TECHNICAL CONSIDERATIONS FOR SUBSURFACE STORAGE TO SUPPORT THE ENERGY TRANSITION

In our previous article "**The importance of subsurface gas storage as part of the energy transition mix**", Gordon Taylor wrote about the need for underground gas storage and its critical role in the energy transition, to provide energy security when renewable sources aren't available, and as a store for carbon dioxide (CO_2).

Whether the outcome is to permanently store gas with CO_2 (following the capture of CO_2 from industrial processes) or storage and recovery of natural gas, and hydrogen in the future, the key attribute of a feasible geologic store, or 'trap', is its ability to receive the gas efficiently, store it effectively and – for natural gas and hydrogen storage – to recover the gas economically.

This article expands on previous insights by providing technical detail on some of the key sub-surface design elements of underground storage of natural gas, CO_2 and hydrogen. Finally, some comments are made on compressed air storage and on auditing of storage capacity.

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NATURAL GAS STORAGE

Natural gas is taking a larger share of the energy mix as countries reduce their reliance on coal for electricity generation, and it's easy to see why. Natural gas can be stored underground and delivers nearly twice as much electricity as coal for the same amount of CO_2 emissions .

The short-term and long-term fluctuations from renewable sources mean they can't always meet energy demand. Natural gas storage can partly address this and can also be used as a strategic reserve to level out shortages in supply. Based on seasonal variations, gas is injected when demand and price are low, then withdrawn again as needed. Natural gas storage also provides short-term protection against unforeseen supply disruption by providing an immediate and reliable energy source which can quickly be utilised to generate electricity. Natural gas storage allows large natural gas consumers to hedge supply and price risk and, should prices suddenly spike, capture the upside opportunity.

How does natural gas storage work?

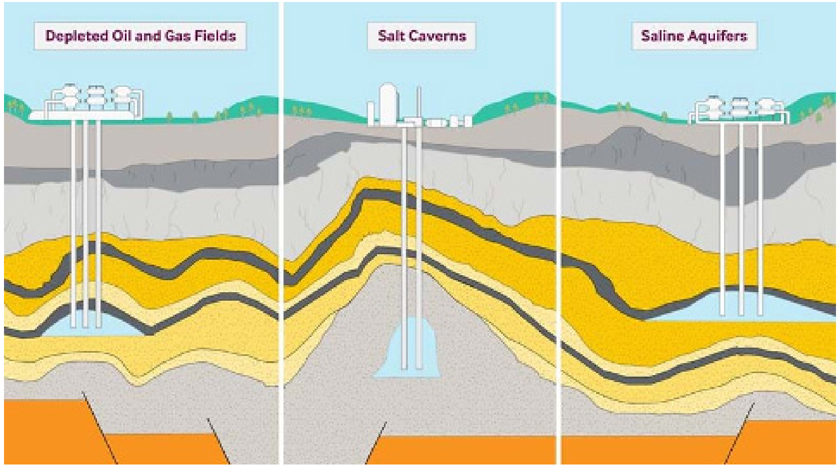
A natural gas storage system needs a working gas volume, injection capacity, withdrawal capacity and a volume of cushion gas. The working gas volume is the volume that can be injected and withdrawn during normal operations. The cushion gas volume is the gas that is required to remain in store to maintain reservoir pressure.

The injection and withdrawal capacity, which are largely dependent on the storage pressure, control the rate at which gas can be injected or withdrawn. If storage pressure is low, gas can be injected at high rates but withdrawn at low rates. Conversely, if storage pressure is high due to considerable working gas in store, injection rates will be low, but withdrawal rates will be high. Depending on the type of storage, studies that may be required include pore and regional scale modelling, geomechanics, trap integrity, rock chemistry, core studies and injectivity/productivity.

For depleted gas fields, there is a well-documented hysteresis in the field's ability to be repeatedly repressurised and depleted, which must also be modelled.

Where is natural gas stored?

The most common types of natural gas storage are in depleted gas reservoirs and salt caverns and, to a lesser extent, in aquifers. Aquifers and depleted aquifers have a much more useful storage capacity for the long-term capture and storage of CO_2 (see below).



Depleted fields: The advantage of depleted gas reservoirs over other types of gas storage is that any unproduced gas can be used as cushion gas, and the fields may also have very large working gas capacity. Depleted reservoirs are also likely to be linked to existing gas infrastructure, which reduces the upfront investment needed.

[1] https://www.eia.gov/tools/faqs/faq.php?id=73&t=11

Detailed modelling is required when identifying and selecting a depleted field as a gas storage site. Ideally, a good candidate for gas storage has:

- A "dry" gas field
- Good reservoir quality – i.e. has high porosity and permeability, which will allow high-rate wells
- Well-defined estimate of gas initially in place ("GIIP")
- Well-defined reserves estimate and time to depletion
- Proximity to the gas "grid"
- Re-usable wells

Before operating a depleted field as a gas store, it may be necessary to undertake a development phase (in addition to drilling wells), in which the reservoir gas is topped up to reach the required cushion gas volume.

Salt caverns: Salt caverns are located in thick halite formations. They are made by pumping fresh water down a borehole into the salt layer to dissolve the salt, then circulating the resulting brine to the surface. This process continues until the required size of cavern is reached.

Hydrocarbon liquid or gas storage in salt caverns is well understood. For example, the US Strategic Petroleum Reserve (SPR), which is the world's largest supply of emergency crude oil, is stored in salt caverns at four sites along the Gulf of Mexico coastline. Natural gas storage in man-made salt caverns is established in the UK in Triassic salt in the Cheshire Basin and in Germany in Permian salt. While the capacity of salt caverns is generally small relative to depleted gas fields, the advantages of salt caverns are:

- The extremely low permeability of halite
- Halite is inert (does not react with stored gas)
- Low construction costs
- Only a small footprint required above ground

Depleted aquifers: Converting an aquifer to a natural gas reservoir requires long, slow injection cycles to displace the water. Depleted aquifers have the largest potential storage capacity compared to other options. However, they are less likely to have the wealth of subsurface technical data available for depleted oil or gas fields.

CO_2 STORAGE

Atmospheric CO_2 is widely accepted to be a major contributor to global climate change. Carbon Capture and Storage (CCS) refers to the process of capturing CO_2, compressing it, transporting it to a storage site, and injecting the fluid into the site for long-term sequestration.

Although various methods of storage have been proposed, geological storage, where CO_2 is permanently stored deep underground, has been studied for decades and is well understood.

Globally, 300 million metric tonnes of CO_2 have been safely captured and stored over the past four decades. CCS is expected to play a very significant role in meeting the global emission targets set out in the Paris Accord. Indeed, most of the accepted forecasts of global energy requirements agree that without CCS it will be impossible to limit global warming to 1.5°C by 2050.

The number of active CCS projects continues to grow. In its latest CCS status report, the Global CCS Institute reported that the CO_2 storage capacity of operational projects, plus projects in development, has grown from 73 Mtpa (million tonnes per annum) at the end of 2020 to 111 Mtpa by September 2021 – an increase of 48%. However, up to 70 new CCS projects will be required each year for several decades. CO_2 capture and removal is set to be a growth industry for many years to come.

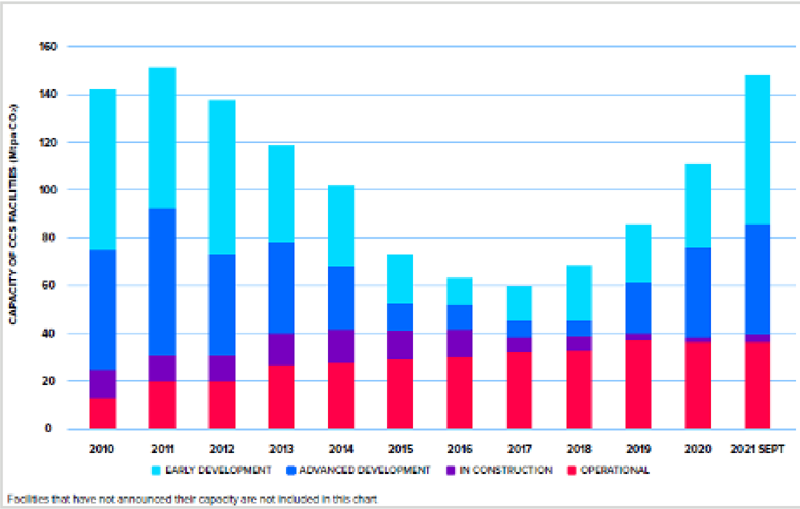


Figure 1: Pipeline of CCS projects worldwide 2010 to 2021

[Global Status of CCS 2021. Global CCS Institute. File: Global-Status-of-CCS-Report-2021_ Global_CCS_Institute.pdf]

How does CO_2 storage work?

The injection of CO_2 into deep geological formations utilises technologies and modelling capabilities that have been developed by the oil and gas industry over many years.

When CO_2 is injected (via a well) into a geologic storage site, the gas flows through the porous media. The storage sites are typically at depths greater than ~1 km. CO_2 will be supercritical at these depths, meaning that the fluid has a liquid-like density (which is favourable for storing large quantities), but a gas-like viscosity (which is favourable for injecting the CO_2). The CO_2 needs to be compressed at surface level before it is injected into the reservoir.

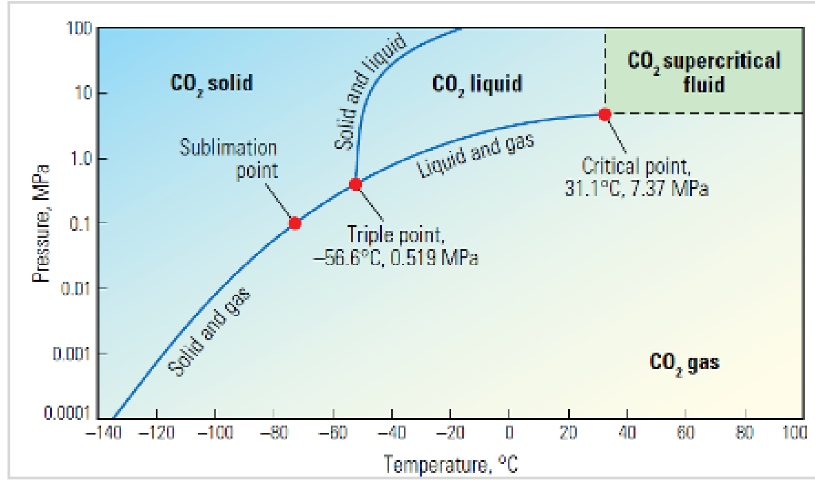


Figure 2: CO_2 Phase Behaviour

[Source: Oilfield Review, September 2015. File: OilfieldReview2015_Sept.pdf]

The CO_2 is permanently trapped in the reservoir through several mechanisms

- Structural trapping by the seal above the storage formation
- Solubility trapping in the water phase within the pore space
- Residual trapping / capillary trapping in the pore space, and
- Mineral trapping, as the CO_2 reacts with reservoir rocks to form carbonate minerals

The nature and the type of the trapping mechanisms for reliable and effective CO_2 storage vary within and across the life of a sequestration site depending on geological conditions. CO_2 trapping is well understood thanks to decades of experience in injecting CO_2 for enhanced oil recovery (EOR) and for dedicated storage.

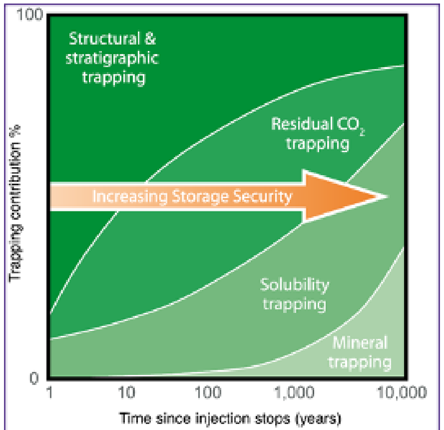


Figure 5.9 Storage security depends on a combination of physical and geochemical trapping. Over time, the physical process of residual CO_2 trapping and geochemical processes of solubility trapping and mineral trapping increase.

Figure 3: CO_2 Storage Mechanisms
[Source: "IPCC Special Report on Carbon Dioxide Capture and Storage". Cambridge University Press. File: IPCC_2005.pdf]

Selection of CO_2 storage sites and the planning of CO_2 storage operations requires predictive models (or "reservoir simulations"). For instance, locating/assessing appropriate sites for CO_2 storage requires an investigation of storage capacity, CO_2 injectivity and the security of containment. These models require data to fully describe the rocks and fluids and may be calibrated against historical operating data (in the case of depleted oil and gas fields).

The oil and gas industry has considerable experience in collecting and validating data, and in constructing reservoir simulations to support safe and cost-effective production of hydrocarbons. The same modelling techniques and tools are used to support CO_2 storage activities and to help in planning the monitoring programme to be followed during and after CO_2 injection.

Modelling/analysis of a CO_2 storage site involves multiple technical disciplines. For instance, an assessment of CO_2 containment (a critical step in planning any CCS project) would involve:

- Seismic interpretation and structural modelling
- Petrophysics and geological interpretation
- Static and dynamic modelling
- Modelling of seal and potential secondary CO_2 migration pathways
- Reservoir injectivity and diffusion rate modelling of the CO_2 during and post-injection
- Identification of potential thermal fracture or solid hydrate precipitation
- Geochemical analysis of CO_2 interaction with formation water and/or mineralogy

There are also several flow assurance issues that need to be considered in the design of the transportation and delivery system (pipelines and wells) which have some specific sensitivities to CO_2 that are not standardly required in more conventional flow assurance modelling. These include:

- Prediction of the thermodynamic behaviour of the multicomponent mixture that will be transported
- The management of fluid phase in the pipeline itself and, critically, at any transition from one pressure regime to another
- Understanding where two phase flows are possible and developing strategies to avoid them where possible
- Mitigation of corrosion risk

Monitoring of CO_2 storage sites, during and after injection, is another key aspect and may be necessary for a significant period (possibly up to 50 years). This involves a range of techniques, including atmospheric, surface and subsurface monitoring at the storage site, aimed at robustly demonstrating there are no fugitive CO_2 emissions from the site.

Where is CO_2 stored?

Geological storage of CO_2 involves the injection of captured CO_2 into a deep underground geological reservoir of porous rock. As with natural gas storage, there are several types of reservoir suitable for CO_2 storage, notably depleted oil and gas reservoirs, or deep aquifer formations (saline aquifers).

Depleted oil and gas reservoirs are porous rock formations that have trapped crude oil or gas over geological time periods before being developed. Such depleted reservoirs are likely to have been characterised and modelled in detail during the planning and operational phases of hydrocarbon production.

Deep saline formations are layers of porous and permeable rocks saturated with brine, which are widespread in both onshore and offshore sedimentary basins. Saline aquifer storage provides a significantly higher storage potential than depleted reservoirs.

HYDROGEN STORAGE

Hydrogen will play an important role in the world's future energy systems, and the need for hydrogen storage will grow as renewable energy generation increases. There are potentially many ways that hydrogen could be stored: in liquid or gaseous state in surface tanks through to underground storage in a gaseous state.

Large scale, commercial underground hydrogen storage has been demonstrated in salt caverns in a handful of projects in the USA and in Europe. The storage facility at Teesside, UK, has been in operation since the 1970s. Salt cavern storage facilities have relatively small storage volumes. In addition, several possible projects are currently being evaluated in Europe. Large scale hydrogen storage, however, would require the use of depleted hydrocarbon fields. Centrica Storage, in a submission to the UK Parliament's Science and Technology Committee, compared the capacity and cost of repurposing the depleted Rough gas field, which was used for natural gas storage from 1985 to 2016, to hydrogen storage. The same graph shows the capacity of all existing salt caverns in the UK (currently used for natural gas storage) compared with Rough.

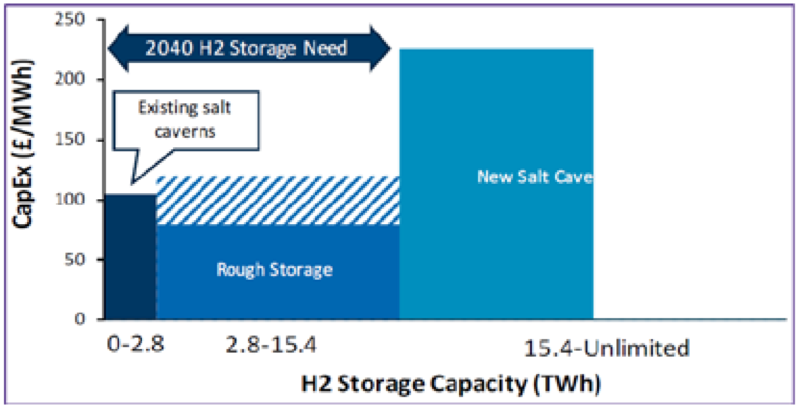


Figure 4: UK Hydrogen Storage Capacity and Costs
[Source: Centrica Storage submission to UK Parliament's Science and Technology Committee https://committees.parliament.uk/writtenevidence/20906/pdf]

Despite the capacity limitations, salt caverns represent a favourable option for hydrogen storage for the same reasons as for natural gas storage (extremely low permeability of halite, low construction costs, and small surface footprint). Additionally, hydrogen is unlikely to react with the halite. As with natural gas storage, cushion gas is required to maintain minimum pressures. The creation of man-made caverns also creates a sump of debris, which reduces storage volume, at the base of the cavern.

To our knowledge the only field tests of hydrogen storage in porous rocks have been in Argentina, and at low pressure in depleted reservoirs in Austria. As hydrogen is not found in its free state in oil or gas reservoirs, there have been concerns regarding whether a depleted field could store hydrogen.

The hydrogen molecule is smaller, more mobile and has greater fugacity than hydrocarbons, nitrogen or CO_2 molecules, so there is concern whether it could be trapped. Additionally, there is concern over biological and chemical reactions between the sealing and reservoir rocks, the cushion gas and other fluids in the reservoir and concern over potential microbial growth.

Considerable research is ongoing and, although in early stages, there appear to be no fundamental issues to prevent hydrogen storage in porous media.

COMPRESSED AIR STORAGE

There is increasing interest in a storage technology that was developed well over 50 years ago: Compressed Air Energy Storage (CAES). CAES is based around a gas turbine cycle. Surplus power is used to compress air using a rotary compressor and then store it, often underground. When power is required, it is released from the chamber and passed through an air turbine that generates electricity from the flow of the high-pressure air. The output can be boosted by burning natural gas in the high-pressure air before it enters the air turbine (as in a conventional gas turbine), albeit with accompanying CO_2 emissions. Compared with other energy storage technologies, CAES plants would have a very large power rating and storage capacity, low self-discharge, and a long lifetime. However, conventional CAES plants have a relatively low round trip efficiency.

As with natural gas storage, a large proportion of the gas injected in a CAES system is used as a cushion.

Although proven technology, only two commercial CAES plants have ever been built. The first CAES plant was at Huntorf, Germany (built in 1978) and is still in operation. There is a second CAES facility in McIntosh, Alabama, USA, with a total storage capacity of 400 MW. Both facilities store compressed air in salt caverns.

AUDITING

Assessing an E&P company's oil and gas Reserves and Resources volumes is a key part of any E&P company's internal governance process. Independent auditing of Reserves and Resources is essential for raising finance for oil and gas developments or when listing the company on a stock market. The most widely used standard for assessing oil and gas volumes is the 2018 Petroleum Resource Management System (PRMS), which was based on a system developed by the Society of Petroleum Engineers (SPE) in the 1960s and which has been modified by the SPE in conjunction with other professional institutions since then. The SPE has developed a similar system for auditing underground storage capacity called the "CO_2 Storage Resources Management System (2017)". Although specifically prepared for CO_2 storage, the principles can be applied to storage of any gas.