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# Large-Scale Hydrogen Underground Storage for Securing Future Energy Supplies

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## 1 Introduction

In recent years the role of hydrogen in future energy scenarios has moved somewhat into the background. Now its significance is being highlighted even more as it may play an important role during and after the transition from fossil fuels to renewable energy sources concerning two areas in particular.

### 1.1 Energy industry

The energy industry is facing the need to store extremely large quantities of energy for long-term to seasonal periods in order to adapt the fluctuating and non-dispatchable energy production from wind and solar resources to the actual demand, which is no longer feasible using conventional technologies. In today's fossil-based energy industry, seasonal fluctuations, strategic reserves, and compensation of shortages and shut-downs are largely balanced out by the storage of fossil fuels (e.g. Germany and France both have reserves covering around 2 months of demand). With a reach of only around 1 hour (Germany), today the storage of electrical energy plays a very subordinate role. The possibility to outsource the storage capacity to fossil fuels will decrease more and more in a future electricity-based energy industry, i.e. the long-term storage capacities for electrical energy will have to be much longer than 1 hour.

In recent years pumped hydro and compressed air energy storage (CAES) systems were almost exclusively seen as suitable methods for balancing out fluctuating wind and PV feed-in into the transmission grids. In contrast, the latest investigations - and particularly the comprehensive study published by VDE [1] have identified the limitations of these storage technologies, particularly with respect to total storage capacities. Hydrogen alone can facilitate the storage of large quantities of energy to balance out long periods of poor wind power supply and seasonal fluctuations. Hydrogen large scale storage will be the only means in the long term to provide electrical energy in quantities and at a quality level consumers are accustomed to, in parallel to the downscaling of major capacities from fossil power plants and nuclear power stations. Furthermore, the relevant large volumes which need to be stored can most likely only be accommodated underground in geological formations – primarily in man-made salt caverns.

### 1.2 Supplying fuel cell vehicles with hydrogen

The limited range and low storage capacity of battery electric vehicles as well as the limited availability of biofuels limiting its long term use to heavy duty transport such as trucks, rail and aircraft, require the use of hydrogen powered fuel cell vehicles for a wide range of vehicle segments. After a transition phase, hydrogen needs to be mainly produced from renewable electricity such as wind and solar power [2]. Also for the transport sector it will be necessary to balance out seasonal fluctuations and to build up reserves to prepare for shortfalls, etc.

Most of today's infrastructure investigations on future hydrogen supply have either addressed the development of hydrogen demand or the build-up of hydrogen refuelling stations including onsite hydrogen storage capacities as well as onboard hydrogen storage. This paper contributes an assessment of the continuous supply of *green* hydrogen throughout the year which takes the utilisation of fluctuating and non dispatchable resources into account.

The first part of this paper looks at the future demand for hydrogen storage capacities for energy supply and for hydrogen as a vehicle fuel. The second part reviews the current status of hydrogen storage in salt caverns, engineering parameters, storage capacities and costs.

## 2 Demand for Energy Storage Capacity

### 2.1 Energy supply

The need for additional energy storage capacities at a grid scale has primarily been studied in the past with respect to providing balancing power, i.e. to level out deviations from wind energy forecasts. Pumped hydro and CAES power plants are as of now the most suitable systems for the electricity generation capacities in the order of a few Gigawatts and for periods of up to hours or a few days. Main reasons are their high efficiency level of 70%+ and specifically their moderate investment and operating costs.

In the long term, however, energy storage systems with considerably higher capacities will be needed. The required capacity will depend on the type of transition scenario (e.g. extended operating periods of nuclear power plants; substitution of coal based power generation to natural gas; nuclear phase-out or optimum or restricted grid extension).

In the *moderate*[1] *scenario,* the residual load, the difference between energy demand and energy generated by wind and solar power, can be largely provided from fossil and nuclear fuels for which no shortage is assumed even for the long-term. However, this would require a considerable extension of the existing electricity grid and a reliable long-term availability of additional very large quantities of natural gas imports should nuclear power be completely phased out. In this scenario, the expected demand for additional storage capacity is considered to be moderate. Assuming that an optimal extension of the electricity grid is not possible, the required storage capacities to compensate the *missing* grid extension may only be accomplished by providing large scale hydrogen storage capacities.

The *optimistic scenario* assumes to completely discard fossil and nuclear power plants and for this reason is the most extreme case. Balancing out seasonal fluctuations of wind power in particular - see Figure 2-1 - requires enormous storage capacities for electrical energy,. A comprehensive study by SIEMENS & ISET [3] has revealed the demand for storage capacity as shown in Table 2-1 under the assumption of an optimum Europe-wide extension of electricity grids. Furthermore, a storage capacity of 2% of the annual wind and solar energy production has been assumed in the study.

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[1] Moderate with respect to the scaling down of fossil and nuclear power plant capacities.

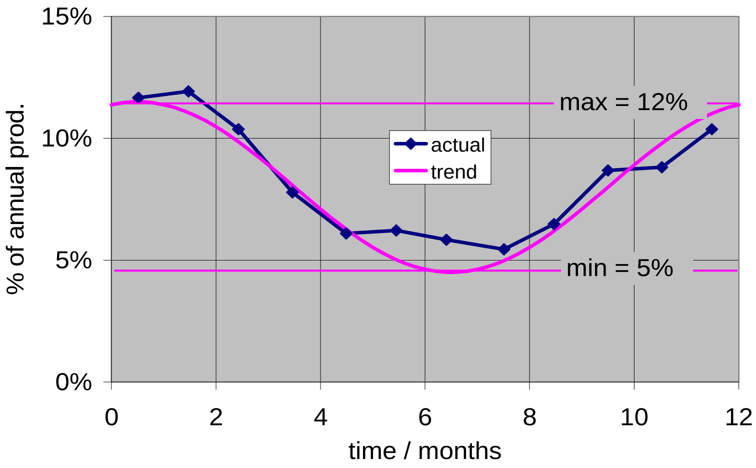


**Figure 2-1: Seasonal wind power variations.**

**Table 2-1: European-wide storage requirements when power is only generated from wind and solar power[2] plants.**

| | | |
|---|---|---|
| Hydrogen | 167 TWh | 0.41 km³ |
| Pumped hydro | 74 TWh | 106 km³ |
| Adiabatic CAES | 80 TWh | 29 km³ |

Achieving these enormous storage capacities using pumped hydro or CAES plants is completely unrealistic (106 $km^3$ of pumped storage volume corresponds to twice the volume of the Bodensee (Lake Constanz). Even the use of hydrogen storages goes very close to the feasibility limits.

The approach investigated in the *Kombikraftwerk* [4] project in which shortages of wind and solar power are primarily compensated by energy provided from biogas power plants is probably unfeasible because of the lack of adequate quantities of biogas.

## 2.2 Fuel supply for the transport sector

The study GermanHy [5] carried out on behalf of the German Federal Ministry of Transport, Building and Urban Development (BMVBS) in co-operation with the National Organisation Hydrogen and Fuel Cell Technology (NOW) has addressed the question "Where will the Hydrogen in Germany Come from by 2050?", and forecasted a realistic hydrogen demand as a transport fuel. Whilst the future overall transport fuel consumption will strongly depend on the selected scenario (moderate, ambitious climate protection and resource shortages), the hydrogen demand by 2050 is predicted to be largely constant and independent of the scenarios and is estimated to around 470 PJ/a or on average 15 GW, which is approximately 20 % of the present grid load in Germany.

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2 The different figures for the energy storage requirements respect the different energy efficiencies of the various storage technologies. The different storage volume requirements also take the different storage densities into account.

Although fuel consumption is largely constant throughout the year, the availability of the main energy source wind is fluctuating both short term and seasonally, see Figure 2-1. In natural gas supply today the only solution for large scale energy storage is the use of underground geological formations for technical, economical and safety reasons. The storage of only 10 % of the annual hydrogen consumption forecast in GermanHy would result in the need to develop more than 50 salt caverns with a volume of about 500,000 $m^3$ each – corresponding to approximately one third of the number of underground gas caverns currently operated in Germany.

# 3 Storage Options

## 3.1 Comparison of large-scale storage options

### 3.1.1 Technical aspects

Given an average load in the German transmission grid of around 70 GW and a maximum output of all currently operated wind power plants of around 24 GW (62 GW expected in 2050), the storage of electrical energy at grid scale for minute reserve (tertiary control) and above is primarily only possible using pumped hydro schemes, CAES or hydrogen storage plants. Pumped hydro plants have the greatest degree of operational flexibility and comprise highest efficiencies of about 80%, yet providing relatively low volumetric storage densities. Furthermore, the potential to add new plants is limited. Future adiabatic CAES power plants are characterised by slightly lower operational flexibility and efficiency, but with higher yet still comparatively low volumetric storage densities. The potential to build new plants, however, is much higher because of the availability of suitable geological formations for underground storage caverns, in particular in regions with high wind power potential.

The storage options mentioned above are based on the *physical* storage of energy. In the case of hydrogen, storage is based on *chemical* principles, which is associated with much higher volumetric storage densities. The hitherto disadvantage is the much lower electricity-to-electricity conversion efficiency of less than 40% for converting electricity into hydrogen by electrolysis, storage and conversion back to electricity in a gas turbine. However, even despite these efficiency restrictions, hydrogen is the only storage option which enables the storage of much larger volumes of electrical energy. In addition, there is an even larger potential of suitable geological salt formations for hydrogen caverns compared to CAES caverns because hydrogen caverns can be installed at much greater depths. Figure 3-1 shows the preferential areas of application for the different storage options.

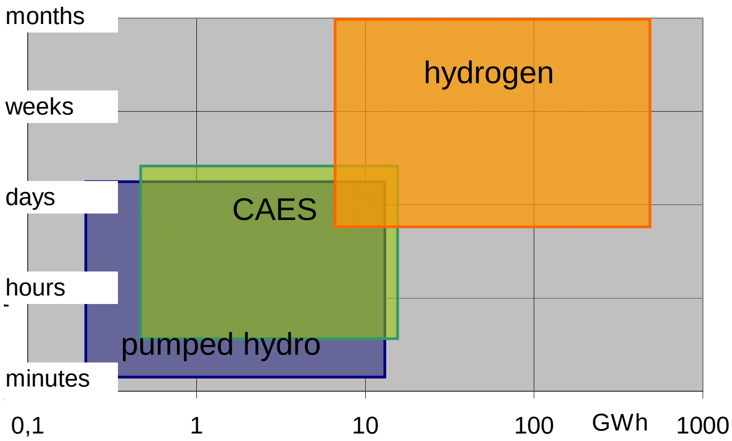


**Figure 3-1: Preferential areas of large scale storage options.**

### 3.1.2 Economic aspects

The VDE ETG study [1] has also quantified the storage costs for the three large-scale storage options: Figure 3-2 displays the results of the two scenarios *load levelling* to balance out short-term fluctuations and *long-term storage* to balance out larger amounts of energy over longer time periods. The parameters applied are power plant output and storage capacities. In the case of short-term storage, pumped hydro and CAES power plants are both associated with similar low costs as compared to hydrogen storage. This is primarily related to the high investment costs for the above ground facilities and the higher operating costs attributable to the lower overall efficiency in case of hydrogen. The situation reverses, however, when considering long-term storage: hydrogen becomes more attractive as a consequence of the dominant costs of long-term storage systems being associated with the number of storage caverns needed. In effect, hydrogen causes much lower storage costs because of its higher storage density reducing the required cavern volume by a factor of about 60.

In conclusion the benefits of hydrogen used as a storage medium for large energy volumes, needed to balance power over long periods, are not associated with technical aspects alone. Hydrogen underground storage also enables much lower costs for storing energy at large scale.

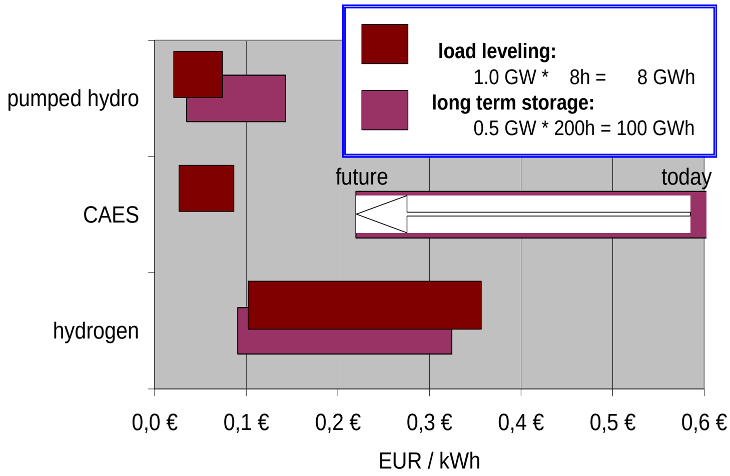


**Figure 3-2: Costs (range) for storing one kWh electric power.**

### 3.2 Options for underground storage of hydrogen

The safe and economic long-term storage of gases – primarily natural gas – in underground geological formations has been standard engineering practise for many decades. The most frequent technique is to use depleted gas fields and natural aquifer formations. Man made caverns in salt formations have gained increasing importance in recent years. Salt caverns are the best option for storing hydrogen because salt is inert with respect to hydrogen – as for natural gas – and is extremely gastight.

The disadvantages of natural reservoirs like depleted fields and particularly aquifer formations for hydrogen storage are possible reactions between hydrogen and micro-organisms, as well as between hydrogen and mineral constituents of the reservoir. Biological or mineralogical reactions of this kind can lead to the deterioration or depletion of the hydrogen storage, or that reaction products can plug the microporous pore spaces.

## 4 Hydrogen Storage in Salt Caverns

### 4.1 Technical parameters

Salt caverns have successfully been used for the storage of gases under high pressure for a long time, see Figure 4-1. The advantages of salt caverns are the extremely high tightness of the salt rock mass, low specific construction costs, and the small footprint required above ground. Typical parameters are 700,000m$^3$ geometrical volume and 20 MPa maximum operating pressure. In Germany about 170 caverns are currently used for the storage of natural gas for seasonal load balancing, shut-down reserve, reserve for extreme weather conditions, and as trading reserve. Interestingly, these major reasons for constructing and operating natural gas storage systems have hardly been discussed so far in the context of a future energy economy primarily based on renewable energy sources.

Despite its high level of fugacity, hydrogen has been successfully stored in salt caverns for decades. A plant with three relatively small single caverns is operated in the UK (Teesside).

Two much larger caverns are in operation in Texas, USA, and a third one is currently under construction. The minor differences to natural gas caverns primarily concern the selection of materials in the access well and the cavern head at the surface.

High pressure gas caverns function by compression and decompression between a minimum and a maximum pressure. The maximum pressure approximately corresponds to 80% of the initial formation pressure at the depth of the cavern roof, whilst the minimum pressure is around 30% of the maximum pressure. If the roof of the cavern is at around 1,000 m depth and the cavern has a geometrical volume of 700,000 $m^3$, the net storage capacity - also known as working gas - will be around 6,000 t. The gas volume remaining in the cavern once the minimum pressure has been reached and therefore not for use, also known as cushion gas, would be around 3,000 t hydrogen in this case.

The maximum acceptable rates for filling and emptying the caverns are governed by the maximum flow rates in the boreholes and the maximum pressure reduction rates in the caverns of 1 MPa/d. As a rule of thumb, maximum withdrawal rates correspond to approximately 10% of the storage capacity per day, with a maximum of 10 turnovers per year.

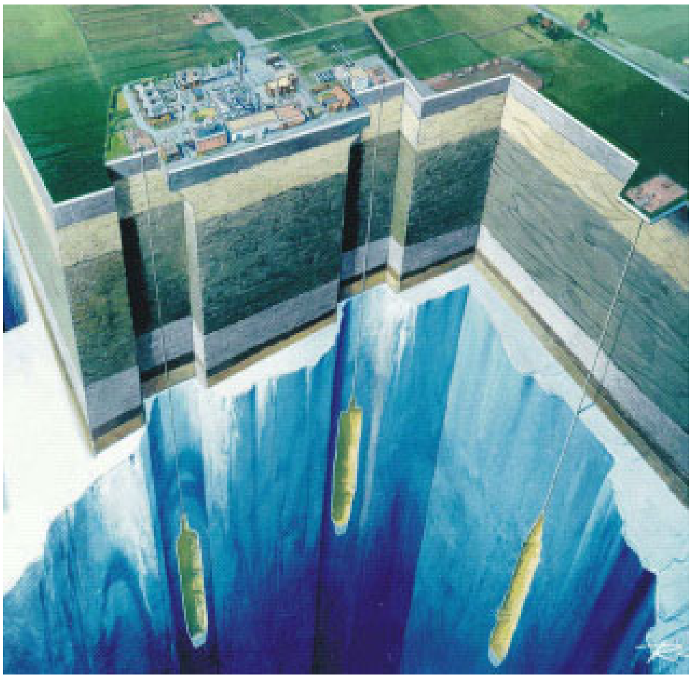

**Figure 4-1: High pressure gas caverns in a salt dome.**

### 4.2 Safety

Underground storage systems provide much higher safety levels than surface technologies do. The “thickness of the walls” in a given cavern is typically several 10 to 100 m, and the operating pressure is always below the encompassing formation pressure which is why a gas cavern can basically never explode. Salt rock is also extremely gas tight with theoretical leakage rates at some 0.01% p.a. The only connection between the cavern and the surface is the access borehole, see Figure 4-1. Several casing strings are cemented into this borehole so that they are completely gas tight. Additionally, a production string is installed which can be replaced if required.

The worst case scenario which can affect the facility is a major damage to the cavern head. To prevent any blow-out, safety shut-off valves are installed in gas caverns about 50 m below the surface. They close automatically if any risk of a blow-out should occur.

### 4.3 Salt formations for constructing storage caverns in Europe

Figure 4-2 shows the – very uneven – distribution of salt formations across Europe, including existing and planned projects for storing fossil fuels. The individual structures can vary considerably with respect to their suitability for developing gas storage caverns. By far the most favourable geological conditions exist in the north-west of Germany and the north-east of the Netherlands. Extended regions in e.g. southern Germany or central France lack either salt formations completely or have unsuitable salt deposits. Another important prerequisite for the construction of caverns is the potential to dispose large quantities of saturated brine in an environment-friendly way produced during solution mining.

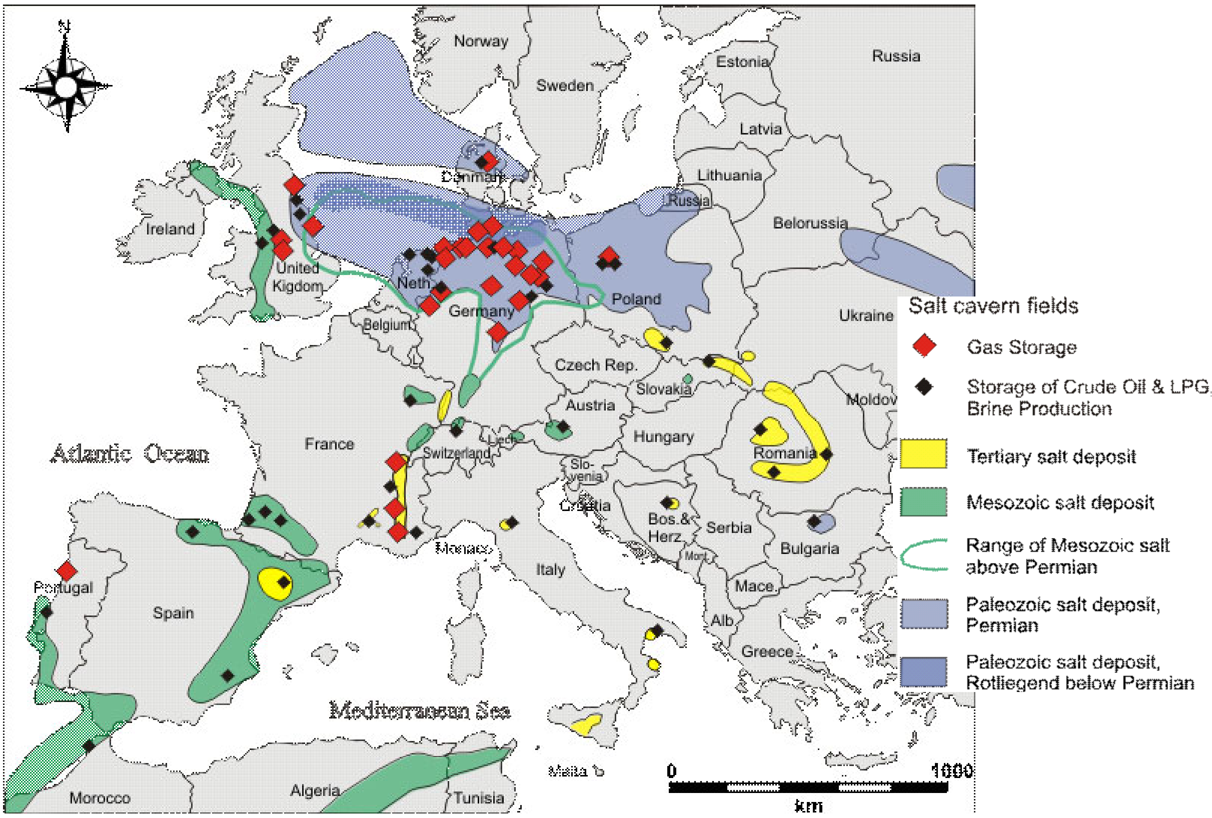


**Figure 4-2: Salt structures and cavern storages in Europe.**

## 5 Outlook

Now that hydrogen's potential role as a transport fuel and for energy storage has become obvious, it is time to improve our understanding of the technical and economic details for the whole pathway. A number of areas should be analysed more closely – specifically as this large-scale technology will need long development lead times.

Examples for further research & development are:

- The dimensioning and economics of surface gas handling equipment for drying, purification, compression or liquefaction
- The systems economy taking into account synergies from dual use (as a transport fuel and for re-electrification)
- The evaluation of regional energy storage potentials
- The future large-scale seasonal energy storage needs in Germany, Europe and the World
- The safety and associated certification issues for underground plants - and to a lesser extent - surface plants.

In preparing for real hydrogen storage applications, the relevant partners should be identified early, and the need for public support for these storage systems for renewable energy has to be addressed if considered important e.g. similar to the feed-in tariffs for renewable energy feed to the electricity grid.

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