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Notes

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Abstract: To utilize the full potential of hydrogen energy in the UK a number of economic, technical and environmental factors must be considered. An important factor in replacing fossil fuels with hydrogen will be the practicality of storing a sufficient quantity to smooth out fluctuations in demand and provide a strategic reserve. This paper investigates the potential for large-scale underground hydrogen storage in the UK by considering the technical, geological and physical issues of storage, the locations of salt deposits, legal and economic aspects. In addition, reference is made to the equations of state applicable to this type of storage. The results of this investigation show that the UK has a number of potential locations where underground storage would provide a strategic reserve of hydrogen.

Diminishing fossil fuel reserves and energy security concerns are driving the UK towards a diverse energy mix, which may include hydrogen as a secondary energy carrier (DTI 2003). If hydrogen is adopted, a degree of buffering will be a required to meet peak demand on a daily, monthly and yearly basis (DTI 2004). A number of end uses are foreseen as potential hydrogen consumers, these include: energy islands, combined heat and power, and personal mobility (cars, buses, etc). The level of hydrogen acceptance/integration is dependant on future social and political developments. A high level of hydrogen acceptance would require an even greater degree of energy buffering, thus large-scale hydrogen storage would be essential.

This paper investigates the potential for large-scale underground hydrogen storage in the UK by evaluating logistical, technical, legal and economic issues. First a review of published literature is provided, starting from the 1st World Hydrogen Energy Conference in 1976 through to a conference on underground gas storage organized by the British Geological Survey (BGS) in 2004. Elements of this paper were previously presented at the International Hydrogen Energy Congress & Exhibition 13–15 July 2005 in Istanbul, Turkey. This paper goes on to highlight the differences in geological aspects of pore storage in naturally occurring structures and man-made caverns. Issues about hydrogen purity on extraction and transportation to and from the underground store are also discussed and common equations used in modelling large-scale underground gas storage are identified. Finally, the UK planning process, social acceptance to underground gas storage and economic aspects of setting up and maintaining this form of storage are introduced.

Background

Hydrogen storage in underground structures such as fossil fuel reserves, water aquifers and salt caverns is not a new concept. Natural gas, for example, has been stored in depleted oil wells since the early 1900s (Katz & Tek 1981). Current advances in borehole and drilling technology and an improved knowledge of rock salt mechanics have made underground gas storage a viable alternative to liquid storage. An initial assessment into the potential for underground storage of CO_2 in UK onshore aquifers has also been undertaken (Holloway & Savage 1993).

At the 1st World Hydrogen Energy Conference a technical and environmental comparison between underground hydrogen storage and existing natural gas storage in naturally formed structures (pore storage: depleted oil/gas field and aquifer scenarios) was presented (Walters 1976). The main conclusion was that there are 'no insurmountable or environmental problems' in using underground hydrogen storage. Carden & Patterson (1979) continuing the work of Walters investigated the losses associated with underground hydrogen storage in any type of structure, with two types

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defined: 'once-only losses' and 'operating losses'. 'Once-only losses' are concerned with potential lost revenue by cushion gas, trapped gas and diffusion leakages. A cushion gas is needed to apply a residual pressure to the storage volume and in turn drive the expansion and extraction process of the storage facility. The volume of cushion gas required is in the order of one third of the total storage volume (Carden & Patterson 1979). In addition to the once-only cushion gas, hydrogen stored within a reservoir rock or formation may also become trapped in, by-passed pores and dead-end pores. The final 'once-only loss' is the saturating of connate water within the reservoir rock, which may be as much as 0.4% for the first cycle (Carden & Patterson 1979). It is likely that the connate water could be trapped in by-passed pores and open pores (Carden & Patterson 1979). Mechanical pumping, friction within the borehole and borehole pressure drop contribute to the 'operating loss', which may be equal up to 1% per cycle (Carden & Patterson 1979).

Lindblom (1985) proposed the use of a 300 million cubic metres (mcm $= \times 10^6$ m^3) network of man-made tunnels for bulk underground hydrogen storage. The proposed network would be mined in a suitable hard rock that is able to withstand above-ambient hydrostatic pressures. The types of rock are not discussed; however, Lindblom (1985) assumes that a water curtain will be used. A water curtain is the saturation of rock above the tunnel to fill micro-cracks in the rock structure and prevent stored product (e.g. hydrogen) diffusing vertically from the storage chamber. Such a containment method is employed in the storage of LPG (propane) in Chalk caverns *c*. 180 m below ground level at Killingholme, North Lincolnshire (Trotter *et al.* 1985; Geological Society 1985). Lindblom's research indicated that bulk hydrogen storage is economical in such a scenario, with the cost estimated at $3.5 to $5.8 per thousand cubic feet (28.32 m^3) in 1985.

A comprehensive techno-economic evaluation of five bulk hydrogen storage scenarios has been published (Taylor *et al.* 1986), with three of the five scenarios investigated concerned with underground storage in salt caverns, rock caverns and depleted natural gas fields. Each underground storage method assessed reached an important conclusion. Man-made salt caverns are found to be the lowest cost method even with the high cost of cavern construction. Rock cavern storage is more expensive due to a higher mining cost, although this cost does not take into account the possible sale price of excavated rock. As for the depleted natural gas field, significant cost is attributed to the initial cushion gas volume as the pore storage exceed 1×10^9 m^3 of gas at normal temperature and pressure (NTP = 293K @ 0.1 MPa).

South Korea makes significant use of underground energy storage facilities for fossil fuels including liquefied petroleum gas (Lee & Song 2003). Lee & Song (2003) also provide insight into underground pumped water storage plants using similar technology, construction methods and the finite element modelling techniques involved in cavern network design.

Schaber *et al.* (2004) identified an interesting comparison between underground hydrogen storage and high-pressure above ground storage. The pressure of underground storage is limited by the strength characteristics of the containing rock or salt formations. The reduced pressure of underground storage, typically a third to half that of above ground storage, aids the overall conversion efficiency of the storage system, as less energy is required for compression of the gas. Although this efficiency increase may be only 2%, because of the size of the bulk storage facility, the actual value of energy reduction represented by this efficiency increase is considerable.

Under Framework 6 of EU funding, the BGS is conducting an investigation into CO_2 sequestration and storage in underground structures/sites, onshore UK, such as those discussed in Holloway (2005). Considerable synergy exists between this work relating to hydrogen storage and that of BGS in the identification of sites and legal aspects. Summaries of the present locations of oil and gas fields and salt basins in the onshore areas of the UK are provided by BGS (2006*a*, *b*) and Evans & Holloway (2009).

Estimating demand and storage requirements

Gauging the potential size of hydrogen storage is somewhat speculative and is dependant upon acceptance and integration of technologies. For a first order approximation the seasonal demand of transport fuel can be used. The volume of underground hydrogen storage needed was determined by the seasonal difference and equated on an energy basis. A hydrogen storage volume of 1930 Million m^3 at NTP was calculated using quarterly transport fuel demand for 2005/06 from the Office of National Statistics (ONS 2006). Such a single volume could not be stored in one structure but a number would be needed in different locations around the UK to minimize any distribution network of the gas. Naturally occurring structures such as, depleted gas and oil wells, and also man-made caverns in rock salt are seen as potential storage volumes.

Underground storage scenarios

Underground storage facilities would allow large volumes of hydrogen gas to be stored without the environmental impact of surface built structures. There are two main types of underground facility applicable to hydrogen storage. These are the use of pore storage (generally in naturally formed structures such as depleted oil and gas fields, and water aquifers) and man-made structures such as salt mines and salt caverns. The physical characteristics of each underground structure type have a bearing on how it may be used for hydrogen storage. In addition, the location of potential salt caverns, in respect to current transport infrastructure, must also be considered for distribution.

The following sections outline the main concepts of the differing storage scenarios or facility types, which are dealt with in more detail in Platt (2009).

Pore storage

Storage volume for hydrogen in the UK could be provided by the pore space (small voids between the constituent grains of sedimentary rocks) in the reservoir rocks in both depleted oil and/or gas fields and water-bearing aquifers. Storage in aquifers follows the same principal as in oil and/or gas fields: a porous rock structure with an impermeable caprock (Fig. 1).

Concerns exist regarding the use of pore storage facilities, as geological faults may allow migration of the stored gas (Evans 2009; Miyazaki 2009). If gas were to leak from the oil/gas reservoir or aquifer, then the safety of the local area maybe compromised and it would have a detrimental effect on public perception of underground gas storage. Hydrogen has a smaller molecular size than that of natural gas (≈ 80% methane) and it may therefore leak from the storage reservoir more readily and rapidly than natural gas. However, given that the diffusion rate of hydrogen in air at NTP is 4.4 times greater than methane it would diffuse more rapidly than natural gas (Lindblom 1985). Consequently, additional constraints on pore storage scenarios must be considered, including location to nature faults and mined structures.

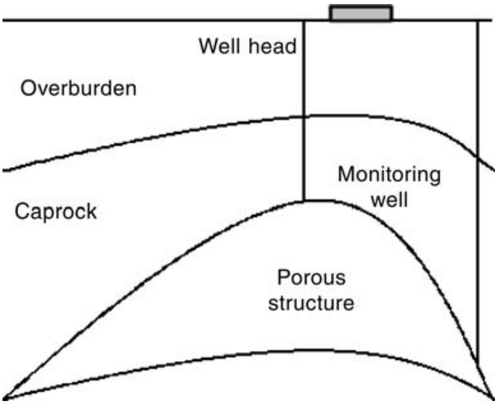

Fig. 1. Depleted oil/gas reservoir or aquifer storage facility.

Man-made structures

Rock salt (halite) is commonly found in two forms: bedded (thin flat layer deposit) and secondly, halokinetic structures where salt has moved (risen) to form salt pillows and domes. Caverns can be formed in both salt dome structures and bedded salt by solution mining; however, if the bedded layer is thin (60–100 m), as it is in some areas of the UK, horizontal-drilling techniques are required (Favert 2003). Solution mining involves a carefully controlled process of pumping water into a well drilled into the salt body, which dissolves to form a cavern (Fig. 2). Salt caverns may range in size, depending on the local geological constraints, between 30 000 m^3 to 1 mcm (Plaat 2009). An increase in cavern volume from ≈75 000 m^3 to ≈500 000 m^3 reduces the total investment cost by a factor of 1.5 to 2 (Chabrelie *et al.* 1998). Even larger caverns, >600 000 m^3, have been mined in salt domes in Germany (Plaat 2004, 2009). In the UK there are no known salt domes in the onshore salt basins with the result that man-made solution-mined structures are restricted to caverns constructed in bedded salt only. However, halokinetic structures are present offshore in the Southern North Sea and could hold future potential (Smith *et al.* 2005).

The operational economics of an underground hydrogen storage cavern is further aided by reducing minimum operating pressure and thus the volume of cushion gas, whilst increasing the maximum operating pressure. If the minimum operating pressure is reduced too far the salt cavern will decrease in volume due to creep of the enclosing salt; (Chabrelie *et al.* 1998). By increasing the maximum operating pressure additional hydrogen is stored improving the cycle efficiency. The maximum operating pressure is limited by rock salt permeability, rock strength and depth of cavern. With its smaller molecule size, than natural gas, the diffusion of hydrogen through rock salt is not foreseen as being any different to the larger molecules. Typical maximum operating pressure ranges from 0.019 MPa to 0.021 MPa per metre in depth of overburden (Chabrelie *et al.* 1998).

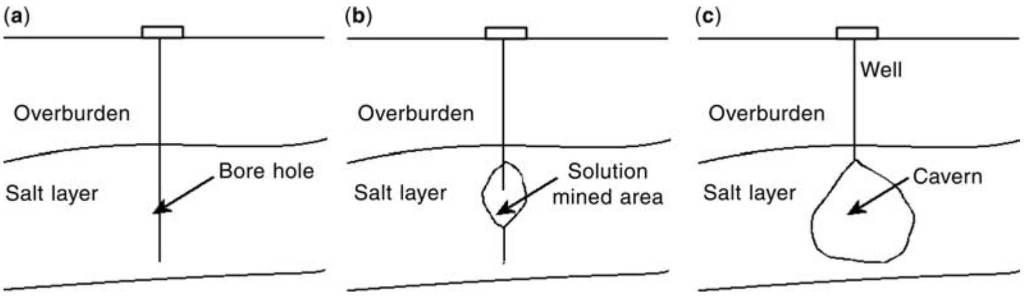

Fig. 2. Construction of a salt cavern storage facility. (**a**) initial borehole (**b**) solution mining and cavern formation in process (**c**) final solution-mined cavern.

A disadvantage of using the solution mining process to construct salt caverns is the brine solution waste product, with approximately eight times the final storage volume of brine is produced when using this mining process (Chabrelie *et al.* 1998). For this reason sites close to the coastline may be preferable as the brine could be pumped out to and disposed of at sea. Road transportation is a possibility for caverns located inland, but additional transportation costs would increase capital investment. The time taken to produce a salt cavern is approximately one to three years depending on techniques used and cavern size. The final installation must be designed to/and meet the relevant requirements of the British Standard EN 1918-3 (BSI 1998).

Existing and future underground storage locations

There are already twenty-seven salt caverns being used for natural gas or hydrogen storage in the UK with three more storing nitrogen (Evans & Holloway 2009). These are located in Cheshire, Stafford, Yorkshire and on Teesside (Fig. 3). A further 79 and 83 natural gas storage salt caverns are planned, but planning permission has not yet been granted for these sites (Evans & Holloway 2009). A map of the UK highlights areas of rock salt deposits; however, studies elsewhere suggest that not all will prove suitable for underground natural gas or hydrogen storage (Evans & Holloway 2009).

In locations where the salt layer has a thickness of 60–100 metres it is debatable whether a vertically-mined salt cavern could be used to store the required volume of hydrogen, although this would be influenced by the depth of the salt body: greater depths would permit higher storage pressures and thus greater volumes of hydrogen. In such locations horizontal drilling with solution mining techniques or a collection of smaller vertical solution-mined caverns could be interconnected. Horizontal drilling was developed in the oil and gas industry and although this technology is not extensively used in the production of salt caverns, is increasingly being used (Beutel & Black 2005). Figure 4 shows the horizontal drill (Well A) and the wellhead used for access to the hydrogen (Well B).

Fig. 3. Map of UK showing existing, planned and potential locations of salt cavern hydrogen storage (Sources: Beutel & Black 2005; BGS 2006*a*) and main roads.

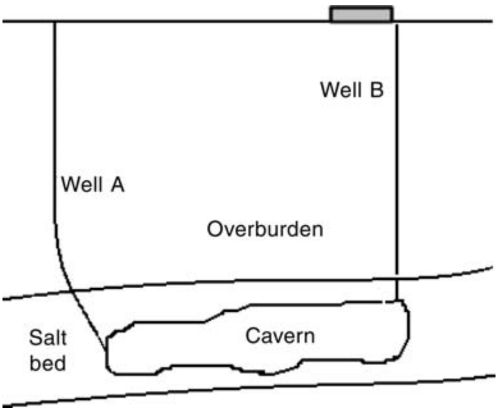

Fig. 4. Horizontal solution mined salt cavern (not to scale).

Hydrogen purity on extraction from store

Hydrogen has a strong chemical affinity to combine with other elements, hence the reason it is not found as a free element in nature. It is here assumed that elements will combine with the hydrogen, especially if depleted oil reservoirs are utilized and which might contain hydrogen sulphide (H_2S) gas. Consequently, when hydrogen is extracted from storage, some secondary processing to remove impurities might be required. Processing will be necessary if the hydrogen gas is intended for membrane fuel cells and/or solid-state hydrogen storage, as sulphur-based gases can poison these devices decreasing their efficiencies (Carrette *et al.* 2001). However, if the end application for the hydrogen is combustion in engines or turbines a limited amount of impurities might not be a concern at this point.

Two common hydrogen purification technologies are Pressure Swing Absorption (PSA) and Membrane Separation, both of which use partial pressure difference as the driving force for impurity removal (Peramanu *et al.* 1999). PSA purifies the hydrogen gas by absorbing the impurities on to a substrate, such as activated carbon, and then pressurizes the system to retain the impurity as hydrogen is released. A series of PSA devices work in unison to yield a constant exit stream of high purity Hydrogen (99%+), depending on tail gas pressure. The remaining impurities are extracted at lower pressures and recycled as feed gas for a Steam Methane Reformer (SMR), or in the case of underground storage it could be injected into the wellhead to offset cushion gas volume. In simple terms, Membrane Separation, works by the introduction of a filter that allows hydrogen gas to pass through while retaining impurities. Hydrogen, on the low-pressure side of the system is then ready for use (90–95% purity), and the impurities are recycled. As in the case of membrane fuel cells, sulphur produced must be removed from the gas stream before coming into contact with the separation membrane (Peramanu *et al.* 1999).

Hydrogen transport to and from store

There are two foreseeable mechanisms for transporting the hydrogen to and from the underground storage. First, the hydrogen could be delivered still combined with another element as in water or natural gas and then be split to yield pure hydrogen gas. This assumes that there is a co-located electrolyser or SMR. Secondly, the hydrogen might be produced at an off-site location by renewable means and then piped to the underground store. However, hydrogen pipelines are not expected until there is >10% penetration of the energy market, based on the economics of distribution (Ogden 2004).

Similar scenarios can be imagined for the withdrawal and export of hydrogen from the underground store. As gas, the transport efficiency of hydrogen by road is poor with a 40 000 kg lorry only transporting 300 kg (Ogden 2004). This gives rise to the requirement for liquid hydrogen transport technologies. However, the energy penalty of hydrogen liquefaction is considerable (Syed *et al.* 1998). At present it is not possible to say which of these options will be preferred, being ultimately dependant on the end applications being served at the time and the economics thereof.

Governing equations of cavern modelling

Once the natural fossil fuel reserve has been depleted or the salt cavern has been constructed, it must be backfilled with hydrogen. There may be residual gas/oil and/or saline water in the reservoir/cavern and this has implications for the diffusion of the hydrogen storage gas with this residue. The aim of this section is to identify the governing equations used for modelling of underground gas storage. The section starts with the ideal gas law and then works towards the quadratic equations of state for complex gas mixtures. Furthermore, system losses are considered in the form of diffusion and pipe conductance.

Equations of state (EOS)

The ideal gas law, equation (1), is the simplest approach to take when considering the physical behaviour of a stored gas. The law shows a close correlation with real behaviour of hydrogen at pressures up to about 12 MPa (Lindblom 1985). By the time a pressure of 35 MPa is reached the deviation is 15%

(Lindblom 1985), highlighting that the ideal gas law is applicable for low-pressure storage only.

$$PV = m\mathrm{R}T \qquad (1)$$

(m, mass (kg); P, pressure (Pa); R, gas constant (kJ (kg K)$^{-1}$); T, temperature (K); V volume (m^3)).

As identified, the ideal gas law is applicable to low pressure hydrogen storage; however, at increased pressures and/or for multi-gas mixtures a more complicated EOS is needed. For such systems cubic equations of state are commonly applied; the two most common are Peng-Robinson (PR) and Soave-Redlich-Kwong (SRK) (Sorensen *et al.* 2002).

The mixing of hydrogen with cavern residues such as hydrocarbons, water (brine) and sodium chloride result in mathematically complex systems. Gregorowicz *et al.* (1996) applied the PR equation of state to analyse a salt cavern used for natural gas storage. The PR equation may also be applied to hydrogen storage. Complexity is further increased by the introduction of time dependency and gas interaction at a molecular level. Since the aim of this paper is to illustrate the concept of hydrogen underground storage, a detailed numerical analysis is not essential; the ideal gas law will be used in the interest of clarity.

System losses equations

Depending on the method of storage being used, depleted field/aquifer or salt cavern, different losses are incurred. If a porous structure is used, the limiting flow rate of gas through the structure is modelled by Darcy's law (equation (2); Carden & Patterson 1979).

$$q = \frac{k\rho}{\mu}\nabla\left(\frac{p}{\rho} + gz\right) \qquad (2)$$

(g, standard gravitational acceleration (m s^{-2}); k, permeability (m s^{-1}); q, volume flow rate (m^3 s^{-1}); ρ, density (kgm^{-3}); μ, viscosity (Nsm^{-2}); ∇, Laplacian operator; z, static head from reference plane).

A significant quantity of hydrogen may be lost by diffusion either into the surrounding rock or the naturally moving groundwater. Equation (3) identifies the diffusion rate (Carden & Patterson 1979):

$$\frac{\partial c}{\partial t} = D\nabla^2 c \qquad (3)$$

(c, concentration (0 to 1); d, diameter (m); D, diffusivity (m^2 s^{-1})).

In all underground storage applications the conductance losses of the pipe between the storage horizon/cavern and surface will limit the rate of gas extraction. Equation (4) implies that the rock salt cavern should be as close to the surface as possible to limit the losses due to pipe length l; the diameter of the pipe d should be as large as possible and the pressure differential ∇p should be minimized to achieve the maximum extraction rate (Carden & Patterson 1979).

$$\nabla p = \frac{8}{\pi^2} f \frac{l}{d^5}\rho Q^2 \qquad (4)$$

(f, friction factor (dimensionless); l, length (m))

Legal, social and economic aspects

In addition to the technical hurdles to be overcome there are the legal, social and economic aspects of storing hydrogen to be considered. For example the planning process for constructing a solution-mined cavern is complex. A brief outline of the UK planning process is discussed in this section. Social resistance to underground gas storage is already apparent in the UK despite being regarded by industry and academic groups as having a good health, safety and environmental record (e.g. Lippmann & Benson 2003; Imbus & Christopher 2005). Finally, there are economic elements to discuss from planning application to operation and maintenance.

Legal aspects

The planning system within the UK has three tiers: national, regional and local government. The national tier is dictated by Government policy. In response to the national tier, a Regional Planning Body sets out a Spatial Strategy for a ten to fifteen year period. The expected needs of land development are identified in the Spatial Strategy and should conform to national policies. At the local level, a development framework is produced, which will include a development scheme, development documents and a statement of community involvement. It is these development documents that are used to produce the Development Plan Documents (DPD), which reflect the national, regional and local needs. DPD are then the starting point for the consideration of any planning application (ODPM 2005*a*). Consequently, in the UK, the planning process of constructing a salt cavern is initially handled at a local level.

Once the application is submitted to the local council they consult their DPD and decide the next course of action. ODPM (2005*b*) states that if more than 25 tonnes of flammable gas is being stored then a 'hazardous consent' must be given by the Health and Safety Commission (HSC). In addition to the HSC becoming involved, an

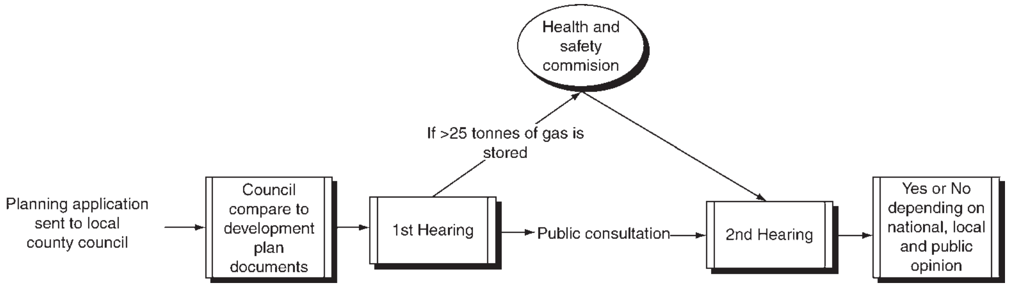

Fig. 5. Flow chart of planning procedure with loops for public consultation.

Environmental Impact Assessment may be necessary depending on the change of land use. Concurrent to these activities it is conventional that an open meeting is held for the public to view the proposal. A 21-day period is then given for public consultation when comments are received. On completion of this statutory period of public consultation, a second open meeting is held where concerns are discussed. If the application is deemed to be too complicated for a local council to evaluate, or it meets with one of five criteria stated in ODPM (2005*a*), the Secretary of State has the right to intervene and decide on the application.

The planning process within the UK is complex and it is beyond the scope of this paper to detail the process for a full range of applications. A planning process flowchart is shown in Figure 5.

Social aspects

The social implication of using existing or manufactured underground storage structures is of high importance to any particular local community. Within the UK, there is a strong collective thought amongst the public that such a scheme is acceptable unless it affects their locality. This is described as a NIMBY (not in my back yard) attitude or more appropriately in the case of underground storage a NUMBY (not under my back yard) attitude! This has already resulted in the formation of an action group to stop underground natural gas storage caverns being developed in Thornton, Yorkshire; where 20 natural gas storage caverns are pending approval (Beutel & Black 2005). Their concerns are based upon the examples where natural gas has leaked from underground storage areas (e.g. Evans 2009; Miyazaki 2009).

Economics aspects

As already stated in the section entitled ‘Man-made structures’, a cavern may take a year or more to mine, which accounts for 25–35% of the total initial investment (Beutel & Black 2005). With any gas storage method a cushion gas is needed initially to pressurize the cavern. As hydrogen gas is an expensive commodity, the initial cost of the hydrogen cushion gas can be significant. However, as the cavern is repeatedly cycled the initial cushion gas cost is reduced (Fig. 6). With regard to the volume of cushion gas and its cost, the estimates vary between sources, with a volume of one third of the cushion gas estimated (Walters 1976), although this value was reduced to one fifth by Amos (1998). More recent measures of the required cushion gas volume are higher, at 1.5 times total volume for a porous structure and half of the total volume for a salt cavern (Plaat 2009).

The cost of cushion gas can be reduced further by minimizing working pressure. Favret (2003) states that a 1 MPa reduction in minimum pressure results in a saving of 10–15% by reducing cushion gas volume and increasing working capacity. There are also running costs to consider. Venter & Pucher (1997) investigated the economics of bulk hydrogen storage in salt caverns, depleted natural gas reservoirs and liquid vessels. They derived a

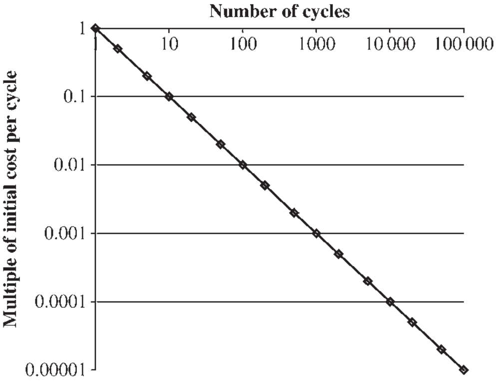

Fig. 6. Depreciation of initial cushion gas cost (log-log scale).

function that determines the cost of hydrogen storage in dollars per year (equation (5)). On applying the cost function to the three methods on a biweekly, monthly and seasonal basis, it was concluded that there is little difference in the overall running costs for mined salt caverns and depleted natural gas reservoirs.

$$(\text{STC} \times \text{P}) + (\text{SRC} \times \text{C}) + (\text{EC} \times \text{SER} \times \text{A}) \quad (5)$$

($ per year; STC, specific transfer equipment costs; P, charging power; SRC, specific reservoir equipment costs; C, reservoir storage capacity; EC, electricity cost; SER, specific energy requirements; A, annual hydrogen input)

The additional cost of secondary processing for extracted hydrogen is to remove impurities. Different technologies for this purpose have been investigated (Peramanu *et al.* 1999), but the final operating cost will only increase by the additional compressor power, which if designed correctly should have little influence.

Summary and conclusions

Primary energy in the UK is anticipated to change from a fossil fuel base to a diverse energy mix that may include hydrogen as an energy buffer. The strategic location of hydrogen buffering is of the utmost importance to ensure a uniform supply over the UK. This paper highlights that depleted oil/gas fields and aquifers are greater in size than most solution-mined caverns and offer favourable volumes when considering the amount of hydrogen to be stored. However, the structural integrity of pore storage sites does not bode well for the storage of gaseous and highly mobile hydrogen. The interaction between highly mobile hydrogen molecules and the pore spaces, caprock and natural faults also needs further investigation.

Consequently, solution-mined salt caverns are identified as the most likely method of storing gaseous hydrogen for energy buffering. Salt reserves within the UK are shown along the current main road infrastructure; however, studies elsewhere suggest that not all salt caverns will prove suitable for underground natural gas or hydrogen storage. The mining cost of a salt cavern is considerable as the process may take a year or more. With advancement in rock salt knowledge, the upper and lower working pressures may be optimized to maximize storage capacity and minimize creep (e.g. Thoms & Gehle 2000; Bérest *et al.* 2001; Bérest & Brouard 2003; Lux 2009).

With no salt reserves in the south central and SE regions of the UK there is the need for another substantial storage method, for example liquid hydrogen. Additional demand in these areas is likely to be driven by personal mobility.

If residual chemical elements are present, within the pore storage/cavern, impurities could be formed and some level of secondary purifying would be needed, especially for membrane fuel cell applications. PSA devices are highlighted as the primary technology for removing these impurities. At a low level of hydrogen penetration into the energy market (<1%), the most economical form of transportation of the hydrogen gas to and from the storage site is likely to be by road (Ogden 2004). Whereas, with a higher penetration into the energy market (>10%), pipelines become the economic option (Ogden 2004). In between these penetration levels a combination of these two methods and liquid hydrogen road transportation would be needed. The final mix of transportation methods would be dependent on many external influences, including factors such as delivery rate and distance from the underground storage. An exact method of transportation to and from the underground store cannot be defined as it will change with the level of hydrogen penetration.

The governing equations for modelling underground storage show that the ideal gas law is suitable for low pressure reserves; however, for increased pressure applications quadratic EOS are needed for accuracy. Complexity of modelling is also increased when using depleted oil/gas reservoirs as the extraction rate is governed by the rock permeability and hydrocarbon residue will mix with the hydrogen being stored.

The legal and planning framework in the UK is complicated. There are already action groups in the UK protesting against the construction of underground natural gas storage caverns in Yorkshire and during a lengthy Public Inquiry into the proposed salt cavern storage facility at Preesall in Lancashire. Even if the political will exists, there may be resistance from UK residents, and similar protests might be expected against proposed underground hydrogen stores.

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