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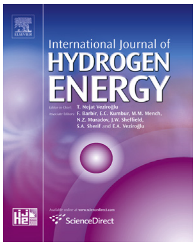

Seasonal storage of hydrogen in a depleted natural gas reservoir

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A B S T R A C T

Hydrogen storage in a depleted gas reservoir or in an aquifer offers the potential for the seasonal storage of inherently variable renewable energy, by the electrolysis of water during periods of excess energy production. Here we investigate whether such storage is technically feasible.

We compared the respective capacities and deliverabilities of hydrogen to established natural gas in a seasonal storage facility, on the basis of an estimated total volumetric capacity of 48 MMm^3, delivery pressures between 5 and 10 MPa and emptying period of 120 days for the Rough Gas Storage Facility (UK). For the modelled scenario, an average power in the order of 4–5 GW would be required during a six month injection cycle to fill the reservoir to capacity. The equivalent hydrogen facility could store and supply 42% of the energy capacity supplied by its natural gas counterpart, and for an emptying period of 120 days could deliver power at an average rate of approximately 100 GWh/day, or ca. 40% of the energy deliverability of natural gas.

There appears to be no insurmountable technical barrier to the storage of hydrogen in a depleted gas reservoir. Hydrogen losses from dissolution and diffusion could be reduced to less than 0.1%. Losses from biological conversion of residual CO_2 were limited even with calcium carbonate dissolution. However, the biological reduction of sulphur minerals to hydrogen sulphide remained a potential problem.

Introduction

The deployment of renewable energies on a scale required for decarbonisation of the energy systems will impose seasonal variations on the supply over which operators will have no control. For example, in the Scandinavian and Baltic area, the monthly average wind speed at a given time of year can vary by more than 20% from one year to the next at one given location [1]. The variability of annual mean values for wind speed were also found to vary between 3 and 7% depending on the site, which led to estimated variations of between 8 and 18% for the energy output from wind turbines at these locations [1]. In this context, large scale, 'seasonal' storage could be very helpful to alleviate shortfall of energy outputs during certain weeks, months or even perhaps in a lean year.

Hydrogen is one option which combines versatility of applications (power, heat, transport and chemical

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feedstock) with a high density of stored energy suitable for long term storage. Currently, it is mostly produced by reforming of natural gas with an energy efficiency of 65–85% [2]. However, it can also be produced directly from renewable power by electrolysis of water, which is the splitting of water into hydrogen and oxygen in electrochemical cells, with an energy efficiency in the range 55–75% depending on the capacity factor (i.e., operating at lower load will increase energy efficiency but require more electrolyser capacity, hence more capital costs) [2,3]. One electrolysis technology in particular, alkaline electrolysis, is considered to be fairly mature, having been deployed in industry for hydrogen production [4]. In alkaline electrolysis, the electrolyte is a concentrated solution of potassium hydroxide (KOH) at 28% wt., for which the conductivity is adequate for temperatures in the region 80–120 °C (depending on the pressure at which the electrolyser operates). The electrodes are typically based on Raney nickel rather than costly precious metals, which is advantageous. A notable development in more recent years is the optimization of electrolysis that can nearly instantly follow the load (i.e. the power supply), making it particularly suited to the use of renewable power from sources like wind, marine or solar energy [5,6]. In addition, operating under pressure also has the advantage of producing a gas that is already pressurized to a certain extent (up to 30 bar), which simplifies any subsequent processing and storage steps by removing the need for several stages of compression, as well as requiring smaller compressors (the pre-compressed feed is more compact) and consuming less power [5,6].

While the gaseous form of hydrogen is often seen as presenting a challenge for its storage on a large scale, it is encouraging that a similar requirement for seasonal storage is currently met for natural gas by underground storage in natural reservoirs. A total of 688 natural gas storage facilities were operated worldwide as of January 2013, with a combined working gas capacity of 377 billion m^3, or 10% of the world consumption (2012 figures, [7]). The 'working gas capacity' of a storage reservoir is defined as the total amount of gas that can be made available to customers, and is one of the two main operational specification of a reservoir. The other major characteristic of a reservoir is the deliverability rate, i.e. the rate at which the gas can be withdrawn from the reservoir. The working gas capacity (WGC) excludes the cushion gas capacity, which represents the volume of gas that must remain unextracted as buffer for reservoir management purpose and for providing the minimum pressure required for meeting the specified deliverability. The main types of reservoirs include salt caverns, aquifers and depleted natural gas or oil reservoirs. Salt caverns typically present smaller working gas capacities but greater deliverabilities than depleted reservoirs or aquifers, contributing worldwide only 7% of the total WGC and 14% of the sites, and yet 22% of the total deliverability (2012 figures, [7]). Depleted natural gas reservoirs are by far the most common amongst these, accounting for 74% of the total number of sites [7]. They have the economic advantage over aquifers of providing cushion gas capacity with their residual native gas.

For example, the Rough Gas Storage Facility (RGSF) is a partially depleted natural gas reservoir in the Southern North Sea, about 18 miles off the coast of Yorkshire, England. It is used to supply natural gas on the UK grid at times of peak demand. With up to 4.7 billion m^3 capacity, the volume of natural gas made available represents 9 days of supply, and it can be extracted at a rate that matches 10% of the UK's peak gas demand [8]. In view of their large capacities and the existing data and experience from natural gas, similar types of reservoirs could be considered for seasonal hydrogen storage.

The idea was initially explored in the 1970's when economies were embracing nuclear and renewable energies as alternatives to fossil fuels, but the body of literature that is available is limited. A preliminary assessment by Carden and Paterson [9] concluded that there were "no unsurmountable physical or chemical problems associated with underground hydrogen storage in sedimentary formations". In particular, the authors provided an initial estimate of the losses of hydrogen to dissolution in the surrounding underground water and further diffusion (including into the water saturated pores of the caprock). Pichler [10] suggested that these estimates be corrected, by including the influence of pressure and salinity on the solubility of hydrogen in water, as well as replacing the pure diffusivity with an effective diffusivity that took into account the constriction and tortuosity of pores. This author then concentrated on evaluating the chemical interactions of the hydrogen with the surrounding minerals in the reservoir. Panfilov [11] modelled the population dynamics of bacterial growth that is known to feed on hydrogen and carbon dioxide to produce methane in some reservoirs, coupled with the reactive transport of these gases in the reservoirs. His work evidenced a possible mechanism for the observed segregation of hydrogen-rich and methane rich areas in the aquifer town gas storages of Lobodice (Czech Republic) and Beynes (France).

In the UK, salt caverns would have great potential for hydrogen storage onshore for the purpose of daily load-following operations, on a decarbonised electricity grid that relied on electrolysis, or other methods for producing hydrogen like reforming and gasification for capturing CO_2 from fossil fuels. However, the total energy stored would be in the few 100's of GWh (150 GWh_e is suggested in Ref. [12]), which compares with about 40 TWh as available from the Rough Gas Storage Facility [8] and hence significantly short of the mark for seasonal storage. Generally, the lack of suitable depleted gas reservoirs onshore for seasonal storage suggests that storage should be done offshore, where many natural gas reservoirs are nearing the end of their productive lives. Public opinion might also favour storage in an offshore setting.

This paper is a preliminary assessment of the feasibility of storing hydrogen in the same type of reservoirs once commercial extraction of their natural gas has ceased, with emphasis on the storage characteristics as expressed in total energy stored ('working gas capacity') and rated capacity of supply ('deliverability'). We also checked the potential impact of the chemical and biological stability of the hydrogen and