Grid Scale Energy Storage in Salt Caverns

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Abstract

Fossil energy sources require some 20% of the annual consumption to be stored to secure emergency cover, cold winter supply, peak shaving, seasonal swing, load management and energy trading. Today the electric power industry benefits from the extreme high energy density of fossil and nuclear fuels. This is one important reason why e.g. the German utilities are able to provide highly reliable grid operation at a electric power storage capacity at their pumped hydro power stations of less then 1 hour (40 GWh) related to the total load in the grid – i.e. only 0,06% compared to 20% for natural gas! Along with the changeover to renewable wind-and to a lesser extent PV-based electricity production this "outsourcing" of storage services to fossil and nuclear fuels will decline. One important way out will be grid scale energy storage in geological formations.

The present discussion, research projects und plans for balancing short term wind and solar power fluctuations focus primarily on the installation of Compressed Air Energy Storages (CAES) if the capacity of existing pumped hydro plants cannot be expanded, e.g. because of environmental issues or lack of suitable topography. Because of their small energy density, these storage options are, however, generally less suitable for balancing for longer term fluctuations in case of larger amounts of excess wind power, wind flaws or even seasonal fluctuations. One important way out are large underground hydrogen storages which provide a much higher energy density because of chemical energy bond. Underground hydrogen storage is state of the art since many years in Great Britain and in the USA for the (petro-) chemical industry.

1 Introduction

Every energy economy, whether based on fossil fuels, nuclear fuel or renewable primary energy sources, requires extensive energy storages at a grid scale to balance out the time-dependent availability of primary energy sources and actual grid load. Despite the enormous investment already made in renewable energy sources, Germany for instance still only has a storage capacity for electrical energy amounting to less than 1 hour's consumption. By comparison, the storage capacities for natural gas and crude oil are sufficient for 2 months. This dramatically illustrates the large future storage demand for electrical energy during the transition from a fossil/nuclear to an electrical power-based energy economy.

Only pumped hydro and underground gas storages are capable of providing the storage capacities at the scale that is forecast. This paper describes and compares the options for the large scale storage of electrical energy, especially in underground geological formations via compressed air and hydrogen; key issues are layout, performance data, state-of-the-art technology and costs.

The published information on the future demand for large scale storages is used as the basis for the discussion here of the options available for each of the potential scenarios from a technical and economic point of view. This is followed by an overview of the geological conditions in Europe specific to the possible construction of underground storages. The final part of the paper discusses how this may be associated with limitations to the realisation of an energy economy based purely on renewable energy sources.

2 Storage demand and resulting storage solutions – current status of the ongoing discussions in Germany

2.1 General

The current discussion about the future demand for energy storages at a grid scale is characterised by major differences in the premises (availability of large or small proportions of conventional energy sources or dispensing with them completely) and the associated large differences in the findings.

The spectrum ranges from a current study by the German transmission grid operators[1], which considers the need for compressed air storage power plants in the near future to be low on the basis of economic considerations and the assumption that fossil and nuclear power plants will be available in the long term; to the work by Greiner, Aarhus University[2], which investigates the enormous demand for storage capacities in case of a future 100% renewable power system scenario for Europe. The following sections of this paper sketch out the typical premises and the associated storage demands.

2.2 Balancing out short-term discrepancies (balancing power)

Assuming that a significant proportion of fossil fuel power plants and possibly also nuclear power plants will remain available even in the long term, temporary shortages in wind power output and PV output can be largely balanced out by the use of these conventional power plants. In this case, additional storage demand mainly focuses on the provision of balancing power, to balance out short-term divergences in wind forecasts in both directions, and to stabilise conventional generation in order to make best use of both fossil as well as renewable generation resources[3]. The appropriate main storage options are the following, which are characterised by their high levels of flexibility: (i) pumped hydro and water storage power plants, (ii) compressed air energy storage (CAES) power plants and (iii) demand side management. Power in-/output is expected to be up to several Gigawatts for up to several hours. Converting large amounts of excess wind power into hydrogen

In the medium term in North Germany in particular, there it becomes apparent that the planned construction of offshore wind farms will give rise to a considerable excess in the generation of wind power. The current excess already leads to the frequent shut-down of wind turbines because of grid bottlenecks – an expensive option because of the high compensation payments then due to the wind farm operators. Even with the necessary expansion of grid capacities, there will still be periods with a major excess in wind power output because of strong winds at times of low grid loads. This excess wind power cannot be fed into the transmission grid: the German state of Schleswig-Holstein bordering on Denmark is expecting excess wind energy in 2020 totalling 4,000 GWh corresponding to 20 % of the offshore wind power[4] generated per year. There are basically three options for using hydrogen generated by excess wind power:

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1 Peter Radgen et.al.: *The Economics of Compressed Air Energy Storage under Various Framework Conditions*; PowerGen Europe 2010, Amsterdam

2 Martin Greiner: *A 100% Renewable Power System for Europe*; Risœ International Energy Conference 2011, Roskilde, Denmark

3 The Boston Consulting Group (BGC): *Revisiting Energy Storage – There is a Business Case*; 2011

4 U.Albrecht: *Wind hydrogen: A module for the future supply of power in North German*; study prepared by Ludwig-Bölkow-Systemtechnik GmbH, Munich, on behalf of the Hydrogen Society Hamburg, the city of Hamburg and the state of Schleswig-Holstein

(i) FEEDING THE HYDROGEN INTO EXISTING NATURAL GAS PIPELINES COMBINED WITH STORAGES: Natural gas pipelines transport large continuous rates of gas. The German gas industry therefore suggests replacing partially fossil fuel (natural gas) with green fuel (hydrogen) in case of need to absorb excess wind power. Studies have shown that 5 to 10% by-volume hydrogen can be mixed into the natural gas without any problems. E.g. the DEUNA pipeline which links Denmark with Germany is designed for a nominal capacity of 430,000 m³/h (V_{st}) corresponding to 4,000 MW; the mixing-in of only 5% hydrogen would correspond to a continuous (!) gross power of around 100 MW or a gross amount of energy equivalent to 876 GWh per year. This highlights the enormous potential of the existing natural gas infrastructure to accommodate excess hydrogen. At E-World 2011, the German Technical & Scientific Association for Gas and Water (DVGW) stated unequivocally that they would support the integration of fluctuating wind power by the option of feeding in green hydrogen into the natural gas distribution grid. Feeding the hydrogen into natural gas pipelines will require large scale storage in salt caverns in order to balance *fluctuating* hydrogen production and the demand for *continuous* injection because of the very rigid specifications for the composition of natural gas.

(ii) MATERIAL USE OF GREEN HYDROGEN: In Germany, 1.8 million tonnes of hydrogen with an energy content of 70 GWh are currently produced every year for the chemical industry: around 50% of this is used for the production of ammoniac as a raw material for fertilisers, while 25% is used by the petrochemical industry. This hydrogen is produced from natural gas, and production is forecast to grow by 10% annually. Major hydrogen consumers are present for instance in the greater Hamburg area. In addition to the above, major carmakers such as Daimler, GM and Volkswagen, are looking intensely at the development of fuel cell powered cars consuming hydrogen. The study mentioned above therefore also looked at the extent to which green hydrogen from excess wind power could be used to supply the future fleet of such vehicles in the greater Hamburg area. Preliminary studies indicated a need of several 500,000 m³ caverns for Northern Germany for the uses stated under (i) and (ii).

(iii) GENERATING ELECTRICITY: This appears actually the most logical option – using the stored hydrogen during demand peaks to generate electricity in combined cycle gas power stations, because with the two options described above, the shortage of renewable power has to be balanced out by conventional fuels. Because of the low overall efficiency achievable today of only 40% (power to power), using hydrogen to generate electricity has so far only played a subordinate role for economic reasons. This option has to compete against the alternative generation of electricity by natural gas, whose proportion has been reduced by mixing in green hydrogen; in this case, generating electricity is no longer restricted to the vicinity of the hydrogen storages or the construction of a hydrogen distribution infrastructure.

2.3 Pure regenerative scenario

In a scenario based exclusively on regenerative sources, the power generators are dominated by wind and PV systems whose availability fluctuates stochastically in a strong way because of the daily cycles as well as the seasonal variations. In the paper by Greiner "*A 100% renewable power system for Europe*" mentioned previously, there is also an estimate of the associated storage demand in Europe required by this scenario; the calculations are based a 60 % wind and 40 % PV power and optimal grid expansion. Assuming wind and PV over-capacity of 50% in order to reduce storage demand, there is a still an enormous storage demand of 35 TWh for an output of 90 GW. The key factor here is balancing out seasonal fluctuations.

Previewing briefly here the discussions in the following chapters, such huge amounts of energy can only be realised in combination with additional pumped hydro storages in Scandinavia and in other parts of Europe, and particularly by a large number of hydrogen storage facilities in salt caverns; a rough estimate results in 400 large caverns compared to some 200 existing gas caverns in Germany today. Alternative storage methods such as

compressed air storages, demand site management, or even batteries can be ignored as completely inadequate solutions in the face of the enormous scale involved.

3 Energy storage in salt caverns

3.1 Large-scale storage options - overview

Only three methods are viable in practise when dealing with storage capacities at scales of GWh to TWh, and power input or output of several 100 MW up to larger GW scales: (i) water reservoirs without pump capacities supplemented by pumped hydro plants, (ii) CAES plants and (iii) hydrogen storage power plants.

PUMPED HYDRO POWER PLANTS are particularly flexible and boast a high efficiency of up to 80%. However, the volumetric storage density is low. In Germany the acceptance of new facilities is limited although there seems to be less resistance in Austria, Switzerland and Scandinavia with the by far largest potential in Europe.

COMPRESSED AIR ENERGY STORAGE POWER PLANTS are much discussed today for future applications because favourable geological conditions exist in the wind-rich areas of the North Sea for the construction of storage caverns in salt formations. The associated environmental impact is low, and investment and operating costs are moderate. The efficiency of future adiabatic facilities could achieve 70%. The volumetric storage density is higher than that of pumped hydro power plants but still low.

HYDROGEN STORAGE POWER PLANTS consist of electrolysers to convert electrical energy into hydrogen, salt caverns including compressor plant to store the gas, and combined cycle gas turbine power plants to generate electricity again. A disadvantage of this option is the low overall efficiency of today <40%; the crucial advantage, however, is the much higher volumetric energy storage density of which is around two orders of magnitude greater.

Fig. 1 compares the volumetric energy densities of the three storage options mentioned above; Fig.2 illustrates some of the typical areas of application of the three storage options referred to above.

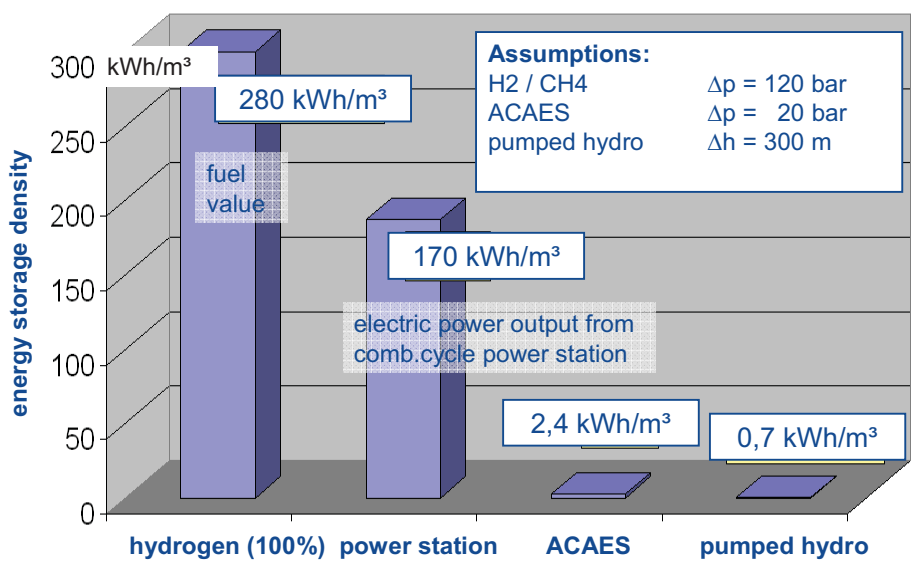

***Fig. 1**: Volumetric energy storage densities*

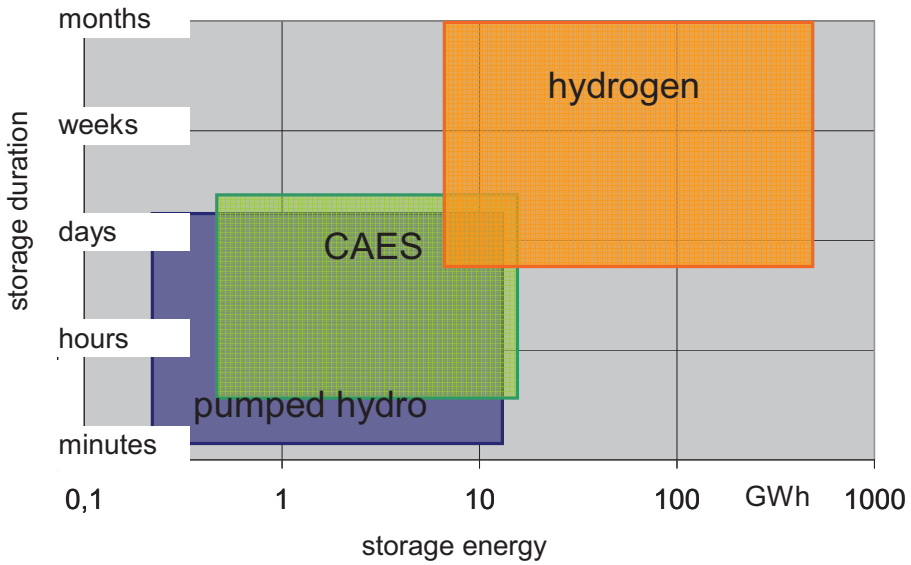

***Fig. 2**: Application ranges for large scale energy storage options*

The below sections focus on the underground storage options.

3.2 Underground storage options – why focus on salt caverns?

The storage of natural gas in depleted oil and gas reservoirs, in aquifer formations or in man-made salt caverns, has been standard practise for many decades. In Germany and in France, over 20% of annual consumption is stored underground. And some 100 new caverns are currently being constructed in Northern Germany. Fig. 3 illustrates the gas storage options in underground geological formations including abandoned mines and hard rock caverns. Natural reservoirs dominate in terms of amount of gas stored underground world-wide. However, the current enlargements in storage capacities in Europe are concentrated on salt caverns because these storages are much more flexible: having much higher injection and withdrawal rates, and the flexibility to handle frequent cycles. The installation of caverns is naturally dependent on the availability of suitable salt formations, as well as the ability to dispose of in an environmentally-compatible way the large volumes of brine produced during the solution mining of the caverns – normally an easy problem to solve when caverns are located close to the North Sea.

Another aspect plays an important role in the selection of suitable storage formations for the storage of air and hydrogen looked at in this paper: after injection of the media, the oxygen in the air or the hydrogen can react with the minerals and the microorganisms present in natural reservoirs. This can result in a loss of oxygen or hydrogen, production of hydrogen sulphide as well as the blockage of the fine pores in the reservoir rocks by the reaction products. To avoid this, caverns are exclusively used as energy storages in those regions which have suitable salt formations available. In the USA, because the regions with large wind resources are often in areas with no suitable salt deposits, the use of pore storages for compressed air and hydrogen are also being analysed. If a means is found of using these formations, it would make considerable additional storage potential available.

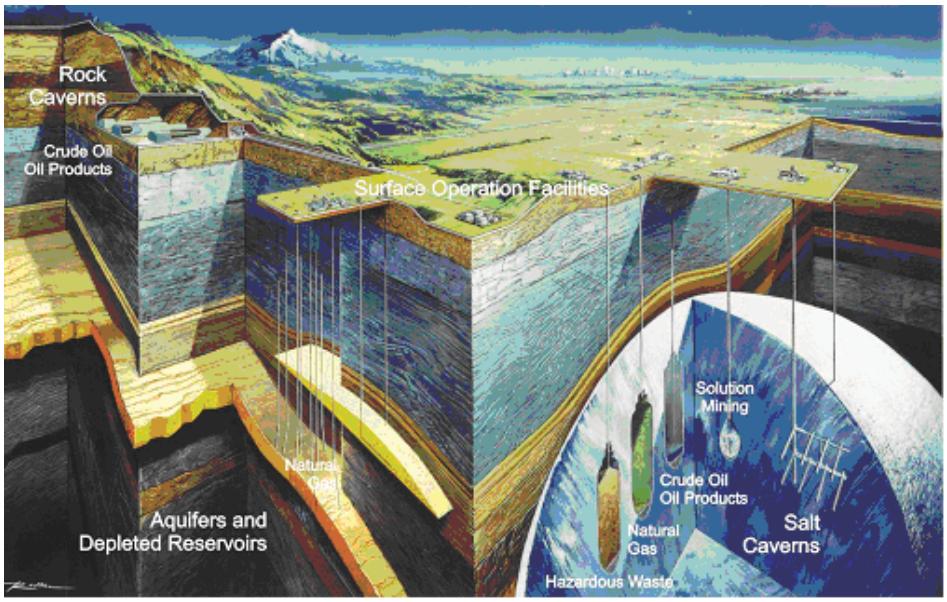

Fig. 3: *Options for underground storage of gases*

3.3 Compressed air energy storage plants

CAES plants have previously been the main focus of discussions when considering the integration of large volumes of wind power into the grid because favourable conditions for the construction of storage caverns exist in the wind-rich areas close to the North Sea. Other reasons include the low environmental impact, moderate investment and operating costs, and the fact that two facilities have already been successfully operated for over 20 years; a 320 MW installation belonging to E.ON KRAFTWERKE in Huntorf, Germany; and a 110 MW facility in McIntosh, Alabama, USA, operated by POWERSOUTH.

The two currently operating *diabatic* facilities do not use the compression heat generated during the compression of the air, which means that natural gas has to be used to heat the air back up during withdrawal from the storage. These CAES power plants are therefore strictly speaking gas turbine power plants with storages rather than a pure storage power plant. The advantage compared to a pure gas turbine power plant is the 40 to 60 % lower consumption of natural gas and the associated emissions of CO_2. The new facilities currently planned in the USA are largely based on the standard components and are much more flexible compared to the two existing plants because of the mechanical decoupling of the compressor side and the turbine side. The efficiency levels are still 42 to 54% depending on the way the waste heat is used.

Research has been carried out for many years in Germany on the *adiabatic* CAES version which also stores and uses the compression heat boosting efficiency to 70 %. However, the development of the various components is very challenging and it will probably take another 10 years before such systems are ready for the market. RWE and GE plan to start a demonstration project in 2016 with an output of 200 MW and storage capacity of 1,000 MWh.

The low volumetric energy storage density of around 3 kWh/m^3 limits the use of this technology to cover very large storage capacities. Installation is also dependent on the availability of suitable salt formations as well as the need to dispose of in an environmentally-compatible way the brine which is generated during the leaching of the caverns; this is not considered to be a problem in the vicinity of the North Sea. Unlike natural gas and hydrogen caverns, CAES caverns can only be constructed within a depth window of 500 to 1,300 m because the operating pressure is directly dependent on the depth, and the power plant components using today's state-of-the-art technology operate

at pressures between 50 to 100 bar. This places an additional constraint on the selection of suitable salt formations. The investment costs range from 550 to 900 EUR/kW[5]

3.4 Hydrogen

The hydrogen option is based on the following components, see Fig. 4: (i) Electrolyser to generate pre-compressed hydrogen and oxygen from water, (ii) storage caverns and (iii) compressor plant to inject the hydrogen into the storage cavern, and later on to withdraw it, reduce the pressure to pipeline pressure.

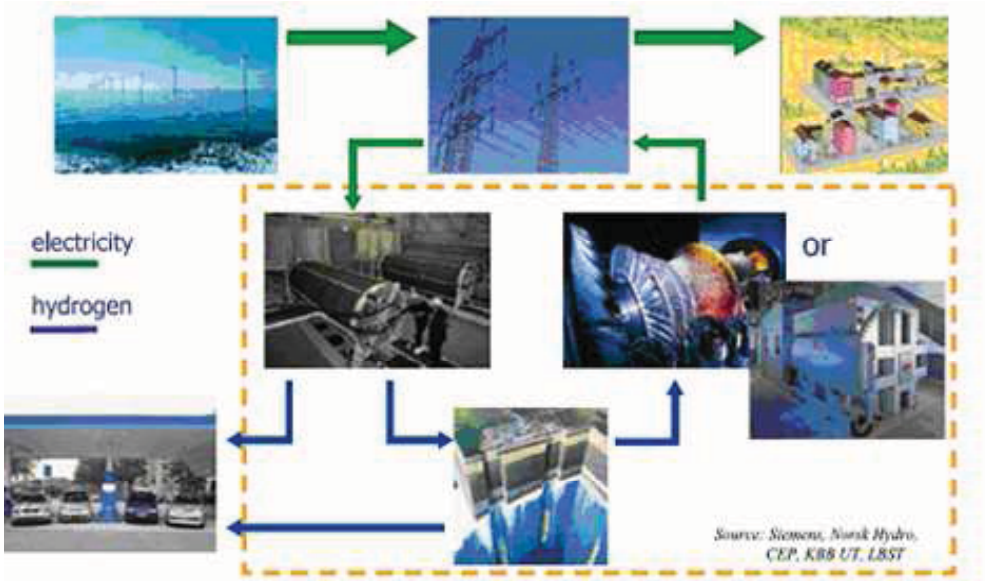

***Fig. 4**: Block diagram of hydrogen storage power plant*

The withdrawn gas may need to be dried because brine residues in the cavern sumps can saturate the gas with water vapour. No other contamination is expected during storage because rock salt does not react with hydrogen.

Practical experience with the storage of hydrogen in caverns has already been gained from an old installation in Teeside, England, and younger facilities in Texas, USA, where a third cavern for the petrochemical industry is currently also being installed. The layout of the caverns largely corresponds to that of modern natural gas caverns, although specific components need to be adapted for future use in Europe in order for them to comply with the latest safety standards such as the installation of special production strings including subsurface safety valves.

Typical dimensions are volumes of 500,000 m^3 with pressure ranges between 60 to 180 bars, which corresponds to a net storage capacity of around 4,200 t or 140 GWh[6]. Practical experience in the USA shows that the losses are negligible at less than 0.1 % p.a.

Because the energy in the hydrogen is chemically bound (just like natural gas), hydrogen caverns can be designed much more flexibly than CAES caverns, and can therefore also adapted better to the local geological conditions. This means that many more salt formations in Europe are potentially suitable for the construction of this type of energy storage than is the case with CAES caverns, as already mentioned above. The CAPEX is according to the *dena Grid Study II* 2,300 to 2,700 EUR/kWh, an estimate with still a major uncertainty.

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5 DENA (German Energy Agency): *dena Grid Study II – Integration of Renewable Energy Sourcesin the German Power Supply System from 2015 – 2020with an Outlook to 2025,* 2011.

6 related to lower heating value

3.5 Geological potential in Europe

Fig. 5 gives an overview of the – very irregular – distribution of salt formations in Europe. The symbols for existing and planned salt cavern projects indicate where formations are present with potential suitability for the construction of future energy storages.

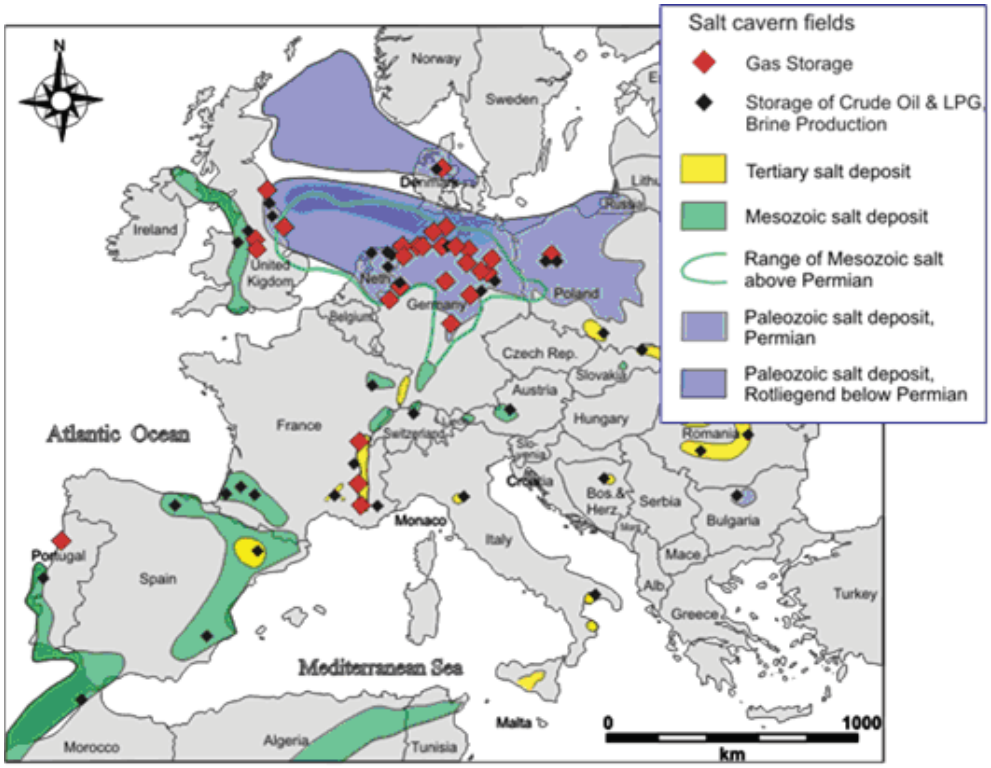

Fig. 5: *Salt formation and cavern projects in Europe*

The map is dominated by the large *Zechstein deposits* (blue colour) which extend from the east coast of England, across the Netherlands, Germany and Denmark, all the way to Poland. This shows that in these countries, and in Central Europe in particular, very favourable conditions exist for the construction of additional storage caverns. The potential in England, however, is restricted to natural gas and hydrogen caverns because the deposits are too deep for the construction of CAES caverns.

The *other salt deposits* younger than the Zechstein have less favourable properties: they are frequently thinner often allowing only smaller cavern volumes, and often have high proportions of insoluble minerals, which means that there are also additional losses in net storage volume. The deposits on the west coast of England are almost completely exploited by natural gas storage caverns – the additional potential is largely only available offshore in the Irish Sea. In France, the salt deposits in question lie at the eastern and the southern edge of the country and are mostly very deep, which will limit construction of CAES caverns. Spain has no gas storage caverns to date even though there is an enormous demand for capacity. This clearly indicates the limited suitability of the salt deposits in this country. Portugal has potential – albeit limited – and one large natural gas storage facility is currently being constructed. According to the information available today, Italy basically has no suitable deposits.

In conclusion, the potential for the construction of energy storages in salt formations is very unevenly distributed and limited. There is a great need to look at the potential in greater detail because otherwise this may give rise to restrictions in the expansion of regenerative energies in Europe; this topic has not attracted a great deal of attention to date.

4 Summary

The transition from fossil and nuclear fuels to regenerative energy sources goes hand-in-hand with a decrease in the importance of the previously dominant role played by conventional energy storage in the form of for example natural gas and crude oil caverns, characterized by the very high volumetric energy storage density. This transition is coupled to an increase in the demand for large-scale energy storages, particularly for fluctuating wind power as well as PV energy.

During the transition period, energy storage will primarily be required to make balance energy available to compensate for divergences in wind power forecasts. Possible options here are pumped hydro storage and CAES power plants, although they are dependent on local topography or geology, and public acceptance.

If the proportion of renewable energies then dominates the energy mix, large volumes of excess wind energy will be generated over longer periods of time which can no longer be stored in pumped hydro and CAES plants for technical and economic reasons. This scenario is behind the current considerations in Germany of converting the excess energy into hydrogen and using this hydrogen mainly for the chemical industry, for powering future fuel cell vehicles, and for replacement of natural gas by green hydrogen.

An energy economy based *purely* on regenerative energy sources will have a very high demand for energy storages, mainly to compensate for the seasonal fluctuations in power generation. Even a rough estimate of the storage capacities involved show that this scenario could only be realised by constructing a enormous number of hydrogen storages in underground geological formations, which then leads to the next question of whether there is adequate geological potential to satisfy this demand. A solution might be to maintain a certain natural gas reserve – even in an - almost complete renewable energy based world.