In focus...

Underground hydrogen storage

Energy efficiency, economics, and commercial deployment

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To add flexibility to heating and power generation energy systems, long-term, high-capacity energy storage will be essential to balance supply and demand. As variable renewable energy makes an increasing contribution to power generation, the requirement for hydrogen as an energy storage medium will increase dramatically to balance the power transmission grid.

The optimum method of power and energy storage depends on the storage duration, energy release rate and storage capacity. Batteries and flywheels are suitable for Kilowatt-hour (kWh) of power to be released within seconds, minutes, or hours. Pumped-hydro schemes can release Gigawatt-hour (GWh) of power over a time span of minutes or hours. Underground molecular energy storage of hydrogen or natural gas is effective when GWh or Terawatt-hour (TWh) of energy storage is required over days, weeks, or months.

Underground natural gas storage

Depleted oil and gas reservoirs, saline aquifers and man-made salt caverns can be used for UGS (underground gas storage) to store natural gas as an energy buffer. As of 2017, more than 100 UGS salt cavern sites were in operation in the world. UGS Norg, operated by NAM in the Netherlands, is one of the largest UGS sites worldwide and has operated successfully for the past decade. Natural gas is stored in a depleted natural gas reservoir close to Groningen.

However, only four salt cavern facilities for underground hydrogen storage (UHS) have been operated worldwide. Three large cavern sites in Texas are operated by Air Liquide, Praxair (Linde) and Conoco Philips at Spindletop, Moss Bluff and Clemens Dome respectively. At Teesside in the UK, SABIC operates three smaller caverns.

Underground hydrogen storage is a highly attractive technology for daily to seasonal energy storage; the lessons from UGS could be extended to scale up UHS in the coming years.

Salt caverns for UHS

Salt caverns are man-made cavities in naturally occurring salt deposits below ground and are created using a technique called 'solution mining'. During this process, a bore hole is drilled from the surface to the underground salt layer and water is then injected to dissolve the rock salts. When the cavern reaches the desired volume, gas is injected to displace the brine.

The salt cavern is then pressurised to its working pressure, which may be up to 200 bar and depends on the depth of the salt cavern. The total gas injected into the salt caverns cannot be recovered because a residual 'cushion gas' pressure of about 50 bar is required inside the salt cavern to strengthen it.

The amount of gas that that can be injected and withdrawn in each cycle is called the 'working gas'. The total gas storage volume is comprised of the cushion gas plus the working gas and typically, 25-30% of the total gas is required as cushion gas in salt caverns. The percentage of cushion gas can be more than 50% if a depleted gas field or saline aquifer is used.

Salt caverns are generally located at a depth of between 500m and 2,000m and have an internal volume in the range of 100,000m^3 to 1,000,000m^3. They are typically 200m high and have a diameter in the order of 50m. The working gas volume of hydrogen stored in such a cavern could generate many GWh of power or heat.

Energy system integration

Germany, the Netherlands, the UK, Denmark, Norway, and Poland have many sub-surface salt caverns which are currently used for natural gas storage. These could be adapted for UHS in the future to provide hydrogen storage capacity. These locations could play an essential role in the European Hydrogen Backbone pipeline transmission and storage infrastructure proposal.

The North Sea and its nearby onshore region could also be an attractive choice for energy system integration. Natural gas can be used to make blue hydrogen, and the carbon dioxide released from that process could be injected into sub-surface geological formations for CCS. Offshore wind power generation is being installed at GW scale enabling green hydrogen production.

The green and blue hydrogen can be stored in multiple salt caverns, thereby fully harnessing natural resources above and below the ground in the region. The North Sea Energy programme and the Zero Carbon Humber project are planning to use this regional capability to create sustainable energy systems.

In the US, a utility-scale project involving Mitsubishi Hitachi Power Systems (MHPS) and Magnum Development is underway. The companies intend to create a massive green hydrogen storage hub close to the town of Delta in Utah by 2025. More than 1 GW of electrolysers will produce hydrogen ▸

Great Salt Lake, Utah

and store it in 100 underground salt caverns for seasonal energy storage.

Delta is close to the Great Salt Lake and Salt Lake City and lies on top of the Delta salt dome, which has ideal characteristics for solution mining to create this massive hydrogen storage infrastructure.

Cost considerations

From an economic perspective, UHS in salt caverns for seasonal storage may be more capital intensive than the use of a depleted reservoir. This is because the salt cavern must be constructed through a leaching process, something that is not required when using a depleted reservoir. The main elements for economic analysis of salt caverns are geological construction, cushion gas investment, surface facility design (compressor and dehydration unit) and drilling wells.

For a typical sizes salt cavern, CAPEX may be in the order of €50-100m and annual OPEX may be around €5m. A major factor is the hydrogen production cost for the required cushion gas and reducing this cost could result in a lower levellised cost of hydrogen storage.

Considering CAPEX and OPEX costs during the lifetime of the operation, the levellised cost for seasonal storage is estimated at €1-2 per kg of stored hydrogen. This could be less than €1 for weekly and monthly storage, due to the higher frequency of the pressurisation and depressurisation cycles. When comparing UGS and UHS, many cost elements are similar. However, hydrogen compressors and well design are more expensive for hydrogen than natural gas.

Energy recovery for improved economics

Pressure energy recovery can improve the economics and energy balance of underground storage. Freddie Sarhan, CEO at Sapphire Technologies in California, explains that “pressure energy recovery is common in natural gas transmission pipeline pressure let-down stations, and the same principle can be applied to let-down stations from hydrogen transmission pipelines and underground gas and hydrogen storage in the future.”

When hydrogen is compressed into the salt cavern, electrical power is consumed to pressurise the gas. “Large piston compressors are ideal to achieve the pressure of 200 bar and process the high flowrates of these utility scale schemes,” says Sarhan. “To recover the available pressure energy from the compressed gas as it is released from the underground storage cavern, a turbo-expander is required.”

Industrial gases operators will be familiar with turboexpanders that are used on air separation plants and nitrogen or hydrogen liquefiers. They are also essential for LNG production. In some cases, the expansion turbine is directly coupled to a compressor, giving rise to the name ‘compander’. Direct coupling is ideal when the energy released from gas expansion is equal to the energy required for compression and both are required simultaneously.

Sarhan comments on turboexpander technology selection, “In the case of underground gas storage, compression and expansion happen sequentially, so electrical power generation is the most effective mode of energy recovery.” Sapphire is currently developing generator-loaded turboexpanders that can be used with hydrogen.

Pressure energy recovery could also be applied to hydrogen refuelling stations. Power is consumed to raise the hydrogen pressure to more than 900 bar. This is higher than the pressure in the vehicle, which is a maximum of 700 bar. “The pressure differential is required to ensure rapid refuelling,” says Sarhan, “and this large pressure differential could be used to generate electrical power.”

Power for hydrogen compression is the main operating cost on an HRS, and electricity is also required for electrolysis if onsite hydrogen is generated for the fuelling station. “We have a vision that power recovered during refuelling can be used on the hydrogen electrolyser to come closer to the long-term energy efficiency targets that have been set for HRS installations.”

Sapphire has developed an inline high-speed turboexpander-generator design that is based on advanced magnetic systems for frictionless operation without the use of expensive and unreliable lubrication systems. This technology forms the basis for Sapphire to produce a standardised range of low-cost hydrogen compatible turboexpanders. They have incorporated the benefits of additive manufacturing (AM) to ensure production flexibility and enable the use of advanced hydrogen-compatible metal alloys.

“The past has been all about large-scale, high-CAPEX, engineered-to-order turboexpanders,” comments Sarhan. “Our disruptive business model will introduce affordable, standardised hydrogen turboexpanders that can use a modular approach to span the range of requirements for smaller-scale power recovery to large-scale applications.” gw