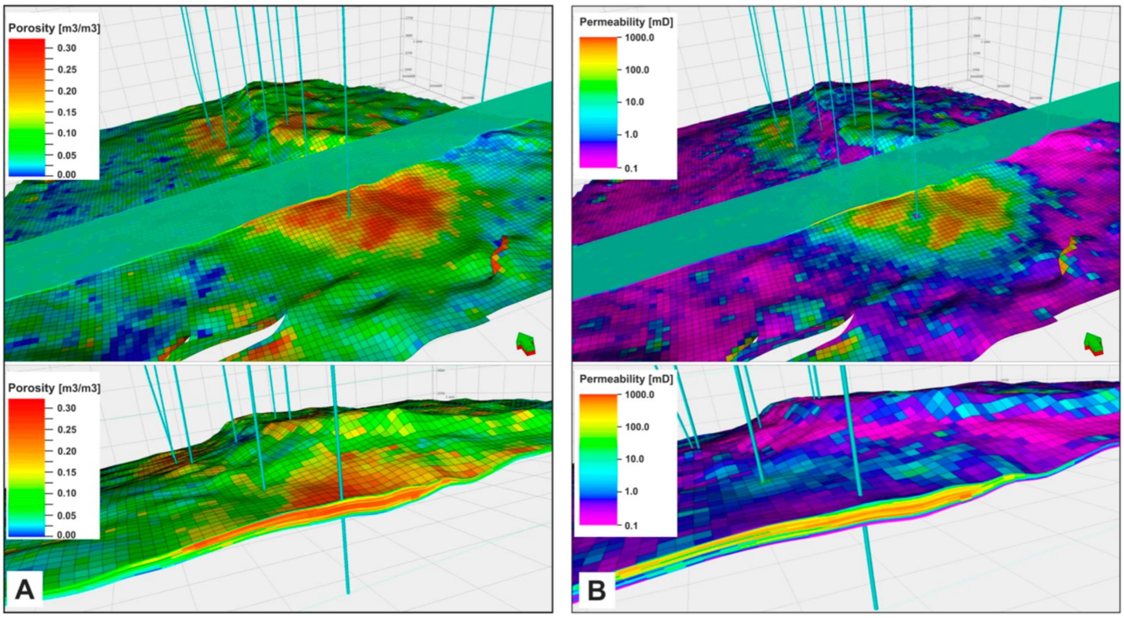


**Figure 3.4** Example of 3D modeling [36].

These simulations are used not just to predict the water or liquid production but also to implement an operational strategy, taking decisions on the quantities to inject or withdraw in a specific area and through which well, or in which layer.

The growth of computational power was an important achievement, but the simulation software development itself led to a better explanation of phenomena through case studies more and more complex. Now is possible to study in a very detailed way tens of possible scenario development at the same time as the pilot project, adapting the productivity to the client's requests. This allows more flexibility in the management of the facility, with an optimization of the storage system. The higher calculation accuracy level is shown by simulations of data measured on-site, or by the tuning of models over a longer period, which are obtained quicker, and in almost all cases, along with some tuning “tricks”, the engineers have more confidence in their result, due to the decreased uncertainty of the simulations. Moreover, the increased complexity of the analyzed phenomena led to very accurate descriptions of faults and gas constituents, through the compositional simulation, that can be done within the reservoir [37]. These improvements and the reduced calculation costs made it possible to study in detail more sites that can be suitable for a storage facility, and by multiplying the number of studies, they became more profitable. Even if is difficult to assess the profitability derived from modeling development since it regards the entire system, it’s clear that now is possible to estimate the performance of a storage facility in advance and with fewer uncertainties than ever [28].

Therefore, the assessment needs to take care of different aspects, such as the reservoir properties, like dimension and geochemical composition, to avoid over-pressuring and over-filling. An appropriate well design to avoid leakages, and a study of the overburden geology to evaluate potential migration pathways. Thus, this investigation aims to assure the capacity of the storage facility to operate at the desired pressure and under some operational parameters. The maximum safe operating pressure is related to the three primary geomechanical factors, which are constituted by the mechanical properties of the reservoir and overburden, the natural state of stress in the reservoir and overburden, the stress changes in the reservoir and overburden due to the pressure cycling.

## 4. DIFFERENT TYPES OF GAS STORAGE FACILITIES

Like many other commodities also natural gas can be stored for a geological time. The processes around gas exploitation require a long time, and when the gas reaches its final destination most of the time is not used immediately, but stored during a low-demand period and used when needed.

The places in which the gas can be stored are many and with different characteristics from each other. The first distinction that is possible to notice is that there are storage facilities above the ground, like above-ground tanks in which the gas can be stored in gaseous or liquid form, and underground facilities, such as depleted oil or gas fields, aquifers, and salt cavities.

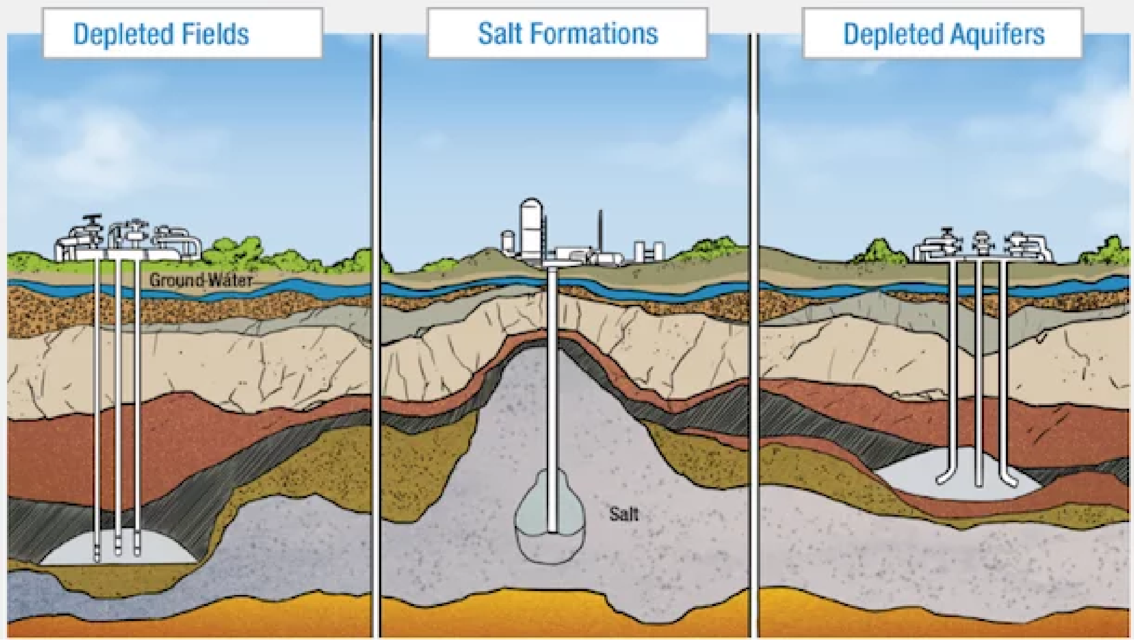


**Figure 4.1** Different types of underground storage facilities [38].

This already influences the position of a storage facility, because is not possible to build a very large above-ground tank in the middle of a city for many reasons as environmental impact or safety. Otherwise, most of the depleted fields are collocated close to the demand center since they don't occupy any space on the surface that can be significantly relevant to represent a problem [39]. There are several other features that characterize the different types of gas storage to focus on, then probably it is better to analyze each storage facility apart from the others to highlight its working principle, the physic that is behind it, and understand the advantages and drawbacks related to it.

## 4.1 DEPLETED GAS RESERVOIRS

Storage facilities in porous reservoirs, e.g. depleted oil and gas fields, are the most common type of reservoir, with more than 100 sites in Europe among the operative, under construction, and planned ones. They seem to be one of the most reliable and cheapest solutions. Most of them are depleted gas reservoirs, even if there are some oil depleted fields used for the same purpose.

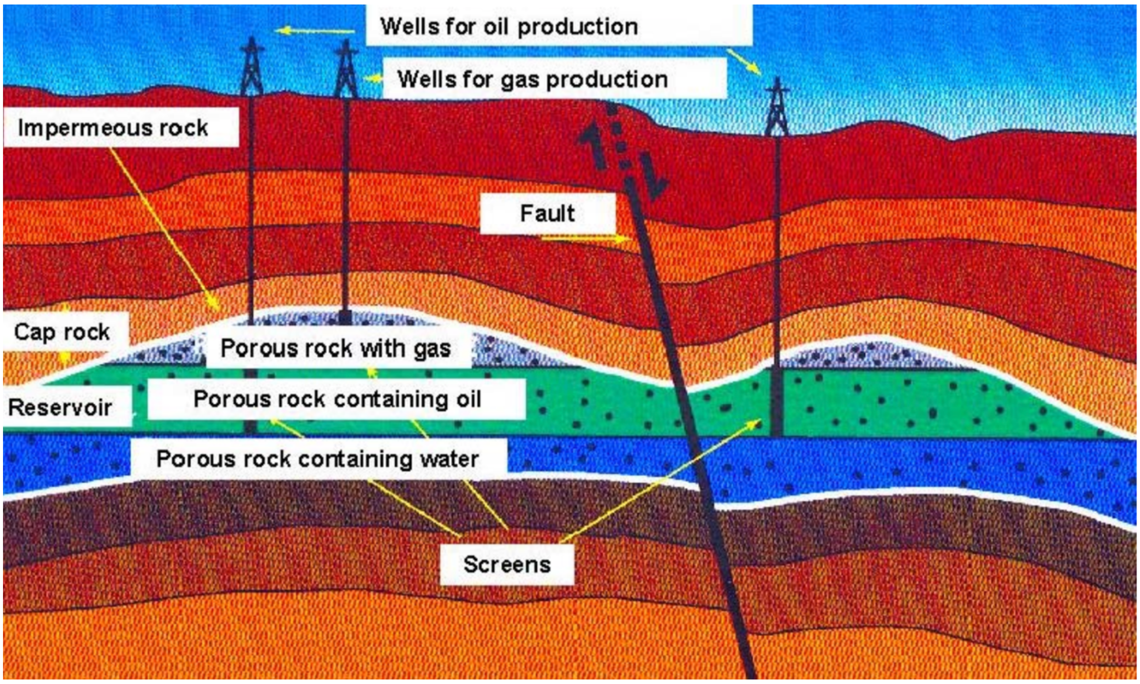


**Figure 4.2** Schematic cross-section of a gas or oil depleted reservoir [40].

The term depleted field refers to a reservoir of oil or gas that has been depleted by its commodity. The scenario, or component spatial distribution, in the depleted reservoirs after primary production depends on various factors. Generally, there are many driving mechanisms for a conventional gas reservoir, e.g. water-drive, compaction drive, or gas expansion drive and each drive mechanism will result in different component distribution.

Some general requirements are preferred in the construction of these facilities:

- The location of the storage site is very important. It should be as close as possible to the pipeline that supplies the gas, but also close to the main consumers. This allows to reduce the capital expenditure for the construction of pipelines, pumping, and transportation costs, increasing the availability of the facility.
- The storage must be airtight, this condition is essential for the feasibility of a reservoir, that must not allow the leakage of gas, not only for the

operational efficiency but also to prevent serious damages to the environment.
- The pressure in the gas transportation and distribution network must be met also in the storage facility.

Checking if the productivity goal can be developed before investing in a storage facility like this is necessary, and the analysis of the tightness of the cap rock, which is the above layer of the storage structure, is needed to avoid the diffusion of the gas outside the storage.

The working principle of depleted fields reservoir is simple since the reservoir used to contain gas or oil in the past, thus it satisfies the porosity and permeability conditions required. Physical and geological characteristics usually have already been analyzed by the petroleum companies that depleted the field itself. These structures have trapped hydrocarbons for millions of years, so they already showed their geological suitability for storage purposes. They don’t require special explorations, and moreover, any pre-existing exploitation well can be adjusted to inject and withdraw gas in the facility, and the infrastructure that was built to support the field can be used for the storage facility. Depleted fields usually have good rock properties and well-developed infrastructure, which makes them a cost-effective option for gas storage. Thus, these are often considered the easiest to develop and the cheapest to operate and maintain of all types of underground gas storage facilities.

According to the GSE (Gas Storage Europe) [10], Ukraine has the biggest UGS capacity and it is operated by the UkrTransgaz, a state-owned company that has 12 reservoirs all over Ukraine, for a total volume of 31 billion cubic meters, a value that covers roughly the total storage capacity of Italy, French, Austria, and

Hungary together [41].

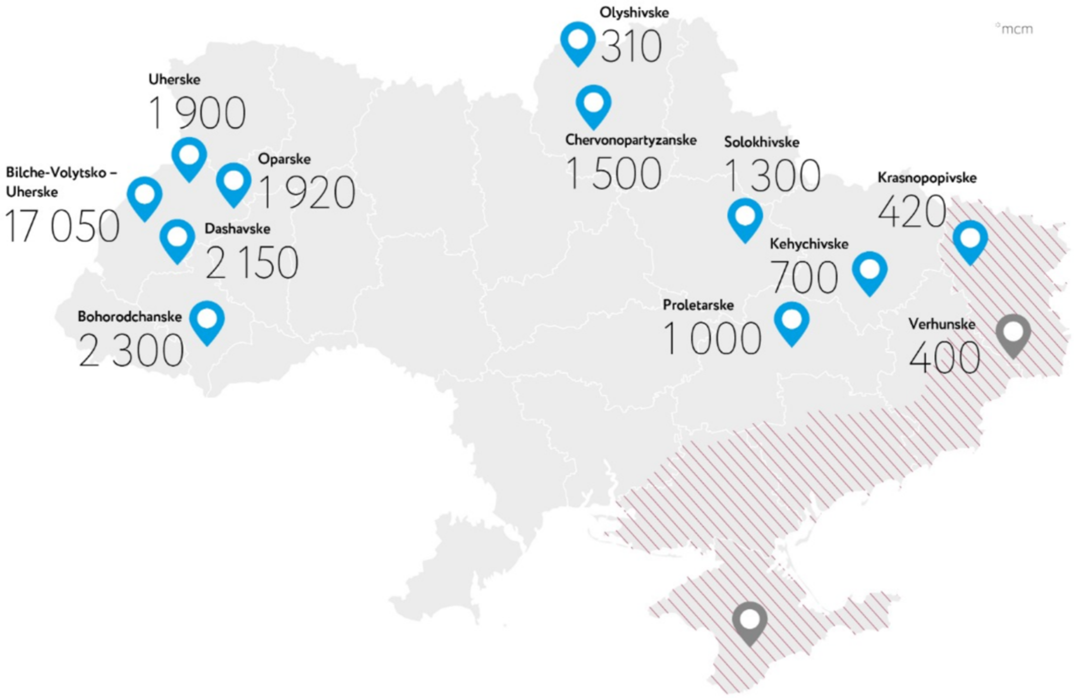


**Figure 4.3** Distribution of UGS in Ukraine and relative capacities in mcm [41].

The official dataset reports, a working gas (technical) of 327.92 TWh, which in this case is equal to the working gas TPA. This acronym stands for Third-Party Access and means that third parties are allowed to access the gas infrastructure, on the basis of published tariffs, which includes also the transmission and distribution pipelines, as well as the storage itself [42]. In Europe, it is considered the main element that allows energy competition in the Internal Energy Market.

The Bilche-Volytsko-Uherske underground gas storage facility, in Ukraine, is the biggest in Europe with a technical capacity of 17,05 billion cubic meters (180 TWh) at 20° C, an injection rate of 120 million cubic meters per day, and a withdrawal rate of 102 million cubic meters per day [43].

To provide a significant range of characteristic values of this type of facility, it’s interesting to compare the biggest storage with the smallest one. The reservoir of Fronhofen-Trigonodus in Germany can store 10,4 million cubic meters (0.11 TWh), with injection and withdrawal technical rates respectively equivalent to

0.51 and 0.76 million cubic meters/day. Eventually is possible to assume that depleted field reservoirs in Europe vary between a few million to a few billion cubic meters in working gas capacity and between some hundred thousand cubic meters to hundreds of million cubic meters concerning the daily injection and withdrawal rates.

The second country with the largest capacity of gas storage in Europe is Germany with 246 TWh, and the third is Italy with 193 TWh, an amount that covers 25% of the 2021 gas consumption [9].

Another important aspect to consider is the quality of the gas that goes into the pipelines. In fact, is not possible to guarantee that any residual gas present in the facility won’t mix with the gas injected in it. To avoid problems related to this scenario different measures can be adopted. One of these solutions can be to increase the volume of the cushion gas, regarding the different compositions of the gas stored and the residual one.

Gas processing plants are often installed above the facility, on the surface, to assure that the gas re-injected into the pipelines has the same composition and quality as the gas transported in the pipelines.

**Figure 4.4** Groningen gas processing plant [44].

A gas processing plant aims to remove impurities and particles that might be inside the gas before selling it, also removing solids and liquids contaminants.
This process can be very complex and usually is developed in 4 different steps. The first step is made to remove the solid largest particles, like sand by using scrubbers for instance, in the presence of heaters to control the temperature. Then the goal is to separate oil, condensate, and water from the gas, obtaining the sour gas. In this step, the gas contains sulfur, which can lead to corrosion in the pipelines. This element, along with carbon dioxide is pulled out with different methods. The last step is focused on the natural gas liquid recovery, where methane is obtained and other valuable liquid hydrocarbons are collected, such as propane, butane, and ethane [44].

## 4.2 AQUIFERS

Aquifers act like natural water reservoirs and are used to store gas by injecting it into the spaces of the reservoir to create an artificial gas field. The amount of gas used in this process is similar to the one used in depleted fields. As the other storage facility, also aquifers have some important characteristics to be respected to assure good productivity of the site. They must be composed of an anticline with sufficient closure, in a porous and permeable medium with good airtight capacity.

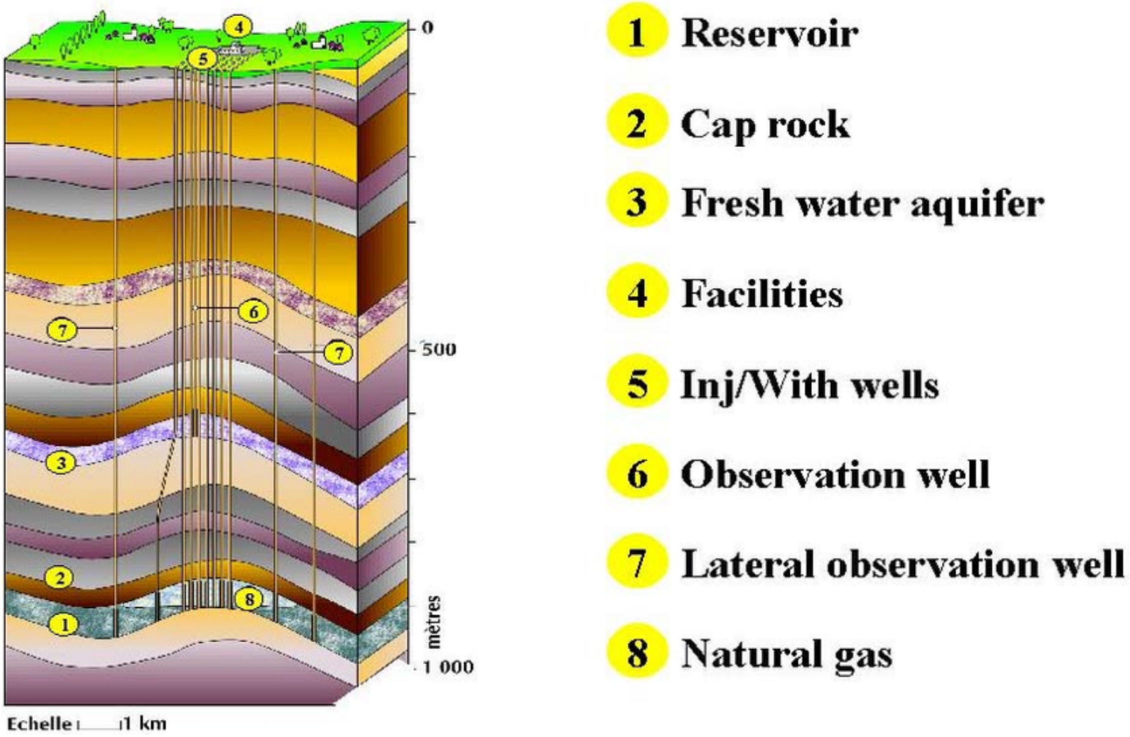


**Figure 4.5** Schematic cross-section of an aquifer converted into UGS [45].

Among the UGS, aquifers are the less used and the more expensive ones for different reasons. The geological characteristics are usually not well known like in depleted fields, and the capital expenditure for this solution increases due to the expense of the analysis of these characteristics, to assure the feasibility of a storage facility. These studies include the seismic monitoring of the site with the technics previously analyzed. The size of the site, the existing pressure, porosity, and permeability are important parameters to study in the project, although the capacity of the formation will be discovered just in the further development of the facility.

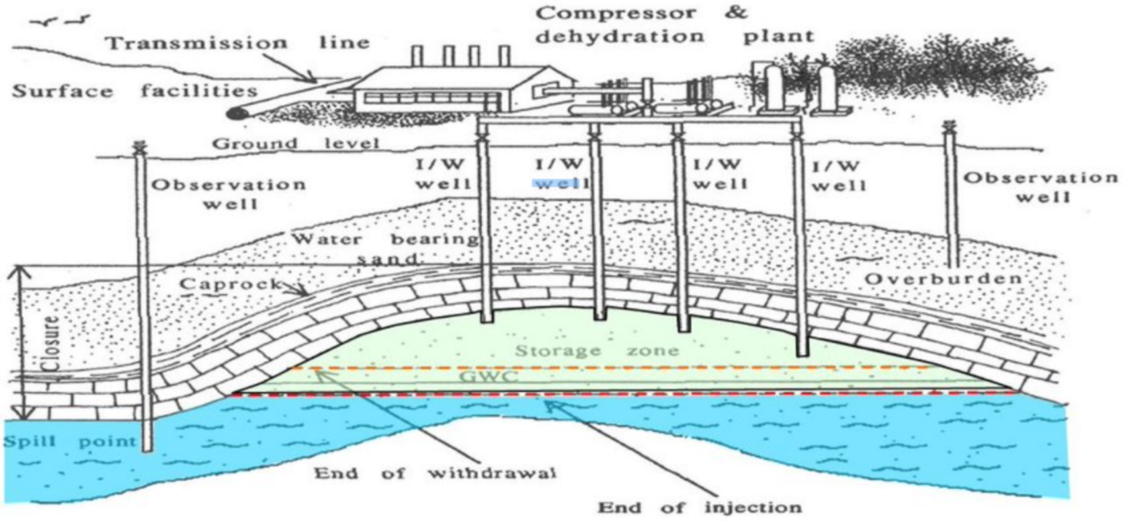


**Figure 4.6** Typical aquifer facility [46].

Regarding technical issues, usually, aquifers require more cushion gas to be injected into the facility to assure a correct operation, because natural gas was not in the formation and so a large part of it would never be recovered. The value of cushion gas can reach 80 percent of the total volume of the total gas, and if extracted, even when the facility is shut down, could lead to damage the formation. The more elevated costs are not just related to the exploration of the geological characteristics but also due to the higher initial operation costs, otherwise the monitoring of the gas-water interface and the long-term tightness can be compared to the ones of depleted reservoirs. This type of facility is used because, sometimes, it represents the only available solution in the area close to gas pipelines.

This facility offers the advantage of being a low-impact solution for the environment because in operation it doesn’t require the disposal of the brine or the injection of fresh water.

Usually, it is used for seasonal balancing and peak shavings according to the facility's characteristics.

In Europe, the biggest aquifer takes place at Inčukalns, in Latvia, with a working volume equal to 24,2 TWh, or 2,3 bcm, an injection rate of 178,5 GWh/day, or 17 mcm/day and a withdrawal rate of 316 GWh/day, or 30 mcm/day . Thanks to this capacity it helps to balance the gas demand in the region with the possibility to inject 17 million cubic meters of gas per day and withdraw 30 million cubic meters per day [10].

## 4.3 SALT CAVERNS

This kind of facility is spreading fast all around the world and particularly in Western Europe, because the knowledge around it is increasing and so is the understanding of its physical and geological characteristics that are interesting for storage purposes. In Germany, there are over 300 salt caverns used to store energy carriers, and in Europe, other countries such as Denmark or Netherlands have a strong presence of salt deposits, with deals to create new storage capacity in the next years, not only for themselves but also to develop an international storage system that allows other nations to access to the facility [47].

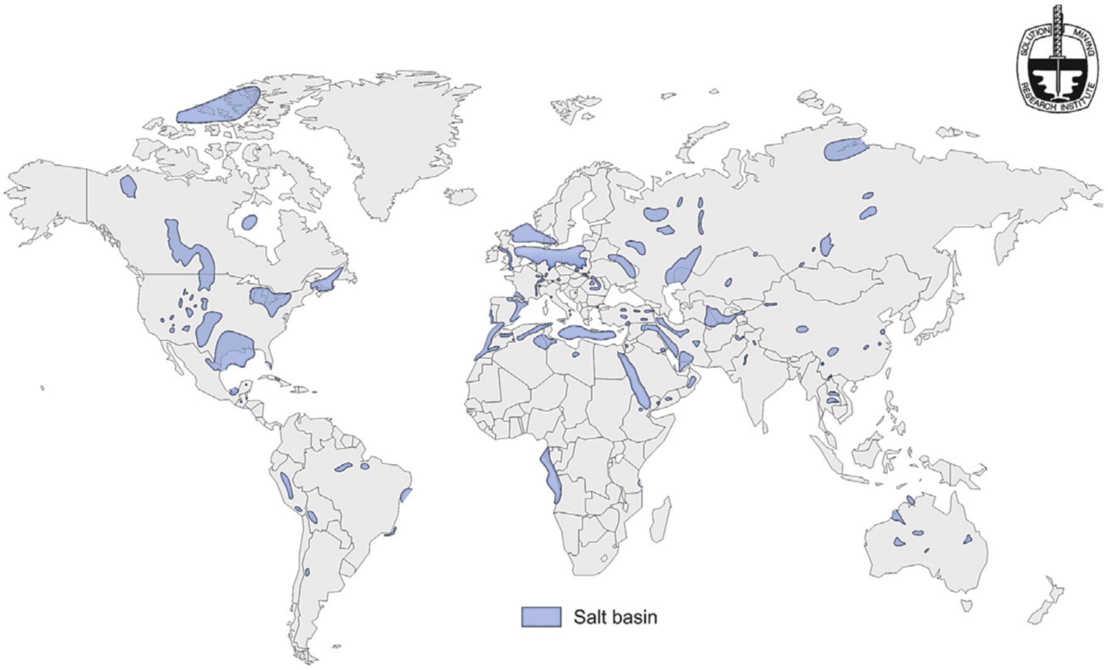


**Figure 4.7** Location of salt deposits around the world [47].

In the past, they have been used to store permanently Liquified Petroleum Gas (LPG), then in recent years, the aim of this structure changes to store natural gas, although the studies around the possibility to store hydrogen in this kind of facilities are becoming more insistent and it seems clear yet that this will be the future trend.

Different types of UGS can be distinguished according to the thickness of the salt, which is expressed in meters. In fact, for a thickness in the range of thousands of meters, the formation is called a salt dome, for a thickness of some hundreds of meters it is named a thick salt layer, and finally, a thin salt layer for a thickness of some tens of meters.

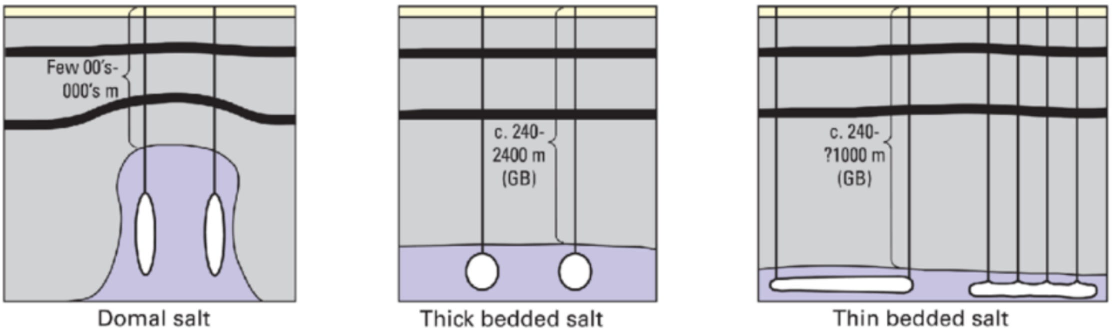
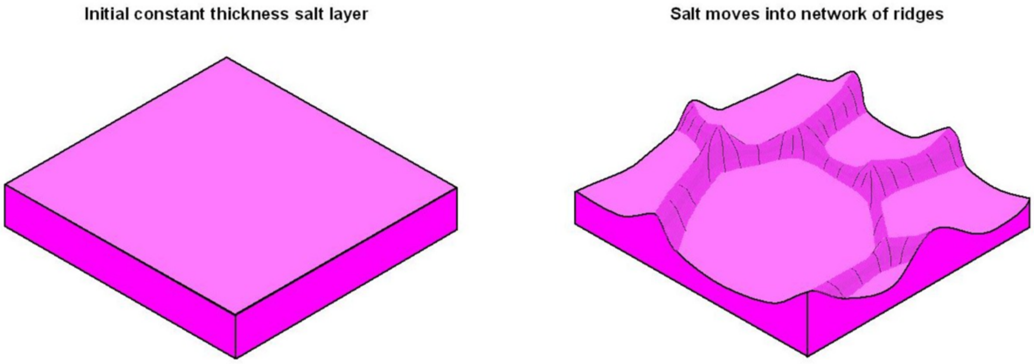


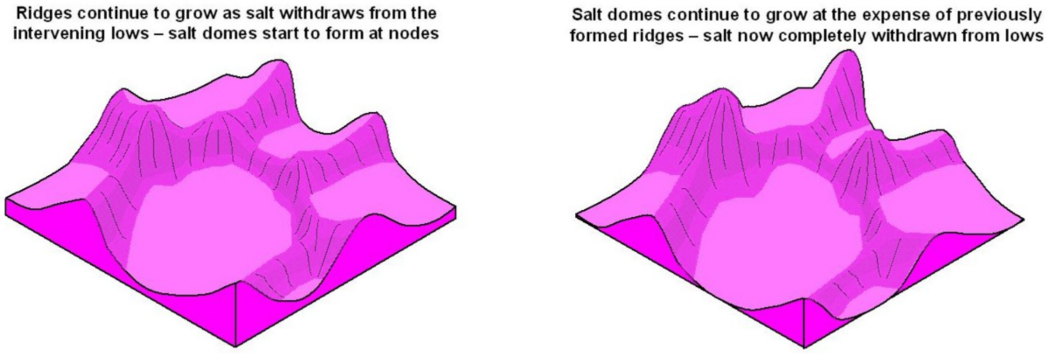
**Figure 4.8** Different types of UGS in salt caverns with relative depth [48].

Basically, salt formation may exist in two different main forms, which are the salt domes and the salt beds, which comprehend the ones that have been called thick and thin salt layers. The salt domes are thick salt accumulations, which have been deposited over a long period and drained from the above layers to create this large structure. Salt domes' wideness can be up to a few hundred meters in diameter and some hundred meters in height. The depth of the commercial facilities usually varies between 500 meters and 2 kilometers under the surface, even if it's possible in some extraordinary cases that they are shallower.



Initial constant thickness salt layer

Salt moves into network of ridges



Ridges continue to grow as salt withdraws from the intervening lows – salt domes start to form at nodes

Salt domes continue to grow at the expense of previously formed ridges – salt now completely withdrawn from lows

**Figure 4.9** Formation of salt domes from initially uniform thickness salt layer due to loading [49].

Salt beds are located closer to the surface and are formed by much thinner layers, that reach no more than 300 meters in height, but due to their wider and thinner shapes, they are more expensive to build and maintain than salt domes, being more suitable to deterioration.

The first caverns were built in the 1960s and 1970s, and since the knowledge in this area was not much developed, they served as a test. With the gathering of experience, they became models for the general elastoplasticity rules needed to design salt cavities, concerning important factors like gallery sizes, pillars, and chambers.

In the 1970s the reservoir of Tersanne, in France, suffered from significant geometric volume losses, that didn't stabilize. This problem led the scientist to start large R&D programs, which found out that the rocks in salt cavities have a non-linear elastoviscous behavior, that could be better analyzed in the 1990s with the advent of 3D software and new technologies. Now is possible to investigate the presence of these reservoirs and predict the geometric variations due to the operation strategy followed in the facility [28].

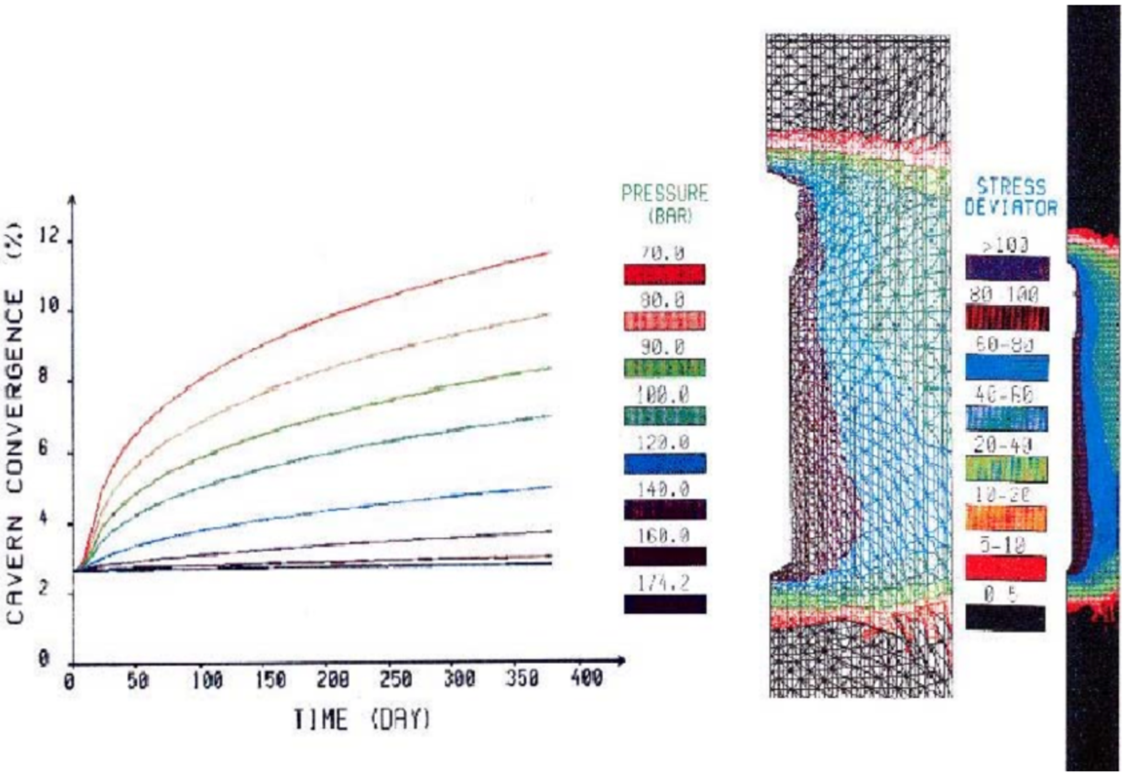


**Figure 4.10** Convergence of a salt cavern and stress calculation about operating pressure [50].

The storage capacity for a given volume of this facility can vary according to the maximum operating pressure, related to the site's depth, and it can reach the value of 200 x $10^5$ Pa (200 bar). Overall, the range for salt cavern storage volume capacity is between 100.000 $m^3$ and 1.000.000 $m^3$, with an average height between 300 and 500m, and a diameter that may vary from 50 to 100m [47].

As anticipated before, the characteristics of this facility are very interesting and are a good media to store gas due to their ability to keep the gas inside allowing just a few of it to escape, if not for intentional extractions.

They have high deliverability, a high degree of availability, short filling periods if large compressor units are used, and a low percentage of cushion gas that can be totally recovered when the facility is no more utilized [28]. The percentage of cushion gas is roughly 33% of the total gas capacity and is the lowest among the UGS.

Moreover, salt is inert with respect to gas and liquid hydrocarbons and salt cavities don't have residuals of hydrocarbons inside as it happens in depleted fields. This is important because allows the salt cavities to be one of the best facilities not just to store natural gas and hydrogen, but also compressed air or carbon dioxide, which otherwise could react with the rocks or the residuals present in the facility and explode. Their deliverability, that for facilities which have between one and three wells can vary from 8,5 to 17 million standard cubic meters per day, allows the salt caverns to be used for shaving peak loads and short-term variations in demand [51]. Salt cavity turnover can be daily or weekly according to the commercial needs of the market in a certain period [52]. Moreover, gas can be extracted from it within a short time notice, like one hour, and this feature increases the reliability that this kind of structure, which has to cover short-term changes in demand and supply gas during emergencies.

### 4.3.1 MINING SOLUTIONS IN SALT CAVITIES

The way they are built is called leaching and is peculiar since it's artificial and it's exploited fresh or sea water to dissolve and extract a certain amount of salt present in the cavity, leaving a large empty space in the formation. The brine, composed of the pumped water and the dissolved salt is then extracted from the facility through the same well that has been drilled to pump the water in it, and that same well will inject and withdraw gas. This procedure is common for all the salt caverns that are meant to be storage facilities and can be an expensive procedure. Mining the cavities can cost 25-35% of the investment and takes years to be completed, using a large amount of water, which may vary from 7 to 9 $m^3$ of water per $m^3$ of rock mined. The brine which is produced by this process can contain 260-310 $kg/m^3$ of salt and the disposal may vary. Sometimes it could be sold to a chemical industry that uses chlorine or sodium, or re-injected underground, in estuaries, or in the sea.

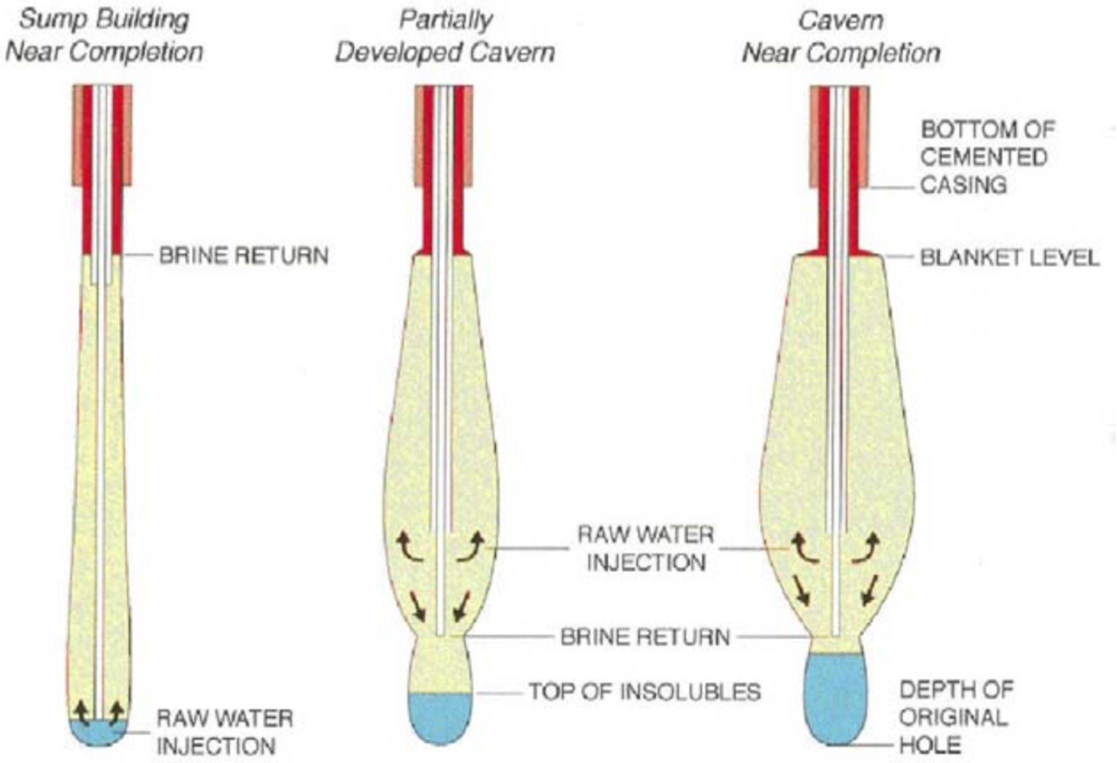


**Figure 4.11** Mining solution in salt domes [53].

Due to the large mining time required to build this facility, usually, the technic of solution mining under gas (SMUG) is adopted during the leaching. To manage the shape of the cavern is often used natural gas or inert gases like nitrogen on the roof of the cavern, or the more convenient diesel oil or LPG.

After the water has been pumped and the salt dissolved the next step is called dewatering, in which gas is injected through the well for the first time between the dewatering string and the production casing, while the brine is extracted from the dewatering tube. Once the cavern is full of gas, the dewatering tube is no longer necessary so it can be cut, left in place, or pulled out of the well. This procedure can take 18 months to be completed.

To save time is possible to operate the SMUG. In this case, the first steps of the traditional mining solution are performed, developing the upper part of the cavern to its designed diameter, while the lower part is not fully developed. This comports some adjustments in the wellhead and the strings used for the solution mining. Now the upper part is dewatered, and the gas pumped into it is ready to be stored. This gas behaves like a blanket for the continued solution mining of the lower part, forming a gas-brine interface that must be monitored constantly and maintained at mid-cavern.

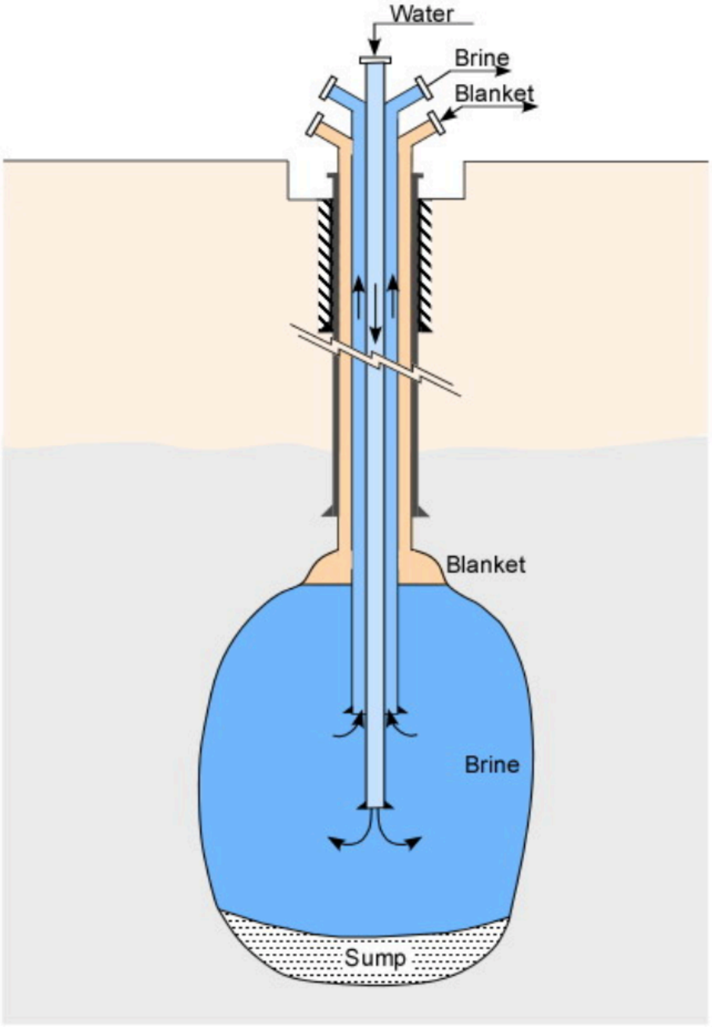


**Figure 4.12** Solution Mining Under Gas (SMUG) [54].

When the lower part of the salt cavity reached roughly the same diameter as the upper part, the same process discussed previously for the upper section takes place here and develops more capacity for storage purposes.

When gas is withdrawn by the facility is possible to inject water, and at the same time is possible to inject gas when the brine is extracted. In this phase, the gas-brine interface is no longer situated at mid-cavern but varies continuously in height and must be monitored even more strictly to avoid the risk of overfilling and maintaining roof protection. If for some reason, there is the need to expand the cavern the SMUG can be resumed anytime.

Overall, this process doesn't only save time, but also the amount of cushion gas to be injected into the facility in this phase is reduced. The deliverability of the gas is influenced by the level of gas in the storage, among other parameters, but thanks to the injection of water which maintains the pressure up, it is possible to have a better deliverability of the facility over time. Every time that all the gas is extracted by the facility and water is injected it's created more volume capacity.

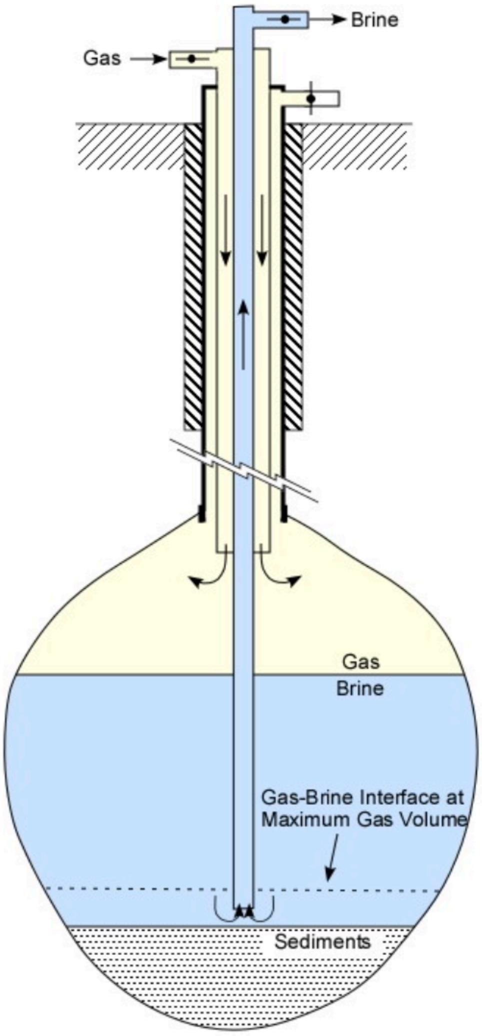


**Figure 4.13** Operations in a salt cavern [54].

## 4.4 GENERAL AND ECONOMICAL CONSIDERATIONS

Many different types of underground storage facilities have been presented. Each one with its characteristics and consideration aimed at explaining the behavior of these systems. When a reservoir is in the project phase, it’s important to understand the parameters that influence the construction and the lifespan of the facility. Not all the different types of facilities meet the demand in the same way or are suitable for a certain region. It has been analyzed how different facilities perform differently under all the main aspects.

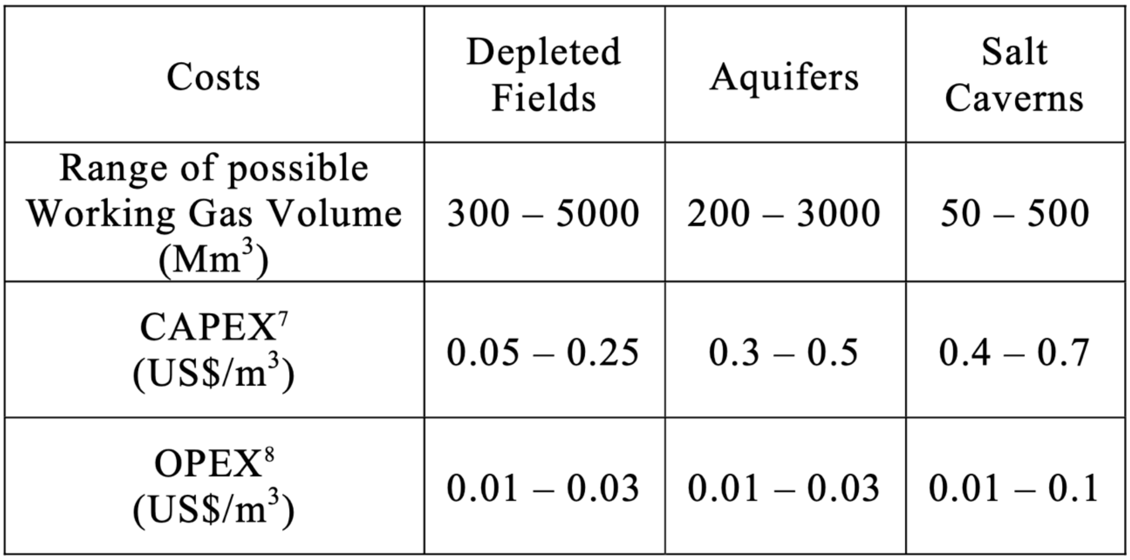
Depleted fields have a large capacity and availability. The reduced general investigation costs, due to their proven ability to store gas for geological eras, and the studies taken by the petroleum industry, allow for reducing the R&D for storage purposes. Saving money in the construction of the facility by reconverting the wells present in that, used by the petroleum industry, and sometimes using the same actual facility can mean a significant cut in the expenditure, for a site that has already low operational costs. Otherwise, the purity of the gas stored is not assured since it's probable that hydrocarbon residuals are present at the site. Overall, these factors bring the depleted reservoirs to be the most used all over the world.

Aquifers need several studies to prove the feasibility of a gas reservoir. They require the maximum amount of cushion gas between all the UGS facilities and most of the time it's not recovered to avoid damages at the formation. They are used in regions in which there is no availability of other solutions.

Salt caverns have high deliverability and are inert to hydrocarbons and other substances due to their physical properties that are suitable and well-performing for the storage of natural gas and other gases. The main problem of these facilities seems to be the elevated cost of the construction and operation.

The cost of a solution is very important to assess the feasibility of the project. Gas storage aims at the reduction of the gas price and its stability, the availability of this commodity in the shortest time possible, and the seasonal balancing, so the economical aspect is fundamental here as in all men's activities.

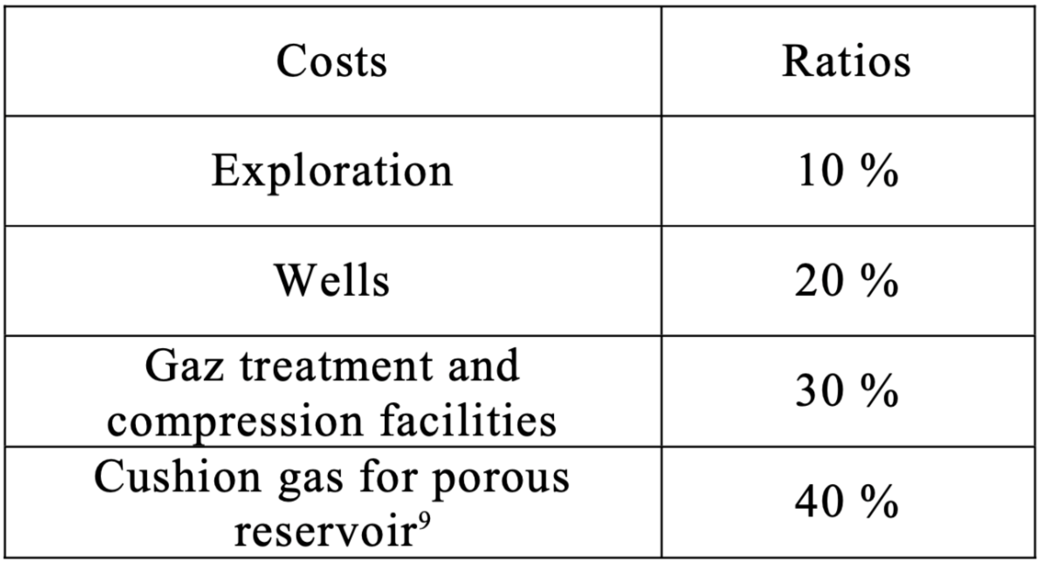
For this reason, it's interesting to highlight the economic aspects of these facilities, first in relation to the capacity. In this way, it will be possible to understand the cost for a certain type of facility to store 1 $m^3$ of gas, making it easier to confront them.



| Costs | Depleted Fields | Aquifers | Salt Caverns |
|---|---|---|---|
| Range of possible Working Gas Volume ($Mm^3$) | 300 – 5000 | 200 – 3000 | 50 – 500 |
| CAPEX[7] (US$/$m^3$) | 0.05 – 0.25 | 0.3 – 0.5 | 0.4 – 0.7 |
| OPEX[8] (US$/$m^3$) | 0.01 – 0.03 | 0.01 – 0.03 | 0.01 – 0.1 |

**Figure 4.14** Average cost (in USD) and capacity for UGS [28].

As anticipated before, here is clear that depleted fields present the lowest capital expenditure (CAPEX) and the highest capacity. Instead, the operation expenditure (OPEX) is higher for salt cavities. All these data are normalized on the $m^3$ of the storage volume.



| Costs | Ratios |
|---|---|
| Exploration | 10 % |
| Wells | 20 % |
| Gaz treatment and compression facilities | 30 % |
| Cushion gas for porous reservoir[9] | 40 % |

**Figure 4.15** Average costs for UGS facilities [28].

The reported costs for UGS facilities such as exploration, wells, gas treatment, compression facilities, and cushion gas for porous reservoirs are all variable. Every facility is different from the others, and also between the same type of facility, as many parameters are considered, and different solutions are applied. These are just average forecasts that must be adapted case by case but are useful to realize the weight of these costs on the total expenditure of a general UGS, to visualize which part of the production cost more, and try to reduce the expenditure. The reported value of cushion gas for porous reservoirs is mainly related to oil fields and aquifers but still must be adjusted depending on the depletion level of the field. For the salt cavity is possible to say that this value covers roughly the expense for cushion gas and leaching facilities.

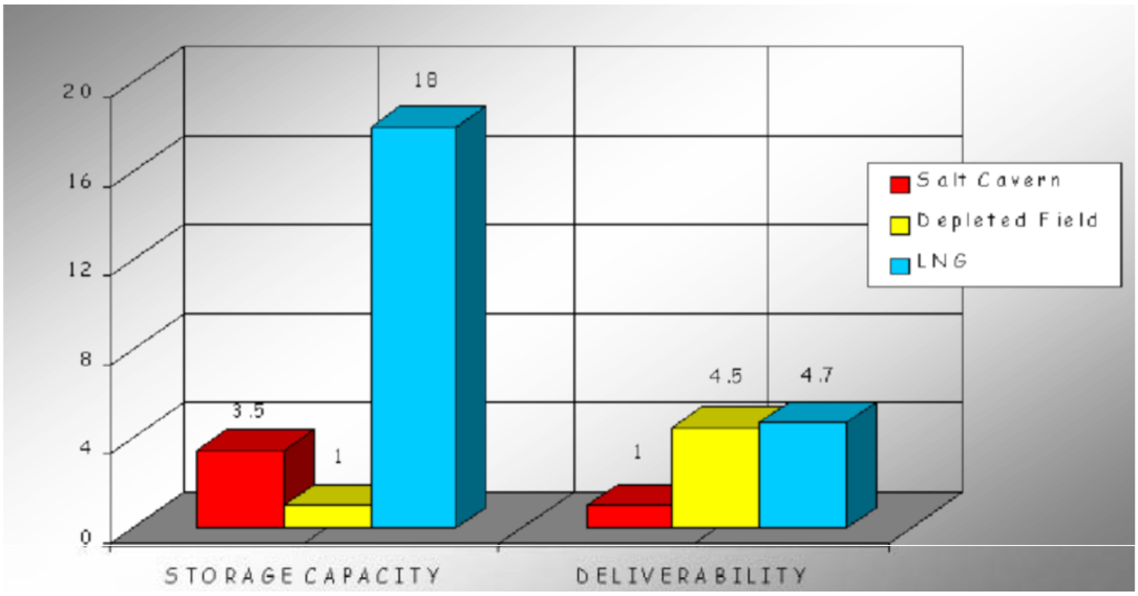


**Figure 4.16** Comparison of costs between UGS and LNG [55].

UGS doesn’t represent the only solution to store gas. In recent years Liquified Natural Gas became more important, even more after the beginning of the Ukraine War. To give the reader a complete idea, the comparison between UGS and LNG has also been performed. The results show that LNG is more expensive for storing and delivering gas than the UGS systems. The LNG solutions are adopted in particular circumstances, where the use of UGS and the gas network is difficult. Storing gas in the liquified form reduces the volume by a factor of 600 times, at -162 Celsius degree for natural gas, but it's more expensive due to the high quality of the materials and the solutions used to keep the gas as cold as needed. Nowadays underground storage continues to be the cheaper method to store and deliver gases. Overall, each type of gas storage facility has its pros and cons, and the choice of which type to use can be taken from their characteristics and factors like capacity requirements, location, energy density, and cost. An appropriate knowledge of the technical features and trade-offs of each type of storage facility is critical to ensure a secure and reliable supply of gas. A combination of the presented technologies may be used to provide a flexible and reliable gas supply system. If large-scale storage is required, underground gas storage facilities may be the best option due to their higher capacity and location close to demand centers. Liquified gas storage might be suitable for remote locations and peak shaving and backup power generation, instead, above-ground tanks can represent a valid option for small-scale storage applications.

# 5. UNDERGROUND HYDROGEN STORAGE

## 5.1 INTRODUCTION

The intensive use of carbon fossil fuels has mainly contributed to the greenhouse gas emissions on the planet Earth, that now suffers from global warming due to this behavior. To fix this problem, the global community is heading into renewable energies such as solar, wind, hydro energy, geothermal energy, and ocean energy, all sources of clean energy that can be exploited avoiding the production of greenhouse gasses. According to the International Energy Agency renewables accounted for 28,7% of the total global production in 2021 and will account for 60,9% in 2030. Now a large part of this production is satisfied by solar panels and wind turbines, that with 2873.2 TWh in 2021 supplied 35,4% of the renewable energy and are expected to produce 66,9% of renewable energy with a total of 15 346,4 TWh within 2030 [56].

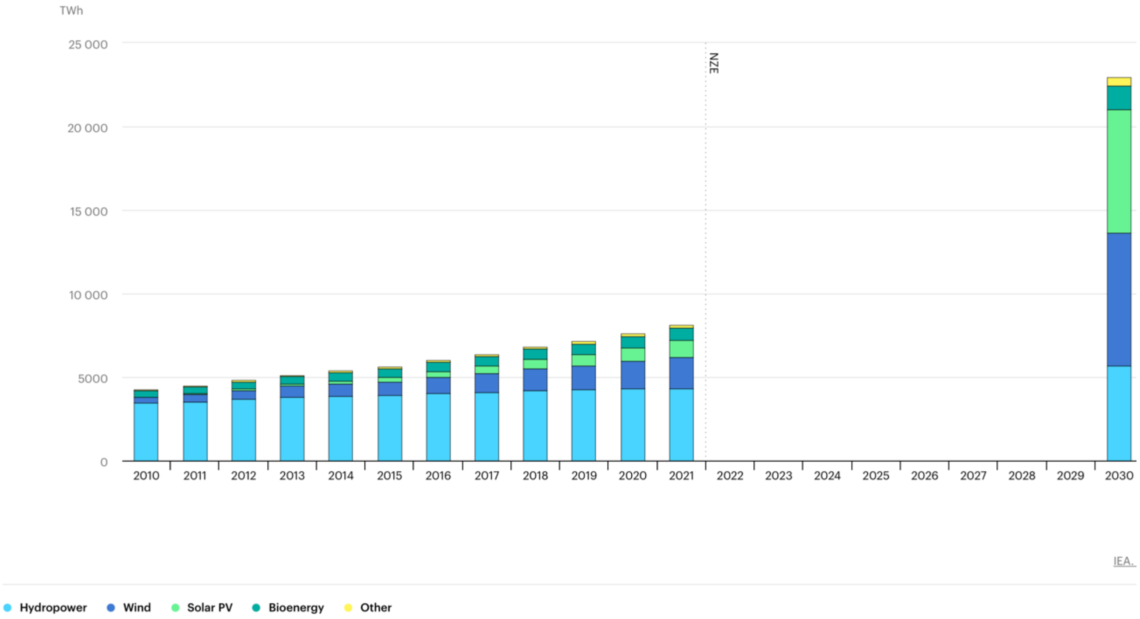


**Figure 5.1** Renewable power energy generation by technology in the Net Zero Scenario 2010-2030 [56].

Nevertheless, these technologies are impacted by a fluctuating behavior that creates a mismatch between energy production and the energy demand of the final users, due to their weather dependency. This is the consequence of sources of energy such as the sun or the wind that are not constant over the days and absent during the night, or not constant over the year. The growth forecast of green energy is consistent, with an estimated average of 12% growth annually over 2022-2030, to reach the goal. Otherwise, is not exactly defined yet how the production will meet the demand. In fact, the storage systems are fundamental in the market to allow complete access to natural resources, storing the excess energy produced to provide it later, or during the night, when needed. Due to the huge amount of energy considered in this operation also the storage system must be bulky, and to be able to satisfy the requirement different forms of energy storage must be used. It’s not likely to think that all the electricity can be stored in huge batteries due to many problems related to this application, such as the technology, the materials, the space, the efficiency, and the safety of this solution. Underground storage is, instead, proven to be able to store a big amount of energy or electricity after converting it into hydrogen, which has a bigger energy content per unit mass than methane or natural gas that is now stored in these facilities.

The future trends, according to the Technical Report of the European Commission, which analyzes part of the 67 possible scenarios publicized between 2017 and mid-2019, are represented by a 25% reduction in natural gas use by 2030, and in 2050 the reduction will be equal to 75%. In this scenario, renewable energy provides between 75% and 100% of the electricity, and an important trade-off between hydrogen and electricity as the final energy carrier in the energy industry will be needed, with a share of hydrogen equal to 5-20% in the energy consumption in addition to about 50% in electricity production [22].

Hydrogen can be used as propellant fuel, inside fuel cells, for agriculture, refinery, and other uses, but in the last years, it has been discussed mainly as an energy carrier. Thus, the energy surplus in the production can be converted into hydrogen and stored to be re-converted into electricity later, when needed, in a zero-emission process. This solution can be applied to balance the energy fluctuation in renewable energy sources to meet the demand.

There are many different ways to produce hydrogen, such as thermochemical processes, electrolysis of water, and biological or direct solar water splitting processes [57-58].

The hydrogen obtained can be stored in high-pressure systems that as usually cylinder shape, in cryogenic tanks, in materials able to absorb it and present a large surface specific area, in host metals, or through oxidation of reactive metals, such as Li, Na, Mg, Al, Zn with water [59].

In the near future, mid to long-term storage of hydrogen will be fundamental to meet the demand at a lower cost, according to the scientists. This could be realized within underground hydrogen storage in well-known underground facilities like depleted fields, aquifers, and salt caverns.

The process to store hydrogen is similar to the one of natural gas, including the previous injection of cushion gas such as $N_2$ and $CH_4$ before the hydrogen injection in the facility. The cushion gas itself doesn't take part in the production of the facility, but it undergoes many cycles of compression and expansion according to the withdrawal and injection needs, always inside the porous media, to maintain the operative pressure at the desired level and minimizing the hydrogen losses. Otherwise, in the withdrawal operation, the cushion gas can mix with hydrogen, so according to the final user aims, is important to have a processing plant that separates the gasses.

In the last decades, many projects have been granted and launched to understand the production, storage, and transport of hydrogen. Some of the most interesting are Roads2HyCOM (2005), Hychico (2006), H2STORE (2012), HyUnder (2012), CEN-CENELEC (2014), InSpEE (2015), and HyINTEGER (2016).

Moreover, different studies and different laboratories proved the feasibility of UHS evaluating capacity [60], security [60], physiochemical [61], geochemical [62], biochemical or microbial [63], and also economic viability [64].

Thus the storage process needs to take care of many different aspects that have to be optimized together to reach a good solution design.

The aim of this chapter is to evaluate the different problems that affect UHS, discussing their nature and solutions that are essential to be able to design an efficient facility in a safe way.

## 5.2 BACKGROUND

12.7 MJ of energy is produced by the combustion of one cubic meter of hydrogen, which is actually lower than the energy potential of methane, which is equal to 40 MJ. The energy used to produce hydrogen is higher than the one it can produce. For this reason, hydrogen is not considered as a source of energy but as an energy carrier. Thanks to its easy conversion into heat or electricity, or its storing energy capabilities, this molecule could fit the important task to balance renewable energy fluctuations.

If a gaseous carrier is used the losses in the transport procedure can be reduced up to <0.1%, instead of the 8% for pipelines of the power network.

One of the benefits to store hydrogen underground, in addition to the large capacity of the facility, which makes the economic perspective cheaper, is the absence of air, in fact, hydrogen is explosive when in contact with oxygen, as might happen in above-ground tanks.

According to some scientific papers, it has been found that storing hydrogen is pretty similar to storing natural gas, for this reason, the experience in natural gas storage is reported into the new hydrogen one in many aspects, like site location, storage techniques, monitoring and even cost life cycle and economic viability.

Naturally, is not reported all in the same way, due to the different physiochemical properties of the two gasses, which led to different behaviors in leakages, monitoring, and chemical affinity, because hydrogen is more likely to have chemical reactions which may lead to leakages. Other hydrodynamic properties like the low viscosity and the high mobility of this molecule lead to other phenomena such as fingering, gas rising, and overriding.

The gas processing plant is not useful just for separating the cushion gas from the hydrogen but, in depleted fields, is needed also to separate hydrogen from the hydrocarbon residuals that may still be present in the facility, to assure an almost 100% pure hydrogen. If the aim of the storage is to maintain the 100% purity of hydrogen through many cycles, for fuel cell application for instance, salt caverns are more suitable since they don’t have residuals that can contaminate it.

Even if the literature affirms that UHS is feasible, further projects to assure it are needed. In fact, there is particular attention on three practical important aspects, location, safety, and simulations of the performance. The site selection needs to be further developed since there are still many regions that could be suitable but there is a non-well knowledge of the region. Safety is the most important aspect of a storage facility and can be improved with a better monitoring technique over time. For a complete understanding of the phenomena, also, an accurate simulation of the performance of the security might be useful and could help to improve further the storage process.

Carden and Patterson, in 1979, discovered that 1% of hydrogen is lost per cycle in a UHS when injected due to operational process, while 0,4% of the hydrogen injected in the first cycle can be lost due to the solution of the hydrogen into the formation brine, although it has been proved that cushion gas improves these performances [65].

In 1986, Taylor et al. went through a techno-economic feasibility evaluation of UHS in the salt cavities, depleted fields, and rock caverns, and came out that salt cavities are the most economical facilities [66].

In 2004, another study executed by Schaber highlighted how UHS is preferred to an above-ground storage system because of the larger capacity [67].

Much research has been done to evaluate potential sites in Europe and out of Europe, and in 2020 Lankof and Tarkowski published a map with high-potential salt caverns for UHS purposes, including storage capacity, energy, and calorific values [68].

In 2020 Shi and other colleagues of his, have studied the potential of a natural gas and hydrogen blend storage in a depleted gas reservoir that was in use for natural gas. They saw how injecting this mix can reduce the permeability of the cap rock, leading to a better gas tightness of the facility, and the pore size distribution changed because of the interaction between rock and fluids [69].

## 5.3 PHYSICAL PROPERTIES OF HYDROGEN

Hydrogen presents different physical properties than methane or natural gas that we are used to store. Having complete knowledge of these characteristics is fundamental to operating in a safe way and planning the operation with efficiency. The density of hydrogen is eight-time less than that of natural gas at the same temperature and pressure, so to store the same mass more pressure is required, and this leads to the importance of the storage capacity in UHS.

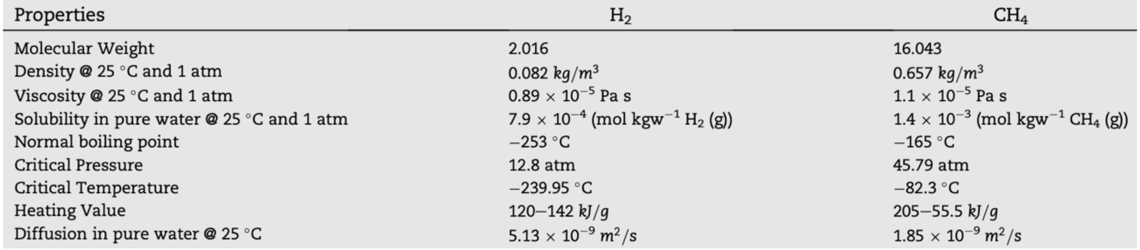
Even the viscosity is less, so considering a facility with a blend of natural gas and hydrogen, or hydrogen with natural gas or methane as cushion gas, it’s clear that this characteristic can be used to improve the efficiency of the withdrawal process, in which hydrogen will be extracted in with more efficiency since it presents higher mobility and so a lower residual of hydrogen in porous media will be trapped.

Another important aspect to consider in aquifers and depleted reservoirs is the solubility of hydrogen, which from preliminary tests seems to be lower than the one of natural gas, which can be an advantage. A higher solubility could leads to higher losses due to the dissolution of hydrogen into water. In a system composed of methane, hydrogen, and brine, this physical characteristic of hydrogen implies less dissolution. Moreover, in a water-hydrogen-salt system, a typical storage system, the presence of salt reduces even more the solubility of hydrogen. The dissolution rate can vary according to pressure, temperature, and contact area, and if the brine is recirculated, changing the hydrogen-saturated brine with a fresh one, the dissolution process is enhanced.

Another type of loss is represented by leakages, due to the molecular weight of hydrogen which is sensitive smaller than the one of air, carbon dioxide, or methane and allows the molecule to diffuse inside the overburden layers [70]. At standard conditions of temperature and pressure, hydrogen diffuses three times more than methane in pure water, but considering a porous medium the diffusion coefficient must be adjusted by scaling it with tortuosity, giving a real effective diffusion coefficient, which is usually smaller than the coefficient in pure water [71].

Considering the weight and not the volume, instead, hydrogen has the highest energy content per unit mass among the fuels, which is roughly 2,5-3 times the one of methane.

These characteristics make clear the difference between hydrogen and methane but are just the principal ones, so a table with other physical aspects of interest is reported down here, to give a complete landscape and a comparison of these properties.



| Properties | $H_2$ | $CH_4$ |
|---|---|---|
| Molecular Weight | 2.016 | 16.043 |
| Density @ 25 °C and 1 atm | 0.082 $kg/m^3$ | 0.657 $kg/m^3$ |
| Viscosity @ 25 °C and 1 atm | $0.89 \times 10^{-5}$ Pa s | $1.1 \times 10^{-5}$ Pa s |
| Solubility in pure water @ 25 °C and 1 atm | $7.9 \times 10^{-4}$ (mol $kgw^{-1}$ $H_2$ (g)) | $1.4 \times 10^{-3}$ (mol $kgw^{-1}$ $CH_4$ (g)) |
| Normal boiling point | −253 °C | −165 °C |
| Critical Pressure | 12.8 atm | 45.79 atm |
| Critical Temperature | −239.95 °C | −82.3 °C |
| Heating Value | 120–142 $kJ/g$ | 205–55.5 $kJ/g$ |
| Diffusion in pure water @ 25 °C | $5.13 \times 10^{-9}$ $m^2/s$ | $1.85 \times 10^{-9}$ $m^2/s$ |

**Table 1** Physical properties of hydrogen and methane [72].

## 5.4 UNDERGROUND HYDROGEN STORAGE IN GEOLOGICAL STRUCTURES

As discussed in the previous chapters underground storage can be built in a porous medium, where the gas stays in the pore space of the sandstone or carbonate formations, or in cavern storage, such as salt cavities, in which the gas is in a man-built void of an airtight rock.

As highlighted before, each type of underground storage has its own advantages and disadvantages derived from its characteristic, with a common factor like the trapping capacity, which is a fundamental requirement of a storage facility. In the evaluation of a storage site also the properties of the gas must be taken into account, in fact, density, compressibility, and solubility are important aspects that might influence the storage itself. For example, in the same volume can be trapped more carbon dioxide than hydrogen due to its higher density and compressibility.

### 5.4.1 SALT CAVITIES

Salt cavities are practical options for hydrogen storage due to their geological conditions, along with the mechanical properties of salt and its resistivity to chemical reactions [73]. Moreover, the salt avoids microbes to consume hydrogen [74]. According to the depth of the facility it can vary the pressure in the site so, at high depth corresponds high pressure and so more hydrogen can be stored, otherwise for low depth and low pressure less cushion gas is needed and so there is a cost advantage. As it has been analyzed in the chapter ‘mining solutions in salt cavity’ water availability is important for salt cavities, along with the distance from the pipelines. The overall price to build a salt cavity can be less than other facilities because the same well is used to build the facility and to inject and withdraw gas from it, also multiple times a year. This solution is good for the mid and short-term and also to shave the peaks of the demand along the seasons, as considered in many papers.

### 5.4.2 AQUIFERS

To store hydrogen efficiently in this kind of facility certain requirements are needed. For instance, the sites where the caprock has very low permeability are preferred to prevent the migration of the gas. When the gas is injected into an aquifer, the different densities of gas and water make the liquid move to the sides or downward, leading to an increase in the pressure of the facility derived by adding material to a closed system without withdrawing water, changing the liquid-gas interface during the operations. In withdrawal operations, the liquid may be produced together with the hydrogen and this represents one of the issues of this kind of solution. Apart from this, other problems may occur in aquifers for hydrogen storage, such as leakages along the undetected faults, biochemical reactions, or reactions of the gas with the minerals of the facility, and the leakage of a relevant amount of pieces of information about the facility itself in comparison with the pieces of information available for other facilities. All these problems conduce to the necessity to acquire new pieces of information by drilling and studying the facility, increasing the cost. So far, in the literature is not possible to find an aquifer that contains just pure hydrogen. But it's possible to find aquifer storage with a half of composition of hydrogen and half of methane in Europe, in places like Engelbostel and Bad Lauchstädt in Germany, Lobodice in Czech Republic and Beynes in France [75]

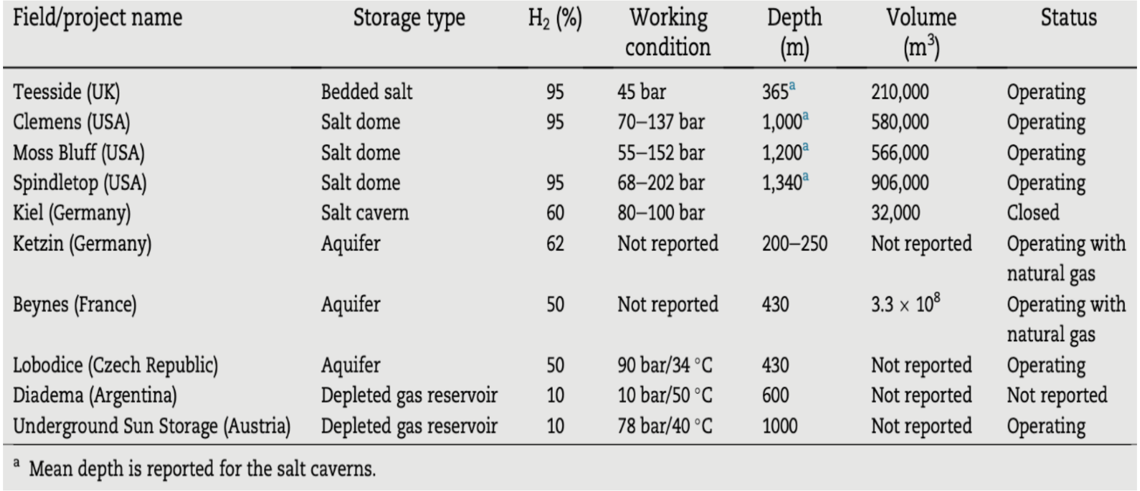
### 5.4.3 DEPLETED FIELDS

As has been stressed before in this analysis, depleted fields are the most appropriate options for gas storage, because of their well-known geological structure, the analysis already performed and the facility built by the petrol industry. Usually, depending on the final purpose of the storage, the presence of some gas leftover is seen as an advantage that allows the owner of the structure to same on the cushion gas. If a very high percentage of pure hydrogen is required, otherwise, it could represent a problem. So when a UHS is planned is important to understand the right time to stop the extraction. This implies a reduction of the time needed and costs. In the new UGS facilities, this period is roughly five years and includes also the withdrawal of the water that may invade the facility after its gas exploitation. In the built facility usually, the operating pressure reaches higher values of the natural pressure of the facility, and this makes it possible to store a higher quantity of the commodity [73].

Overall, to build a hydrogen storage facility in a depleted gas field a comprehensive study is required, due to the possible presence of residual oil in the site, the chance to have chemical reactions, and the conversion of hydrogen into methane or other substances. In the hydrogen-oil interface is possible to see a reduction of hydrogen purity, or even the dissolution of hydrogen inside the oil, which causes hydrogen loss.

### 5.4.4 WORLDWIDE OPERATING AND POTENTIAL SITES

All around the world, there are just four sites that are already storing hydrogen with a purity of 95% or higher and are situated in the United States of America and in the United Kingdom. In all these cases salt cavities have been chosen due to their characteristics. The Teesside project is operative since 1972 and shows how a salt cavity is a good choice. The other storage projects are resumed in Table 2, where the reader can find also gas storage made of hydrogen mixed with other gasses that are operative.

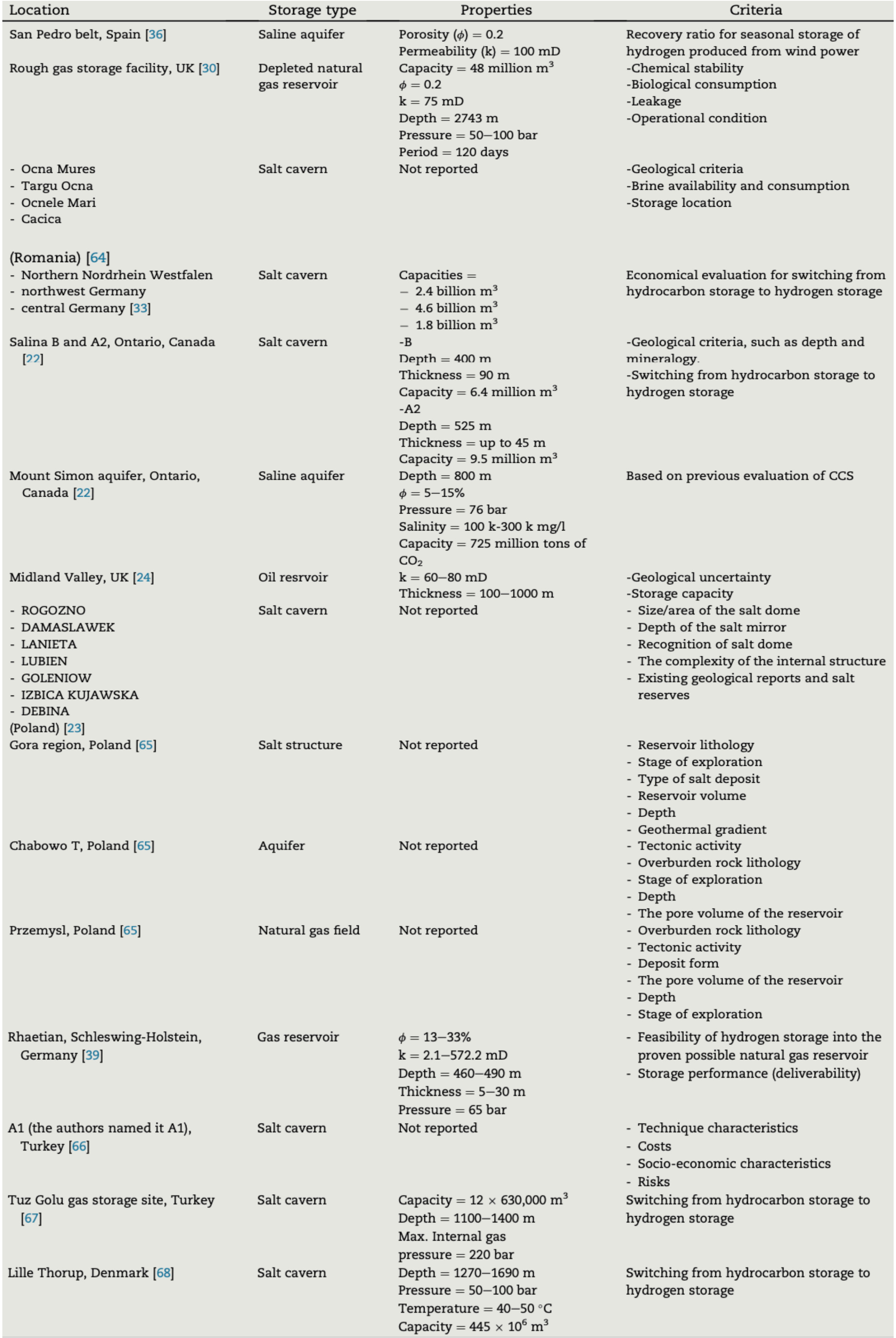


| Field/project name | Storage type | $H_2$ (%) | Working condition | Depth (m) | Volume (m$^3$) | Status |
|---|---|---|---|---|---|---|
| Teesside (UK) | Bedded salt | 95 | 45 bar | 365[a] | 210,000 | Operating |
| Clemens (USA) | Salt dome | 95 | 70–137 bar | 1,000[a] | 580,000 | Operating |
| Moss Bluff (USA) | Salt dome | | 55–152 bar | 1,200[a] | 566,000 | Operating |
| Spindletop (USA) | Salt dome | 95 | 68–202 bar | 1,340[a] | 906,000 | Operating |
| Kiel (Germany) | Salt cavern | 60 | 80–100 bar | | 32,000 | Closed |
| Ketzin (Germany) | Aquifer | 62 | Not reported | 200–250 | Not reported | Operating with natural gas |
| Beynes (France) | Aquifer | 50 | Not reported | 430 | $3.3 \times 10^8$ | Operating with natural gas |
| Lobodice (Czech Republic) | Aquifer | 50 | 90 bar/34 °C | 430 | Not reported | Operating |
| Diadema (Argentina) | Depleted gas reservoir | 10 | 10 bar/50 °C | 600 | Not reported | Not reported |
| Underground Sun Storage (Austria) | Depleted gas reservoir | 10 | 78 bar/40 °C | 1000 | Not reported | Operating |

[a] Mean depth is reported for the salt caverns.

**Table 2** Worldwide hydrogen storage operating sites [72].

The importance of hydrogen is rising in the scientific and engineering world, and this is also more appreciated when the facility is located close to a renewable energy power production plant, due to the main purpose of hydrogen storage related to the exploitation of renewable sources. The only safe and successful method to project a UHS is to evaluate the storage type, capacity, chemical stability, and economics. A first approach to evaluate the potential sites to store hydrogen around the world has been done in Table 3.



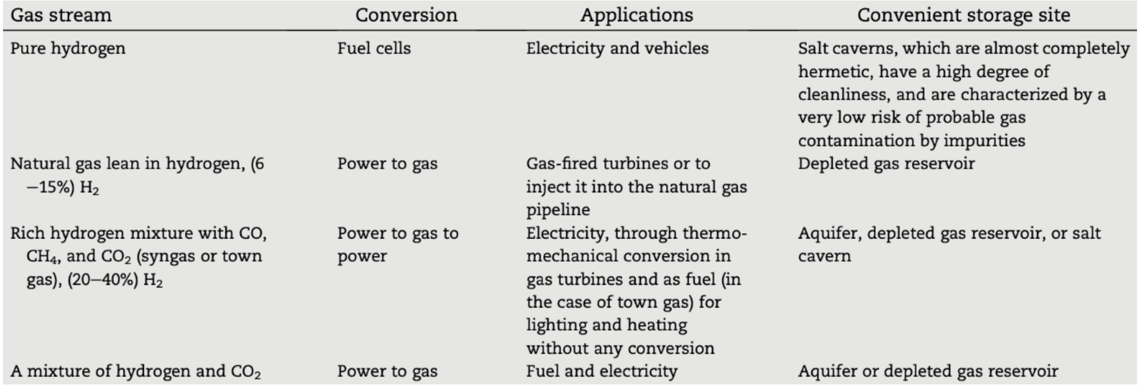
| Location | Storage type | Properties | Criteria |
|---|---|---|---|
| San Pedro belt, Spain [36] | Saline aquifer | Porosity ($\phi$) = 0.2<br>Permeability (k) = 100 mD | Recovery ratio for seasonal storage of hydrogen produced from wind power |
| Rough gas storage facility, UK [30] | Depleted natural gas reservoir | Capacity = 48 million $m^3$<br>$\phi = 0.2$<br>k = 75 mD<br>Depth = 2743 m<br>Pressure = 50–100 bar<br>Period = 120 days | -Chemical stability<br>-Biological consumption<br>-Leakage<br>-Operational condition |
| - Ocna Mures<br>- Targu Ocna<br>- Ocnele Mari<br>- Cacica<br>(Romania) [64] | Salt cavern | Not reported | -Geological criteria<br>-Brine availability and consumption<br>-Storage location |
| - Northern Nordrhein Westfalen<br>- northwest Germany<br>- central Germany [33] | Salt cavern | Capacities =<br>– 2.4 billion $m^3$<br>– 4.6 billion $m^3$<br>– 1.8 billion $m^3$ | Economical evaluation for switching from hydrocarbon storage to hydrogen storage |
| Salina B and A2, Ontario, Canada [22] | Salt cavern | -B<br>Depth = 400 m<br>Thickness = 90 m<br>Capacity = 6.4 million $m^3$<br>-A2<br>Depth = 525 m<br>Thickness = up to 45 m<br>Capacity = 9.5 million $m^3$ | -Geological criteria, such as depth and mineralogy.<br>-Switching from hydrocarbon storage to hydrogen storage |
| Mount Simon aquifer, Ontario, Canada [22] | Saline aquifer | Depth = 800 m<br>$\phi$ = 5–15%<br>Pressure = 76 bar<br>Salinity = 100 k-300 k mg/l<br>Capacity = 725 million tons of $CO_2$ | Based on previous evaluation of CCS |
| Midland Valley, UK [24] | Oil resrvoir | k = 60–80 mD<br>Thickness = 100–1000 m | -Geological uncertainty<br>-Storage capacity |
| - ROGOZNO<br>- DAMASLAWEK<br>- LANIETA<br>- LUBIEN<br>- GOLENIOW<br>- IZBICA KUJAWSKA<br>- DEBINA<br>(Poland) [23] | Salt cavern | Not reported | - Size/area of the salt dome<br>- Depth of the salt mirror<br>- Recognition of salt dome<br>- The complexity of the internal structure<br>- Existing geological reports and salt reserves |
| Gora region, Poland [65] | Salt structure | Not reported | - Reservoir lithology<br>- Stage of exploration<br>- Type of salt deposit<br>- Reservoir volume<br>- Depth<br>- Geothermal gradient |
| Chabowo T, Poland [65] | Aquifer | Not reported | - Tectonic activity<br>- Overburden rock lithology<br>- Stage of exploration<br>- Depth<br>- The pore volume of the reservoir |
| Przemysl, Poland [65] | Natural gas field | Not reported | - Overburden rock lithology<br>- Tectonic activity<br>- Deposit form<br>- The pore volume of the reservoir<br>- Depth<br>- Stage of exploration |
| Rhaetian, Schleswing-Holstein, Germany [39] | Gas reservoir | $\phi$ = 13–33%<br>k = 2.1–572.2 mD<br>Depth = 460–490 m<br>Thickness = 5–30 m<br>Pressure = 65 bar | - Feasibility of hydrogen storage into the proven possible natural gas reservoir<br>- Storage performance (deliverability) |
| A1 (the authors named it A1), Turkey [66] | Salt cavern | Not reported | - Technique characteristics<br>- Costs<br>- Socio-economic characteristics<br>- Risks |
| Tuz Golu gas storage site, Turkey [67] | Salt cavern | Capacity = 12 × 630,000 $m^3$<br>Depth = 1100–1400 m<br>Max. Internal gas pressure = 220 bar | Switching from hydrocarbon storage to hydrogen storage |
| Lille Thorup, Denmark [68] | Salt cavern | Depth = 1270–1690 m<br>Pressure = 50–100 bar<br>Temperature = 40–50 °C<br>Capacity = 445 × $10^6$ $m^3$ | Switching from hydrocarbon storage to hydrogen storage |

**Table 3** Worldwide potential hydrogen storage sites [72].

## 5.5 HYDROGEN STORAGE

### 5.5.1 MECHANISM AND MONITORING

In order to realize a good project is fundamental to understand the mechanism beyond the operation of a facility spread along its lifetime, which may vary according to the technique used to produce hydrogen, or on its application, and may comport the mixture with different gasses like carbon dioxide, carbon monoxide, methane, and nitrogen. These considerations are resumed in Table 4. In the future, for the thermochemical transport of energy, a solution of hydrogen mixed with other gasses like energy carriers might be probable. Related to the stored gas, the wide experience in storing carbon dioxide and natural gas is helpful, in fact, the structure used to store the carbon dioxide is similar to the one needed to store hydrogen. Otherwise, they present many differences. The final purpose is also different because the CO2 trapping is meant to be for the long term and the withdrawal is not present, because the goal is to remove the carbon dioxide from the atmosphere and not to use it later, and this implies also lower attention on the co-production of CO2 with other existing gases or fluids in the facility, and on the number of cycles and the idle time before injection and withdrawal. Otherwise, there are other concerns that are not related to hydrogen such as the risk of leakage from the caprock, or the risk of corrosion of the downhole facility that is high when it's in contact with carbon dioxide. Moreover, CO2 can dissolve the caprock and lead to important leakages [76].  Regarding the natural gas storage, the geological structure needed to store hydrogen is similar, for instance, it must present a well confined porous and permeable formation inside an impermeable cap rock to guarantee minimal leakages. Despite the different physical and chemical features of hydrogen and natural gas, it's from the natural gas experience that engineers are inspired to project hydrogen storage facilities, with the only difference in the withdrawal frequency of the gas that is frequent for hydrogen purposes. Nevertheless, the lower density, viscosity and molecule size of hydrogen can lead to leakage and so the loss of hydrogen can be high. In aquifers, the injection pressure should be higher to overcome the natural pressure of the aquifer itself, and thus the water is displaced by the well, but due to the lower viscosity and density, the fingering and the gas overriding of injected gas are granted. The experience gained with natural gas teaches that aquifers have constant pressure and variable volume in a few months period and constant volume and variable pressure over a period of a few days [65]. These variations in aquifers, when hydrogen is injected, are controlled by flow behavior which depends on geometrical factors, porosity and permeability, reservoir geometry, fluid saturation, and well locations. Darcy's law can describe these phenomena. To estimate the location of the transition zone, in contrast to hydrogen and water saturation, the capillary pressure and relative permeability curves are used, and this depends also on the mobility ratio of the fluid phases [65]. Nevertheless, the saturation of fluids changes along different phases of cycles, so a flow behavior study is suggested for each cycle. These conditions that may affect the hydrogen production or the facility itself can be managed by choosing an optimal injection rate and selecting a reservoir with low heterogeneity. Also, steeply dipping structures and thick formations help to inhibit fingering [77].



| Gas stream | Conversion | Applications | Convenient storage site |
|---|---|---|---|
| Pure hydrogen | Fuel cells | Electricity and vehicles | Salt caverns, which are almost completely hermetic, have a high degree of cleanliness, and are characterized by a very low risk of probable gas contamination by impurities |
| Natural gas lean in hydrogen, (6−15%) $H_2$ | Power to gas | Gas-fired turbines or to inject it into the natural gas pipeline | Depleted gas reservoir |
| Rich hydrogen mixture with CO, $CH_4$, and $CO_2$ (syngas or town gas), (20–40%) $H_2$ | Power to gas to power | Electricity, through thermo-mechanical conversion in gas turbines and as fuel (in the case of town gas) for lighting and heating without any conversion | Aquifer, depleted gas reservoir, or salt cavern |
| A mixture of hydrogen and $CO_2$ | Power to gas | Fuel and electricity | Aquifer or depleted gas reservoir |

**Table 4** Convenient storage site and energy application based on the composition of the injected stream [72].

The hydrogen withdrawal needs to be more frequent and with higher rates than the natural gas one to meet the market demand. Is difficult to maintain the rates constants due to many variables, for instance, because of the expansion of gas inside the facility that depends on time, the loss in flow pressure, and inside the reservoir during the process. Thus, a good amount of gas remains inside the facility at each cycle, roughly one-third of the total capacity, and to fix this problem other cheaper gases may be used, such as CO2, CH4, and N2. On the other hand, this solution could represent a problem for hydrogen loss and so the hydrogen inside the cushion gas is usually between 1-3% [78]. Another problem could be represented by the dissolution of a part of the hydrogen into the oil phase in a depleted oil reservoir, and typically the solubility is lower than 1,5 mol% at 100°C and 150 bar in heavy oil [79]. The losses of hydrogen inside the facility can also be due to microscopic and macroscopic trapping, dissolution in water depending upon the recovery rate, capillary forces, initial water saturation, and diffusion coefficient [77]. Another problem may be represented by the production of cushion gas with hydrogen production, but from the natural gas experience, where low-value town gas has been used as cushion gas, came out that just 1% of cushion gas can be produced after many cycles [80]. In certain circumstances, according to the condition of some parameters like the extent of fingering, the gas dissolution and diffusion, mixing, surface tension, solubility, water saturation, capillary effect, and withdrawal rate, it's feasible that a few of other substances are produced together with hydrogen, such as water vapor, free water or other contaminated gasses. Engineers try to avoid it because it means energy loss, extra effort, and tools to process the gas produced and obtain pure hydrogen. As for the cushion gas in the withdrawal operation, also this phenomenon is reduced over time, but it still needs to be controlled. Another concern can be represented by geochemical, biochemical, and microbial reactions that might take place quite often in the hydrogen storage process and are discussed in the next chapter. These reactions may lead to hydrogen loss and lower the efficiency and are supported by the variety of ions, microbes, minerals, and other catalyst elements, in undesired reservoir conditions depending on temperature, pressure, and salinity. Moreover, the hydrogen losses are important to project storage, and there are different aspects to consider, like the caprock sealing strength and losses through it that depend on the permeability and the capillary pressure in the caprock, the injection and withdrawal rate together with the wells' materials and the physical properties of them, the number of wells, frictional pressure drop, and eventually the facilities for gas treatment and the energy they use, the pumping loss in porous media that depends on the permeability of the medium, and energy dissipation in capillary hysteresis [80]. Additionally, one of the main operational problems is hydrogen embrittlement which may change the physical and mechanical properties of the subsurface tools [80,81].

Another important aspect of UHS is related to monitoring different things, for instance, is important to monitor the position of the hydrogen and of the cushion gas that must stay inside the geological formation and don't leak or migrate, or the geochemical and microbial activities. However, the most important thing, whatever is the monitoring technique adopted, is the frequency of monitoring, considering the cyclic nature of this kind of storage. Regular monitoring leads to a more safe and efficient process.

### 5.5.2 OPTIMIZATION OF INJECTION AND WITHDRAWAL STRATEGIES

To meet the energy demand usually a UHS undergoes different cycles, that are characterized by injection, withdrawal, and idle phases. These phases can vary also according to the season, which can require a different amount of energy. In Figure 4.2 the largest quantity required in injection and withdrawal rates (qm) is kept constant for a fixed time (three months) then the rate is divided by two for the following month. The idle period usually is located between the injection and the withdrawal and lasts one month. The rates are increased linearly to prevent a steep pressure rise in the storage, in this case an aquifer is analyzed. The area enclosed in each cycle represents the working gas volume of that cycle, but it happens very often to change the periods to perform more cycles during peaks and fluctuations.

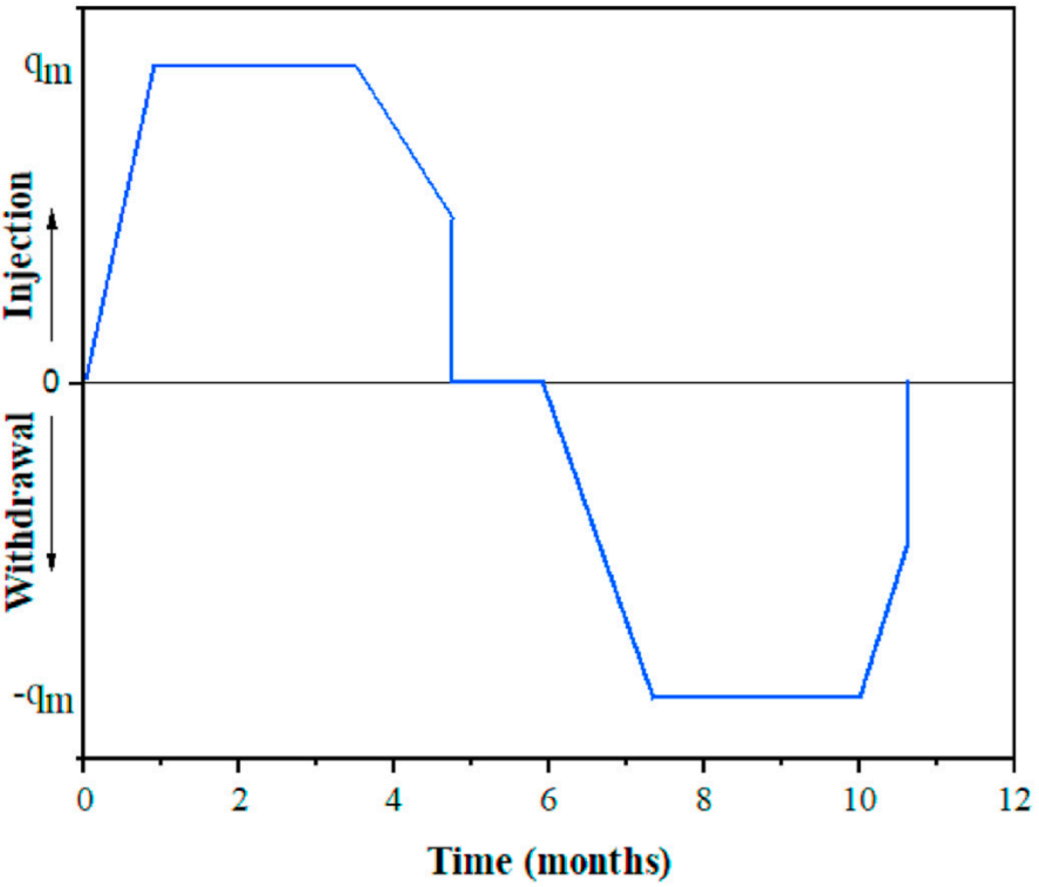
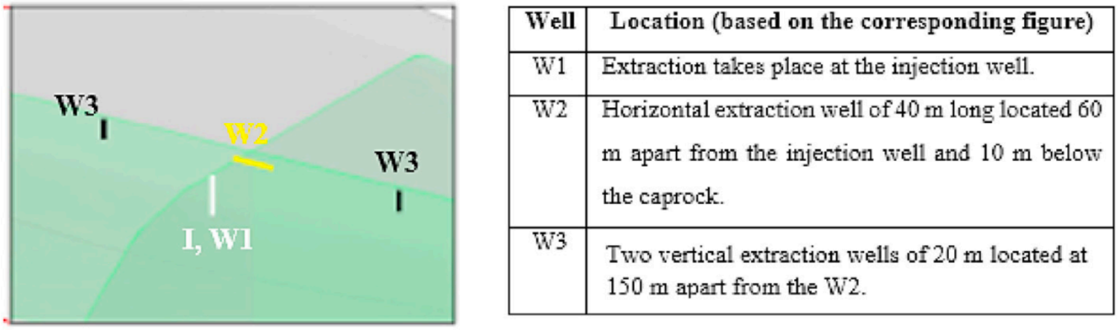


**Figure 5.2** Example of a yearly injection, idle, and withdrawal cycles [72].

The flow rate of hydrogen is usually higher than methane due to the lower viscosity and high mobility, so large size wellbore can reduce the effect of this issue [80], and to avoid the embrittlement of the wellbore casing materials are used, choosing the ones that can be in contact with hydrogen and undergo a pressure between 70 and 140 bar. Thus, the natural gas wells don’t fit this kind of facility and this can cause a cost increase. The attention on the flow rate is high because a too-low injection flow rate may cause gas fragmentation, so more time for the gas to be trapped somewhere, but too-high flow rates may cause gas rising and lateral spreading, so optimize the flow rate is essential, and it has to meet the bottom-hole pressure criteria, along with capillary entry pressure and fracture pressure [82].

Engineers have made different solutions to fix this problem and one of them consists of two separate wells, so with the injection well is possible to inject the hydrogen on the bottom of the storage decelerating the gas rising (driven by buoyancy) and reducing the extent of lateral spreading, and the withdrawal well is situated in the top part of the reservoir [83]. With a high withdrawal rate there is the possibility to get a gas mixing (gas-gas or gas-water) and so to produce a large amount of cushion gas, or water, together with hydrogen, requiring a treatment plant to separate them. As seen before for the cushion gas, also for water production it has been seen that drastically reduces over each successive cycle. If this rate is excessively high and non-optimized, it’s possible to have water coning, a phenomenon where due to the dominance of viscous force over gravity the water overrides gas and breaks through the production well. Sainz-Garcia et al. (2017) have presented an analysis of different configurations with wells at different orientations and locations (W1 vertical, W2 horizontal, W3 vertical) and one injection well ( I vertical ), as it’s possible to see in the next figure.



| Well | Location (based on the corresponding figure) |
|---|---|
| W1 | Extraction takes place at the injection well. |
| W2 | Horizontal extraction well of 40 m long located 60 m apart from the injection well and 10 m below the caprock. |
| W3 | Two vertical extraction wells of 20 m located at 150 m apart from the W2. |

**Figure 5.3** Location of injection and withdrawal wells [72].

From this test, the data are analyzed on the production of hydrogen, which increases every year, through the different wells. For W2 and W3 the percentage of hydrogen recovery is important also after just one injection/production cycle. For W1 the water coning phenomenon has ruined the result of the first year. At the end of the cycle W3 got the best result, then using more wells for extraction located below the caprock (in the top part of the reservoir) can lead to a good amount of water produced and reduce the formation of water coning.

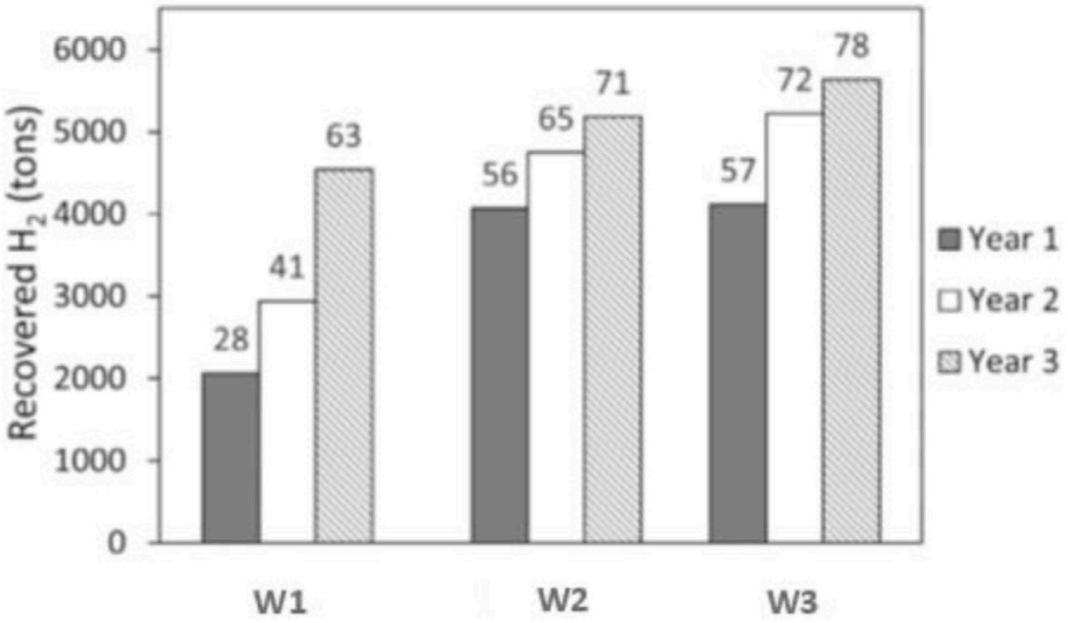


**Figure 5.4** Amount of hydrogen produced in different years from different extraction wells. Hydrogen recovered (produced/injected) [72].

Another study, conducted by Katarzyna and Radosław (2019) [84], performed on an aquifer in Poland, has determined that the water production increase with flow rates of 1-5 kg/s, but always been less in each successive cycle, increasing the hydrogen produced instead. According to their study, the optimal flow rate for storage purposes is 0,51 kg/s as the injection rate and 3 kg/s as the withdrawal rate to avoid water coning.

### 5.5.3 MICROBIAL AND GEOCHEMICAL ACTIVITIES

To fully understand the mechanisms inside the hydrogen storage process is needed a study to investigate the reaction between the injected gas and the pre-existing minerals, gases, ions, bacteria, etc. This will ensure a safe (to minimize any leakage risk) and successful (to avoid the conversion of hydrogen into other gases or reducing its purity) storage process. The electron-donor nature of hydrogen makes it seems like a source of energy for microorganism, and its concentration can control the reaction speed [63], which is usually high since the concentration is high.

In general, the abiotic and biotic processes are related to hydrogen consumption and production. The abiotic processes are made with non-living components such as rocks, water, and gasses. The biotic components, instead, are made of living components like bacteria that might be present in the porous of the facility [83]. To have an abiotic process temperature up to 600°C may be needed, but for biotic processes, the operating temperature of the storage is already enough. It's not reported in the literature about hydrogen generation through these processes, which include nitrogenases, a process that produces hydrogen gas as byproduct of nitrogen fixation [85]. In this chemical reaction, one mol of nitrogen is used to produce 1 mol of hydrogen and 2 mol of ammonia, and this could be important where the cushion gas is nitrogen. Another process, that has been reported in Chimaera seep in Turkey, is methanation, where hydrogen is converted into methane at 50°C [86].

Many biotic processes, such as methanogenesis, acetogenesis, sulfate reduction and iron (III) reduction, can consume hydrogen. To have methanogenesis are needed archaea microorganisms, CO2, a pressure of 90 bar, and a temperature between 30 and 40°C. The reaction is reported below [83]:

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \tag{1}$$

An example of this reaction is the Lobodice town gas storage project, where a large amount of gas has been converted into methane [87].

The reaction related to acetogenesis, which converts acetate into acetic acid, is the following [83]:

$$2CO_2 + 4H_2 \leftrightarrow CH_3COOH + 2H_2O \tag{2}$$

There are microorganisms called sulfate-reducing bacteria (SRB) that use hydrogen to produce hydrogen sulfide in UGS at a temperature around 39°C up to 110°C. For example, in the case study of Cavallaro et al. (2005), it's been reported of an increase in $H_2S$ production due to active sulfate-reducing bacteria that entered in contact with water flooding in Las Heras-Cerro Grande oilfield in the Gulf of San Jorge Basin, Argentina [88]. The reaction is the following [83]:

$$SO_4^{2-} + 5H_2 \leftrightarrow H_2S + 2H_2O \tag{3}$$

Along with hydrogen sulfide ($H_2S$) also water is produced, and this represents another problem because it increases water saturation and so there is less space for hydrogen.

In UHS another possible hydrogen reaction is made through the iron-reducing bacteria (IRB), which enhance the reaction between hydrogen and $Fe_2O_3$ [83]:

$$3Fe_2O_3 + H_2 \leftrightarrow Fe_3O_4 + H_2O \tag{4}$$

This reaction creates water as the previous one but can also lead to precipitation or dissolution of minerals inside the storage or the caprock. The rate of the dissolution or precipitation of minerals depends on the pressure, temperature, bacteria, ions, and pre-existing minerals. If this phenomenon happens also the porosity and the permeability of rocks change [89].

The caprock integrity is safe until the precipitation rate is higher than the dissolution rate, especially near the wellbore, but the reduced permeability and porosity may reduce the efficiency in injection/withdrawal operations. When the precipitation rate is smaller than the dissolution rate, otherwise, the integrity of the caprock may be compromised, and so the enhanced porosity and permeability can lead to hydrogen loss and leakages, proportionally to the enhancement of these two parameters of the reservoir, increasing the operational efficiency.

### 5.5.4 PHYSICS OF HYDROGEN FLOW IN POROUS MEDIA AND HYDRODYNAMICS ACTIVITIES

Another important aspect to consider in hydrogen storage is the rock-fluid and fluid-fluid interactions. The data reported in the literature for dynamics of fluid in porous media are rare for hydrogen-water systems, in particular for relative permeability, capillary pressure, interfacial tension, and contact angle. The same problem is reported for hydrogen-oil systems.

In 2018, Yekta et al., made experiments on steady-state core flooding with a sample of sandstone, which has a porosity of 19,5% and permeability of 44mD, and with mercury injection method to investigate over capillary pressure (MICP). These experiments on core flooding and capillary pressure allowed the scientists to evaluate the interfacial tension between water and hydrogen at 55 bar and 20°C as 0,051 N/m and at 100 bar and 45°C as 0,046 N/m [90]. The interfacial tension between methane and hydrogen is reported as 0,065 N/m at 55 bar and 20°C, or 0,0589 N/m at 100 bar and 38°C. Thus, the values are lower for water-hydrogen systems than for methane-hydrogen systems.

Moreover, the contact angle, especially the value of cos q at the experimental condition stated before is respectively 0,93 and 0,82 [90].

When the gas is injected into the facility, either depleted reservoirs or aquifers, it replaces the pre-existing water or gas and stays at the top of the storage facility, close to the caprock, so the role of the threshold capillary pressure is very important here because it maintains the caprock integrity. This parameter defines the pressure at which is possible for hydrogen to enter the largest available pore in the rock and is reported in the next equation [91]:

$$Pc_{th} = \frac{2\sigma cos\theta}{r} \tag{5}$$

Where $Pc_{th}$ is the threshold capillary pressure, $\sigma$ is the interfacial tension, $\theta$ is the contact angle and r is the radius of the largest pore. Thus, this relation is controlled by two important and critical parameters like the interfacial tension $\sigma$ and the contact angle $\theta$, but as it has been said before the data around the contact angle are limited and so the value used is always the same for every kind of gas in the water-gas system. Otherwise, the interfacial tension of water-hydrogen systems is known and less than the methane-hydrogen one, so the threshold pressure will be lower and the risk of leakages through the caprock will be higher.

Another important factor for hydrogen storage is viscous fingering. The hydrogen fingering was analyzed by Patterson in 1983, and this highlighted fingering can be considered as a source of losses, dependent on the injection rate [92]. Viscous fingering comes out of viscosity and density differences, and surface tension forces. In fact, the fingering phenomena (interface instability) develops perpendicularly to the flow direction, inside water, our high-viscosity fluid, with a frequency that decreases along with the flux, due to the shielding phenomenon [93]. In the process, the area between the injected gas, the rocks, and the water increases, and so does the possibility of hydrogen to dissolute into the water according to the gas diffusion. Also, the interaction with rocks can be higher.

Concerning methane and hydrogen storage, when they have the same injection rate, and so same Darcy velocity, it's important to remember that hydrogen has less viscosity and so it has less sweep efficiency. Talking about an aquifer or a depleted reservoir it leads to less volume of water or gas that can be swept by hydrogen injection, and so less space for storage purposes.

Otherwise, hydrogen has also less interfacial tension, and so lower capillary force, resulting in less capillary trapping, than hydrogen is easier to extract. According to the following figures extracted from the paper written by Yekta et al. in 2018, it's possible to see the relative permeability and the capillary pressure curves, and how the hydrogen values are relatively low.

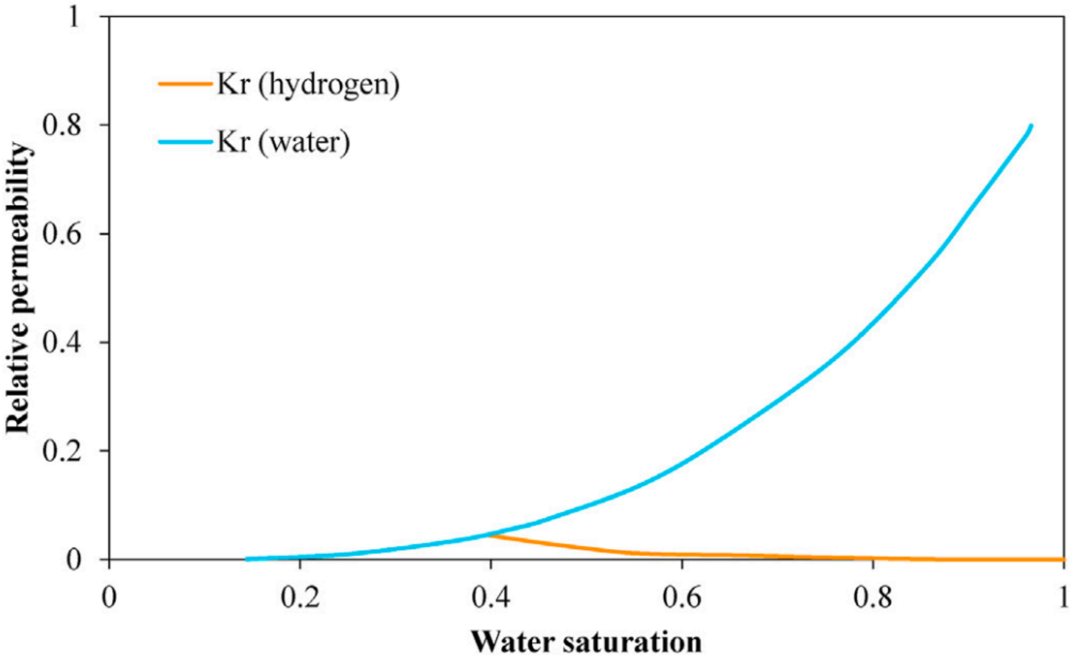


**Figure 5.5** Relative permeability of hydrogen-water system [72].

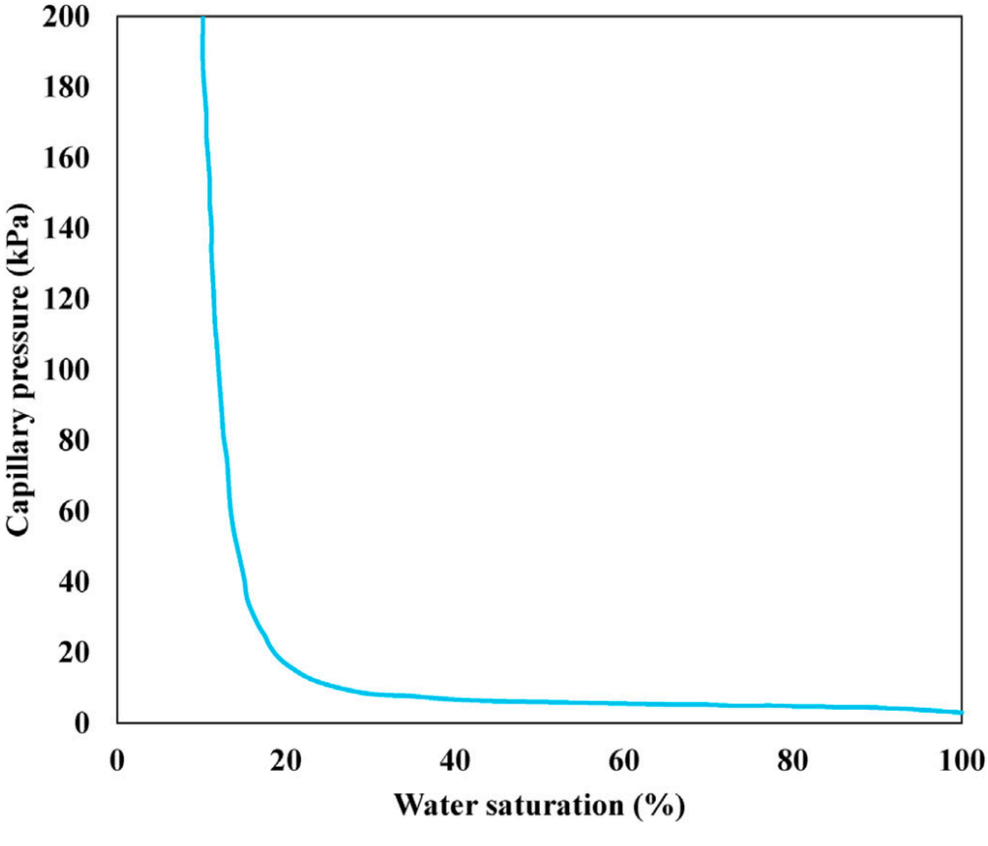


**Figure 5.6** Capillary pressure of hydrogen-water system [72].

The efficiency can be reduced and the hydrogen losses can be increased through the relative permeability and the capillary pressure hysteresis. The relative permeability can be influenced by the saturation history, which is known as hysteresis. In the operation processes like injection and withdrawal of hydrogen, the gas saturation in the facility can vary according to the quantity injected or withdrawn, but the mobility of hydrogen is different due to the trapping of hydrogen in the facility, which is represented by the hysteresis effect on the relative permeability curves. Increasing the number of injection/withdrawal cycles also the trapping of gas will be increased, reducing the relative permeability for the next cycles.

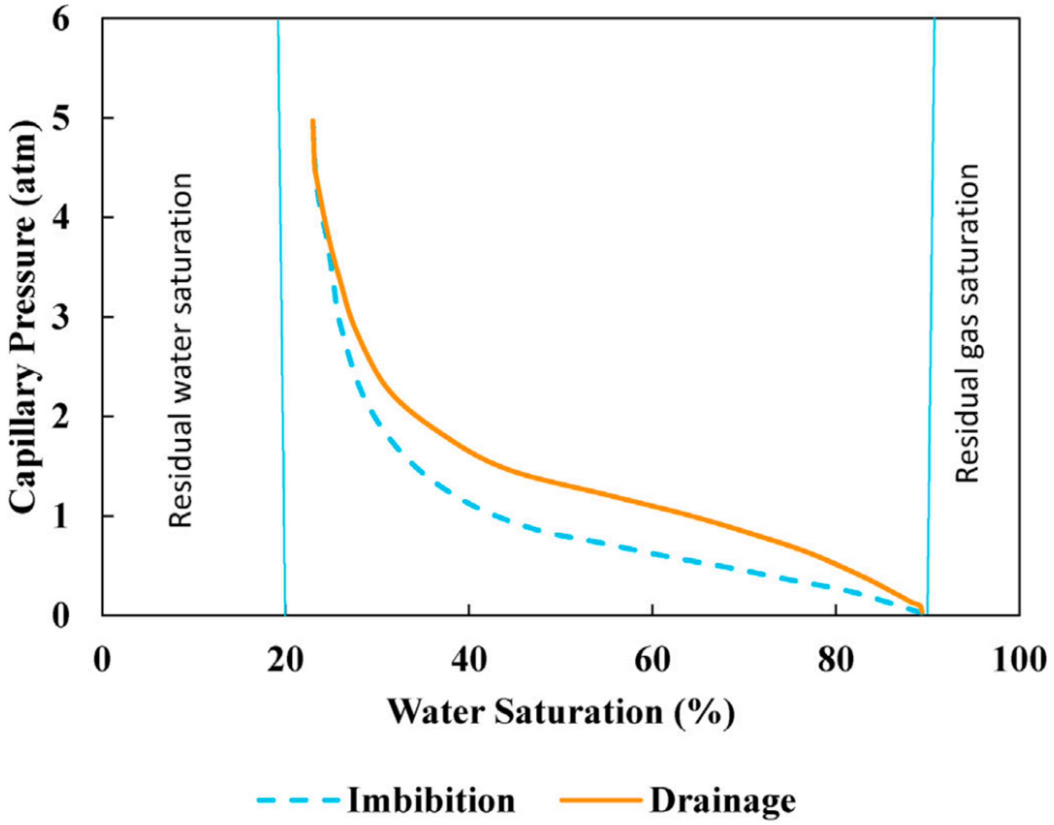


**Figure 5.7** Schematic of capillary hysteresis (imbibition happens during the withdrawal process and drainage in the injection process) [72].

The capillary pressure can control the spatial disposition of the fluids inside a porous media, and it depends on the past cycles, having different behaviors (pathways) for the same process, as shown in figure 4.7. This phenomenon is very important to be considered because the goal of a storage facility is to be able to perform cycles, but each cycle influences the following one, according to capillary hysteresis.

### 5.5.5 THE ECONOMICS OF UHS

The economics of this process would include the capture cost, the transportation cost, the storage cost, the injection and withdrawal cost, and the monitoring cost, but in this paper, the focus is on the underground storage cost, and so on capital and operating costs. Aspects like injectivity, pressure change, maintenance, cyclic operation cost, and annual throughput are considered together with the net storage cost. The storage cost may vary significantly according to the facility chosen for the project and if there is a need to cap any potential leakage point [72]. In 1986, Taylor et al. cataloged the different capital and operational costs for different kinds of facilities, including the underground one [66]. The capital costs are divided into the compressor cost (operating units and power required), foundation and erections costs, the installation cost of transformer and primary breaker, cost of building, cooling, heating, ventilation, lighting, alarm system and gas monitoring, cost of the gas holder, dependent on the capacity, cost to connect the gas network pipelines to the storage and the compressor, cost of wells and wellhead equipment. The most expensive factor mentioned is the compressor cost. Moreover, concerning a cavern it has to be considered also the cost of cavern construction, which is the second highest after the compressor cost, brine lagoons, reinforcement, grouting, plugs, surface work, and handling equipment [66].

In comparison with natural gas storage, for hydrogen, the cost of surface and subsurface equipment, borehole tubing, and pipelines is usually higher due to the special materials required to avoid hydrogen embrittlement which may lead to mechanical or physiochemical failure.

Concerning now the operating costs, the main ones are represented by hydrogen generation through electrolysis, cost of power, cooling water, utilities, labor (operation and maintenance), supervision, administration, and maintenance materials. However, also the cushion gas needs to be considered in the calculation, even if it's a hidden cost that the final user will not access, so it has to be as low as possible [66]. Eventually, after the last cycle, especially in salt cavities, the cushion gas can be withdrawn through the brine displacement. A complete review of cost analysis of different UHS is accessible in these papers [64,94,95,96,97].

According to Taylor the storage itself can increase the cost of hydrogen technology between 30 and 300%, so benefits must exist to a storage facility. In fact, the interaction between the system utilization and the capital cost is significant [66].

According to the analysis performed by Tarkowski et al. in 2019, the highest construction and operational cost among the principal types of underground facilities to store hydrogen is the one for aquifers, followed by caverns and depleted reservoirs. Moreover, the application in depleted oil fields results more expensive than in depleted gas fields [73].

In 2011 and 2014, Lord et al. assessed the capital expenditure for each kind of storage, and the results were that for depleted reservoirs the cost to store hydrogen is 1,23 USD/ Kg, for aquifers is 1,29 USD/ Kg, and for salt caverns is 1,61 USD/ Kg [72,98,99].

Even if these studies have been performed, it has to be said that so far there is no completed and detailed lifecycle cost assessment for each kind of underground hydrogen storage, both in pure and mixed solutions, and so what is reported here is still uncertain.

### 5.5.6 CHALLENGES, FEASIBLE STRATEGIES, AND ROAD MAP

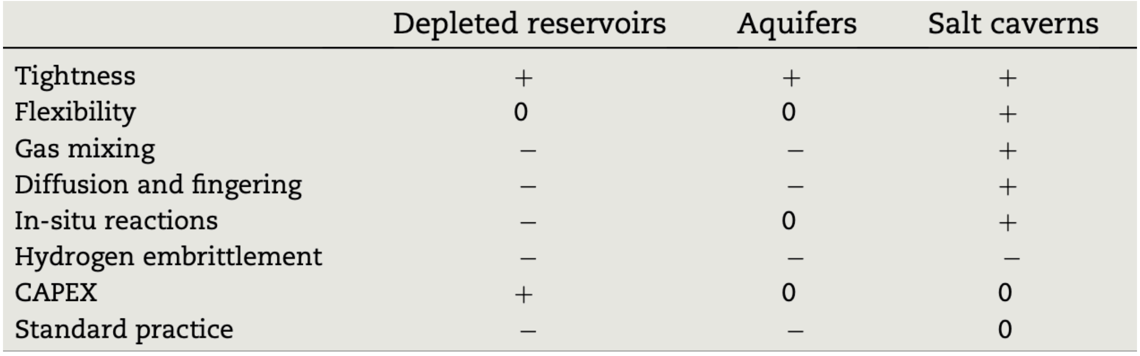
Storing natural gas is a routine procedure nowadays, but is more difficult to find information or past experiences about storing hydrogen around the world. The data collected are also discussed due to the new entity of these studies, which need time to be confirmed. To project a good storage facility there are many parameters to consider such as geological criteria, engineering, economic, legal, and social issues. For sure the most important one is geological criteria, because it cannot be changed and can affect many aspects like operational costs, efficiency, and risks, and because of it thay have the priority over the other parameters.

Probably salt cavities are the best option for UHS but the number of cavities is limited. Instead, the depleted oil fields are easier to find but they present the problem that the hydrogen could react with the residual oil. Saline aquifers can fit the requirements for hydrogen storage purposes but due to their less-known geological structure and the high amount of cushion gas are not the best option. In 2014 a study conducted by Bai et al. stated that in a depleted oil or gas field the needed cushion gas is roughly 33% of the total volume for hydrogen storage and roughly 50% for methane, instead these numbers go up to respectively 33-66% for hydrogen and 80% for methane [100]. Usually, the best option is represented by the depleted gas fields, which have a well-known geological structure, pre-existing facilities, and inexpensive operation, apart from the already well-shown tightness of the caprock.

The permeability is the ability of a porous media to deliver the fluid. A good value of permeability for hydrogen storage is between 2 and 600 mD but higher values are preferred to guarantee an optimal injection and withdrawal phase of hydrogen. Salt cavities have very high permeability, close to a non-porous medium, and moreover, they avoid the risk of hydrogen reactions with rocks, microbial, or residual fluids, which is high in aquifers and depleted fields. For instance, the $SO_4^{2-}$ is usually present where there is water or groundwater, and having a lower concentration reduces the risk of consuming hydrogen in the reaction that produces hydrogen sulfide. Thus, the salt cavities are not preferred just for their low microbial or geochemical interaction but also for the absence of clay, in fact, storage facilities with a high concentration of clay have reported phenomena of hydrogen trapping, mineral dissolution, and mineral precipitation. According to these parameters, the preferred ones are the salt cavities, the second is aquifers, followed by depleted gas fields, and then depleted oil fields.

One of the main issues related to underground hydrogen storage is the treatment of the contaminated water produced with hydrogen due to water coning, which may contain toxic chemicals and reduce the economic viability of the project. This phenomenon is strictly related to the storage site.

In the following table are reported all the influential parameters for hydrogen storage in the different types of facilities.



| | Depleted reservoirs | Aquifers | Salt caverns |
|---|---|---|---|
| Tightness | + | + | + |
| Flexibility | 0 | 0 | + |
| Gas mixing | − | − | + |
| Diffusion and fingering | − | − | + |
| In-situ reactions | − | 0 | + |
| Hydrogen embrittlement | − | − | − |
| CAPEX | + | 0 | 0 |
| Standard practice | − | − | 0 |

**Table 5** Comparison of different underground storage options (+, 0, - represent feasible, medium, and poor respectively) [72].

Nevertheless, due to the characteristics of the hydrogen molecule and the purity required the availability of these options change and more practice and technical revisions are required in the future.

# 6. CONCLUSIONS

The aim of this paper is to inform the reader about future hydrogen storage trends. Most of the experience related to hydrogen storage comes from past experience in natural gas storage, then to explain the future trend, the used technique, the advantages and the issues, the economics, and the project variables, it was necessary to start from the state of the art of the underground gas storage in Europe and all over the world.

The narrative involved the gas market, and the importance to have a gas storage system to meet the energy demand while limiting the dependency on other countries and increasing the security of the gas supply; along with the technical aspects that are fundamental to have a complete engineering picture of the project. Every kind of facility has been analyzed in detail, investigating the main advantages and issues related to their use, and presenting a complete panorama of the available solutions in terms of physical and geochemical laws and phenomena which rule the facility, economics, and comparison between the main selected facilities.

Analyzing the future of the gas market and the energy demand, hydrogen resulted as one of the main players for the next years due to its good energy-carrier behavior. In fact, the forecasts state that hydrogen will be important not only for those heavy transport solutions that cannot be electrified but also to meet the energy demand. Hydrogen has been identified as the future energy carrier that can relate the fluctuating production of renewable energies to the energy demand, converting the renewable energy surplus into hydrogen through the electrolysis process, and then using it to produce energy anytime when needed. In this panorama, where natural gas will be cut as an energy source, it’s important to understand if the same facilities can be used to store hydrogen.

This feasibility study started from the different physical and chemical characteristics of methane and hydrogen, and developed through the scientific literature to find examples of existing plants or projects which confirmed the possibility to switch the purpose of these facilities, under certain conditions. With respect to methane, in fact, hydrogen resulted more difficult to be stored due to the major problems related to its leakages and losses, geochemical and microbial activities, different physics of hydrogen flow in a porous media, and hydrodynamic activities. All these problems have been discussed, highlighting the principal causes and the possible solutions, along with an optimization of the injection and withdrawal operations and an economic analysis.

The result of this research led to a complete overview of the underground storage facilities, with particular attention to hydrogen applications and future trends, allowing the reader to be able not only to understand the differences and the problematics of every kind of storage facility, but also to evaluate personally which kind of facility could fit better a different aim according to the capacity, the location, the purity required and the final user.

Thus, according to this study, it has been demonstrated that it’s possible to extend the life of underground gas storage to make a revolutionary change in Green House Gasses control worldwide. The investigation of this technology, now more than ever, is crucial to develop a green and sustainable energy market in the future.

# BIBLIOGRAPHY AND SITOGRAPHY

[1] https://www.iea.org/reports/how-to-avoid-gas-shortages-in-the-european-union-in-2023/the-need-for-action

[2]https://www.ilsole24ore.com/art/gas-prezzi-picchiata-europa-sono-tornati-livelli-giugno-AEYBoX9B

[3]https://tradingeconomics.com/commodity/eu-natural-gas

[4] https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WEOEUR&fuel=Natural%20gas&indicator=NatGasConsBySector

[5]https://www.britannica.com/science/natural-gas

[6]https://www.storengy.fr/en/our-sites/beynes

[7]https://energy.ec.europa.eu/system/files/2022-04/Quarterly report on European gas markets_Q4 2021.pdf

[8] https://fsr.eui.eu/the-role-of-gas-storage/

[9]https://elements.visualcapitalist.com/europes-gas-storage-compared-to-historical-consumption/

[10]https://www.gie.eu/transparency/databases/storage-database/

[11] https://www.statista.com/statistics/1294025/quarterly-gas-in-storage-in-the-european-union/

[12] https://www.euronews.com/green/2023/02/24/europes-energy-war-in-data-how-have-eu-imports-changed-since-russias-invasion-of-ukraine#:~:text=Sharp%20decline%20in%20natural%20gas%20imports%20from%20Russia&text=In%202021%2C%20the%20EU%20imported,12%20per%20cent%20in%20October

[13] https://iea.blob.core.windows.net/assets/c6ca64dc-240d-4a7c-b327-e1799201b98f/GasMarketReportQ12023.pdf

[14] https://www.energymagazine.com.au/2022-lng-exports-top-90b/#:~:text=In%202022%20Australia%20is%20again,total%20exports%20of%2081.2Mt.

[15] https://en.wikipedia.org/wiki/Liquefied_natural_gas#Trade

[16] https://www.eia.gov/todayinenergy/detail.php?id=54780

[17] https://excelerateenergy.com/capabilities/fsru/

[18] https://www.rwe.com/en/research-and-development/project-plans/floating-lng-terminals/

[19]https://www.acer.europa.eu/gas-factsheet

[20] https://en.wikipedia.org/wiki/Natural_gas_storage

[21] https://memgraph.com/blog/gas-pipelines-in-europe

[22]https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiC1fWqm_v-AhUP-DgGHfhrAKQQFnoECBEQAQ&url=https%3A%2F%2Fpublications.jrc.ec.europa.eu%2Frepository%2Fbitstream%2FJRC118592%2Ftowards_net-zero_emissions_in_the_eu_energy_system_-_insights_from_scenarios_in_line_with_2030_and_2050_ambitions_of_the_european_green_deal_on.pdf&usg=AOvVaw0OHlJ-_6gh1FWVQEw1JCFB

[23] https://www.eia.gov/naturalgas/storage/basics/

[24] https://www.eia.gov/naturalgas/storagecapacity/definitions.php

[25] https://www.kyos.com/faq/what-is-working-gas-volume/

[26] https://www.lacimagroup.com/wp-content/uploads/2020/08/Gas-storage-overview-static-valuation.pdf

[27]https://www2.bgs.ac.uk/groundwater/shaleGas/3DGWV/home.html

[28] F. Favret, *Up-to-Date Researches and Future Trends in Underground Gas Storage Facillties: A State of the Art Review*, In "Hetland, J., Gochitashvili, T. (eds) Security of Natural Gas Supply through Transit Countries. NATO Science Series II: Mathematics, Physics and Chemistry, vol 149. Springer, Dordrecht",159-171, https://doi.org/10.1007/1-4020-2078-3_8

[29]https://www.cgg.com/geoscience/subsurface-imaging/time-lapse-4d-seismic

[30] S. Vidal, P. Longuemare, F. Huguet, *Integrating geomechanics and geophysics for reservoir seismic monitoring feasibility studies*, in "SPE European

Petroleum Conference" held in Paris, France, 24-25 October 2000. https://doi.org/10.2118/65157-MS

[31]C. Sambo, C. Iferobia, A. Babasafari, S. Rezaei, O. Akanni, *The role of time-lapse (4D) seismic technology as reservoir monitoring and surveillance tool: a comprehensive overview,* in " Journal of natural gas science and engineering ", vol. 80, August 2020, 103312, 1-3, https://doi.org/10.1016/j.jngse.2020.103312

[32]https://glossary.slb.com/en/terms/c/caprock - :~:text=1. n. %5BGeology%5D,cannot migrate beyond the reservoir.

[33]https://www.britannica.com/science/darcy#:~:text=measure%20of%20permeability&text=unit%20of%20permeability%20is%20the,atmosphere%20per%20centimetre%20of%20thickness.

[34] A. Atangana, *Principle of groundwater flow,* in "Fractional Operators with Constant and Variable Order with Application to Geo-Hydrology", 2018, chapter 2, 15-22, https://doi.org/10.1016/B978-0-12-809670-3.00002-3

[35] M. Kurihara, J. Liang, F. Fujimoto, L. Nghiem, P. Sammon, *Development and Application of Underground Gas Storage Simulator*, in "SPE Asia Pacific Conference on Integrated Modelling for Asset Management" held in Yokohama, Japan, April 2000. https://doi.org/10.2118/59438-MS

[36] M. Słota-Valim, A. Gołąbek, W. Szott, K. Sowiżdżał, *Analysis of Caprock Tightness for $CO_2$ Enhanced Oil Recovery and Sequestration: Case Study of a Depleted Oil and Gas Reservoir in Dolomite, Poland, in "Energies* 2021", *14*(11), 3065; https://doi.org/10.3390/en14113065

[37] M. Lebon, R. Nabil, P. Lehuen, *Case Study of Gas BTU Control For Operational Strategy and Inert Gas Injection Planning,* in "SPE Annual Technical Conference and Exhibition" held in New Orleans, Louisiana, September 1998, https://doi.org/10.2118/49220-MS

[38]https://earthworks.org/issues/aquifers/

[39] http://naturalgas.org/naturalgas/storage/

[40]https://www.researchgate.net/figure/Schematic-cross-section-of-a-depleted-oil-gas-field_fig2_226244610

[41] https://utg.ua/en/utg/company/ukrtransgaz-today.html

[42] https://regulationbodyofknowledge.org/glossary/r/regulated-third-party-access/#:~:text=Glossary%20%2D%3E%20R,the%20basis%20of%20published%20tariffs

[43] N. Iwaszczuk, I. Zapukhliak, A. Iwaszczuk, O. Dzoba, O. Romashko, *Underground gas storage facilities in Ukraine: current state and future prospects,* in *"Energies 2022",15*(18), 6604, 10-11, https://doi.org/10.3390/en15186604

[44]https://fluidhandlingpro.com/gas-processing/

[45]https://www.researchgate.net/figure/Schematic-cross-section-of-an-aquifer-converted-into-UGS_fig3_226244610

[46] https://www.researchgate.net/figure/Typical-aquifer-natural-gas-underground-storage-reservoir-facility-Tek-1996_fig2_337567064

[47] S. Donadei, G. Schneider, *Compressed air energy storage in underground formations,* in "Storing energy with special reference to renewable energy sources", 2016, 113-133, https://doi.org/10.1016/B978-0-12-803440-8.00006-3

[48]https://www.researchgate.net/figure/Schematic-diagram-illustrating-the-various-types-of-salt-bodies-in-which-salt-caverns_fig1_369377726

[49]https://upload.wikimedia.org/wikipedia/commons/2/2d/SaltTectonics1.jpg

[50]https://www.researchgate.net/figure/Cavern-convergence-and-stress-calculations_fig10_226244610

[51] F. Civan, *Natural gas transportation and storage,* in "Encyclopedia of energy", 2004, 11, https://doi.org/10.1016/B0-12-176480-X/00276-X

[52] S. Mokhatab, W. A. Poe, J. Y. Mak, *Handbook of Natural Gas Transmission and Processing (Fourth Edition),* in "Principles and Practices", 2019, 1-35, https://doi.org/10.1016/B978-0-12-815817-3.00001-0

[53]https://www.researchgate.net/figure/Solution-mining-in-salt-dome_fig9_226244610

[54]https://www.solutionmining.org/

[55]https://www.researchgate.net/figure/Comparison-of-costs_fig13_226244610

[56]https://www.iea.org/reports/renewable-electricity - :~:text=The share of renewables in,growth of 0.4 percentage points.

[57] D. Das, T. N. Veziroglu, *Hydrogen production by biological processes: a survey of literature,* in "International Journal of hydrogen energy", 2021, 13-28, https://doi.org/10.1016/S0360-3199(00)00058-6

[58] Z. Wang, R. R. Roberts, G. F. Naterer, K. S. Gabriel, *Comparison of thermochemical, electrolytic, photoelectrolytic and photochemical solar-to-hydrogen production technologies,* in “International Journal of hydrogen energy”, 2012, 16287-16301, https://doi.org/10.1016/j.ijhydene.2012.03.057

[59] A. Züttel, *Hydrogen storage methods*, in “Naturwissenschaften 91”, 2004, 157-172, https://doi.org/10.1007/s00114-004-0516-x

[60] A. Lemieux, K. Sharp, A. Shkarupin, *Preliminary assessment of underground hydrogen storage sites in Ontario, Canada,* in “International Journal of hydrogen energy”, vol.44, 2019, 15193-15204, https://doi.org/10.1016/j.ijhydene.2019.04.113

[61] N. Heinemann, M. G. Booth, R. S. Haszeldine, M. Wilkinson, J. Scafidi, K. Edlmann, *Hydrogen storage in porous geological formations-onshore play opportunities in the midland valley (Scotland, UK),* in “International Journal of hydrogen energy”, vol. 43, 2018, 20861-20874, https://doi.org/10.1016/j.ijhydene.2018.09.149

[62]C. Hemme, W. Van Berk, *Hydrogeochemical modeling to identify potential risk of underground hydrogen storage in depleted gas fields,* in “English applied sciences”, 2018, 8(11),2282, https://doi.org/10.3390/app8112282

[63] V. Reitenbach, L. Ganzer, D. Albrecht, B. Hagemann, *Influence of added hydrogen on underground gas storage: a review of key issues*, in “*Environmental Earth Sciences*”, vol. 73, 2015, 6927-6937, https://doi.org/10.1007/s12665-015-4176-2

[64] J. Michalski, *Hydrogen generation by electrolysis and storage in salt caverns: potentials, economics, and system aspects with regard to the Germany energy transition,* in “International Journal of hydrogen energy”, vol. 42, 2017, 13427-13443, https://doi.org/10.1016/j.ijhydene.2017.02.102

[65] P. O. Carden, L. Patterson, *Physical, chemical and energy aspects of underground hydrogen storage,* in “International Journal of hydrogen energy”, vol. 4, 1979, 559-569, https://doi.org/10.1016/0360-3199(79)90083-1

[66] J. B. Taylor, J. E. A. Alderson, K. M. Kalyanam, A. B. Lyle, L. A. Philips, *Technical and economic assessment of methods for the storage of large quantities of hydrogen,* in “International Journal of hydrogen energy”, vol. 11, 1986, 5-22, https://doi.org/10.1016/0360-3199(86)90104-7

[67] C. Schaber, P. Mazza, R. Hammerschlag, *Utility-scale storage of renewable energy,* in “The electricity journal”, vol. 17, 2004, 21-29, https://doi.org/10.1016/j.tej.2004.05.005

[68] L. Lankof, R. Tarkowski, *Assessment of the potential for underground hydrogen storage in bedded salt formation,* in "International Journal of hydrogen energy", vol. 45, 2020, 19479-19492, https://doi.org/10.1016/j.ijhydene.2020.05.024

[69] Z. Shi, K. Jessen, T. T. Tsotsis, *Impacts of the subsurface storage of natural gas and hydrogen mixtures,* in "International Journal of hydrogen energy", vol. 45, 2020, 8757-8773, https://doi.org/10.1016/j.ijhydene.2020.01.044

[70] D. R. Simbeck, *$CO_2$ Capture and Storage—The Essential Bridge to the Hydrogen Economy,* in "Greenhouse Gas Control Technologies - 6th International Conference", vol. 1, 2003, 25-30, https://doi.org/10.1016/B978-008044276-1/50005-2

[71] L. Shen, Z. Chen, *Critical review of the impact of tortuosity on diffusion*, in "Chemical engineering science", vol. 62, 2007, 3748-3755, https://doi.org/10.1016/j.ces.2007.03.041

[72] D. Zivar, S. Kumar, J. Foroozesh, *Underground hydrogen storage: a comprehensive review,* in "International Journal of hydrogen energy", vol. 46, 2021, 23436-23462, https://doi.org/10.1016/j.ijhydene.2020.08.138

[73] R. Tarkowski, *Underground hydrogen storage: characteristics and prospects,* in "Renewable and sustainable energy reviews", vol. 105, 2019, 86-94, https://doi.org/10.1016/j.rser.2019.01.051

[74] A. Sainz-Garcia, E. Abarca, V. Rubi, F. Grandia, *Assessment of feasible strategies for seasonal underground hydrogen storage in a saline aquifer*, in "International Journal of hydrogen energy", vol. 42, 2017, 16657-16666, https://doi.org/10.1016/j.ijhydene.2017.05.076

[75] M. Panfilov, G. Gravier, S. Fillacier, *Underground storage of H2 and H2-CO2-CH4 mixtures*, in "ECMOR X-10th European conference on the mathematics of oil recovery, 2006, https://doi.org/10.3997/2214-4609.201402474

[76] T. Ajayi, JS. Gomes, A. Bera, *A review of CO2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches,* in "Petroleum Science 16", 2019, 1028-1063, https://doi.org/10.1007/s12182-019-0340-8

[77] KH Coats, JG. Richardson, *Calculation of water displacement by gas in development of aquifer storage,* in "Society of petroleum engineers journal", vol.7, 1967, 105-112, https://doi.org/10.2118/1723-PA

[78] BS. Srinivasan, *The impact of reservoir properties on mixing of inert cushion and natural gas in storage reservoirs*, in "Master, petroleum and natural gas engineering", 2006, http://refhub.elsevier.com/S0360-3199(20)33142-6/sref74

[79] R. Torres, JC. de Hemptinne, I. Machin, *Improving the modeling of hydrogen solubility in heavy oil cuts using an augmented grayson streed (AGS) approach*, in "Oil & gas science and technology-revue D ifp energies Nouvelles", 68, 2013, 217-233, https://doi.org/10.2516/ogst/2012061

[80] S. Foh, M. Novil, E. Rockar, P. Randolph, *Underground hydrogen storage final report"*, in "Inst Of gas tech. Upton, NY", 1979, https://doi.org/10.2172/6536941

[81] AS. Lord, *Overview of geologic storage of natural gas with an emphasis on assessing the feasibility of storing hydrogen*, Albuquerque, NM: SAND-, Sandia National Laboratory, 2009, https://doi.org/10.2172/975258

[82] WT. Pfeiffer, S. Bauer, *Subsurface porous media hydrogen storage e scenario development and simulation*, in "Energy Procedia", vol.76, 2015, 565-572, https://doi.org/10.1016/j.egypro.2015.07.872

[83] M. Panfilov, *Underground and pipeline hydrogen storage*, in "Compendium of hydrogen energy", vol.2, 2016, 91-115, https://doi.org/10.1016/B978-1-78242-362-1.00004-3

[84] L. Katarzyna, T. Radosław, *Numerical simulation of hydrogen injection and withdrawal to and from a deep aquifer in NW Poland*, in "J Hydrogen Energy", vol.45, 2020, 2068-2083,https://doi.org/10.1016/j.ijhydene.2019.11.055

[85] HS. Shafaat, O. Rudiger, H. Ogata, W. Lubitz, *[NiFe] hydrogenases: a common active site for hydrogen metabolism under diverse conditions*, in "Biochimica et Biophysica Acta (BBA)- Bioenergetics", 2013, 986-1002, https://doi.org/10.1016/j.bbabio.2013.01.015

[86] G. Etiope, M. Schoell, H. Hosgormez, *Abiotic methane flux from the Chimaera seep and Tekirova ophiolites (Turkey): understanding gas exhalation from low temperature serpentinization and implications for Mars*, in "Earth and Planetary Scientific Lettetter", vol.310, 2011, 96-104, https://doi.org/10.1016/j.epsl.2011.08.001

[87] P. Amigan, M. Greksak, J. Kozankova, F. Buzek, V. Onderka, I. Wolf, *Methanogenic bacteria as a key factor involved in changes of town gas stored in an underground reservoir*, in "Microbiology Ecology", 1990, 221-224, https://doi.org/10.1111/j.1574-6968.1990.tb03944.x

[88] AN. Cavallaro, MEG. Martinez, H. Ostera, H. Panarello, RR. Cordero, *Oilfield reservoir souring during waterflooding: a case study with low sulphate concentration in formation and injection waters,* in "SPE International Symposium on Oilfield Chemistry", 2005, https://doi.org/10.2118/92959-MS

[89] A. Shabani, D. Zivar, *Detailed analysis of the brine-rock interactions during low salinity water injection by a coupled geochemical-transport model*, in "Chemical Geology", 2020, 119484, https://doi.org/10.1016/j.chemgeo.2020.119484

[90] Yekta AE, Manceau JC, Gaboreau S, Pichavant M, Audigane P. *Determination of hydrogenewater relative permeability and capillary pressure in sandstone: application to underground hydrogen injection in sedimentary formations*, in "Transport in Porous Media", 2018, 333-356, https://doi.org/10.1007/s11242-018-1004-7

[91] Chatzis I, Morrow NR. *Correlation of capillary number relationships for sandstone*, in "Society of petroleum engineers journal", 1984, 555-562,http://refhub.elsevier.com/S0360-3199(20)33142-6/sref103

[92] L. Paterson, *The implications of fingering in underground hydrogen storage*, in "International Journal of hydrogen energy", vol. 8, 1983, 53-59, https://doi.org/10.1016/0360-3199(83)90035-6

[93] CK. Ho, SW. Webb, *Gas transport in porous media*, in "Springer", 2006, https://doi.org/10.1007/1-4020-3962-X

[94] U. Lindblom, *A conceptual design for compressed hydrogen storage in mined caverns*, in "International Journal of hydrogen energy", vol. 10, 1985, 667-675,https://doi.org/10.1016/0360-3199(85)90006-0

[95] O. Kruck, F. Crotogino, R. Prelicz, T. Rudolph, *Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe*, in "Underground Technologies GmbH", 2013, http://refhub.elsevier.com/S0360-3199(20)33142-6/sref63

[96] A. Le Duigou, A-G. Bader, J-C. Lanoix, L. Nadau, *Relevance and costs of large scale underground hydrogen storage in France*, in "International Journal of hydrogen energy", vol. 42, 2017, 22987-3003, https://doi.org/10.1016/j.ijhydene.2017.06.239

[97] RD. Venter, G. Pucher, *Modelling of stationary bulk hydrogen storage systems*, in "International Journal of hydrogen energy", vol. 22, 1997, 791-798,https://doi.org/10.1016/S0360-3199(96)00210-8

[98] AS. Lord, PH. Kobos, GT. Klise, DJ. Borns, *A life cycle cost analysis framework for geologic storage of hydrogen: a user's tool*, in "Sandia national laboratories", 60, 2011, http://refhub.elsevier.com/S0360-3199(20)33142-6/sref116

[99] AS. Lord, PH. Kobos, DJ. Borns, *Geologic storage of hydrogen: scaling up to meet city transportation demands*, in "International Journal of hydrogen energy", vol. 39, 2014, 15570-15582, https://doi.org/10.1016/j.ijhydene.2014.07.121

[100] MX. Bai, KP. Song, YX. Sun, MQ. He, Y. Li, JP. Sun, *An overview of hydrogen underground storage technology and prospects in China*, in "Journal of petroleum science and engineering", vol. 124, 2014, 132-136, https://doi.org/10.1016/j.petrol.2014.09.037 2

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