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Microbial Risks Associated with Hydrogen Underground Storage in Europe

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Summary: To ensure a supply of H₂ throughout the year, it is essential to have large-scale storage to balance expected fluctuations of energy-production/demand. Underground storage has been proposed as a favourable solution. Many of these potential underground storage sites harbour diverse microbial communities and H₂ is not only a perfect energy carrier for human industry but also for microbial metabolisms. While microorganisms consume the H₂, they can induce microbial-triggered risks including loss of the stored H₂, risks to operational safety and deterioration in quality by H₂S production, biocorrosion and changes of the reservoir properties. As the demand for more H₂ storage rises, it is therefore important to understand the extent of the microbial presence and activity within the different types of sites (salt caverns, porous media including aquifers and gas reservoirs). Our CETP-sponsored R&D project HyLife works on providing valuable insights on what types of microbes are present and how they will influence the stored H₂ through extensive sampling across Europe. Direct results are a) aligned and tested methodologies to maximize comparability, b) an open database on detected microorganisms within the broad range of storage site conditions, c) microbial factors for field screening to minimize the risk when selecting sites.

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Microbial risks associated with hydrogen underground storage in Europe – HyLife project

Introduction

Many renewable energy systems utilize “Power-to-Gas” technologies, which use renewable electricity to produce hydrogen (H₂), a universal energy carrier. H₂ can be utilized, transported or stored for later use for several industrial sectors like chemical industry, heavy transport and steel production. To ensure a secure supply of H₂ throughout the year, it is essential to have flexible, large-scale storage to balance expected fluctuations of energy-production and -demand. Underground/subsurface storage has been proposed as a favourable solution for mid-to long-term storage, due to the large available volumes that could hold up to 920 TWh; this would be sufficient for a mid-range scenario of 2,500 TWh of annual H₂ demand in 2050 with at least 30% storage capacity (Tarkowski 2019). It is a known fact that many of these potential underground storage sites harbour diverse microbial communities and that H₂ is not only a perfect energy carrier for human industry but also for microbial metabolisms. While microorganisms consume the H₂, they can induce microbial-triggered risks including loss of the stored H₂, risks to operational safety and deterioration in quality by H₂S production, biocorrosion and changes of the reservoir properties. As the demand for more H₂ storage rises, it is therefore important to understand the extent of the microbial presence and activity within the different types of sites (salt caverns, porous media including aquifers and gas reservoirs). The CETP-sponsored R&D project HyLife works on providing valuable insights on what types of microbes are present and how they will influence the stored H₂ through extensive sampling across Europe. Direct results will be a) aligned and tested methodologies to maximize comparability, b) an open database on detected microorganisms within the broad range of storage site conditions, c) microbial factors for field screening to minimize the risk when selecting sites. We will also assess related environmental risks, test potential mitigation options and produce insightful techno-economic business analyses. Here we want to give our first update on the goals, work and recent results of the HyLife project.

Background and motivation

Hydrogen (H₂) will play a vital role in the European green energy transition to balance the fluctuating supply of renewable energy generation and demand. Excess renewable electrical power (wind, solar) is converted to H₂ (Power-to-gas) and stored for later use. For such an energy system to be stable, sufficient storage volume is needed in the range of approximately 30% of the expected energy demand. Underground H₂ storage in a) salt caverns or b) porous media-type storages like depleted gas fields or aquifers, is a promising approach due to the available large volume storage capacities, flexibility, and low operational costs (Fig 1). Indeed, introduction of H₂ into the subsurface can induce a range of complex reactions, specifically microbial redox reactions. H₂ is an attractive electron donor for a diversity of microorganisms in the anoxic subsurface environments. In principle, microbial H₂ consumption can be coupled to the reduction of nitrate, ferric iron, sulphate, elemental sulphur or carbon dioxide (CO₂) to produce nitrogen, ferrous iron, hydrogen sulphide (H₂S), acetate or methane (CH₄) (figure 1, right side). Such microbial activity can induce a variety of microbial-triggered risks: a) loss of the stored H₂ and changes in gas composition, b) risks to operational safety and deterioration in quality by H₂S formation, c) damage of the technical equipment by biocorrosion and microbial triggered precipitates, d) subsequent environmental risks by H₂S leakages outside the storage sites, e) changes of the reservoir properties by biofilm formation and precipitates (Dopffel et al. 2021). Until now, most experience in subsurface gas storage is based on natural gas, which significantly differs from H₂ regarding biogeochemical reactions. Overall, knowledge on microbial H₂ consuming activities in subsurface reservoirs is scarce and seemingly site dependent. To ensure a safe, efficient, and economically successful underground H₂ storage, the understanding of the microbial impact is crucial.

Salt caverns are confined and artificially leached with volume space typically in the range of ~ 500.000 m³ (corresponding to 133 GWh)(Caglayan et al. 2020). They are proposed to be ideal for short- to mid-term storage, with opportunities for rapid injection and withdrawal of gases. Most currently existing caverns are used for natural gas, oil or chemical storage, all located onshore in different salt structures across Europe especially in North-Eastern Germany, Netherlands, France and Spain. Leaching and

operations will lead to introduction of microorganisms or activation of native species, similar to reported observations in oil and gas reservoirs.

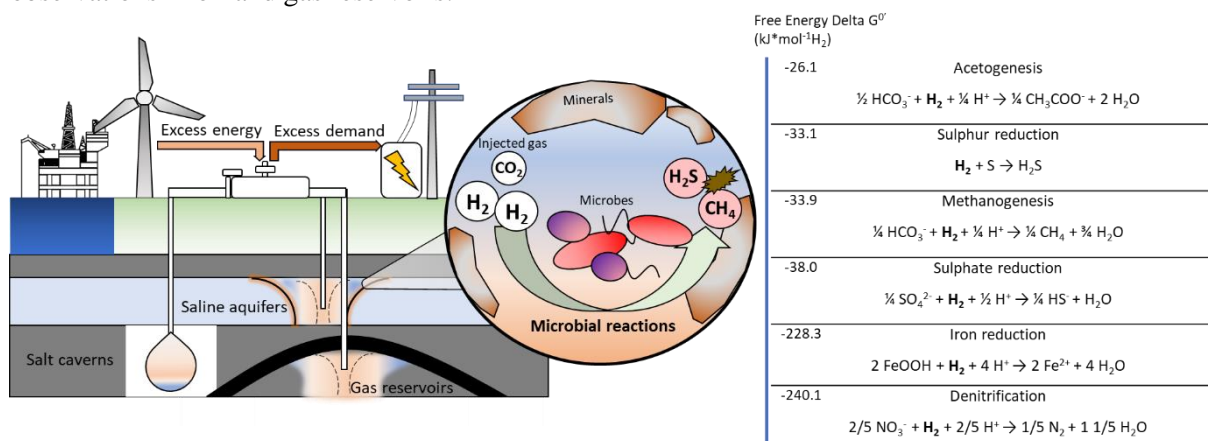


Figure 1 Overview of the concept of inter-seasonal energy storage in subsurface structures. Excess energy is used to produce high-energy carriers like H₂, which are injected into subsurface structures (salt caverns, aquifers or gas reservoirs). Within these subsurface environments the injected H₂ can be used as electron donor by a variety of different microbial metabolisms (shown at the right).

These specially adapted extremophilic microorganisms can live or even require high-salt conditions for their survival. The microbial communities living within salt caverns have been scarcely studied, but up until now all investigated caverns harboured a diverse set of microorganisms (Schwab et al. 2022). Whether all communities are capable of consuming H₂ is not clear and also if always similar communities are present. Salt caverns are leached in different geological salt structures, and the mineralogical composition differs significantly even within one salt dome. Such variations will affect the hydrochemical composition of the brine and the types of microorganisms.

European porous rock reservoirs have different lithologies and physical properties (temperature, pressure) affecting the hydrogeochemical conditions of the fluids and subsequently the microbial activities. Compared to salt caverns, porous rock reservoirs often have a lower salinity and a much greater surface area in which microorganisms can thrive. This makes it more likely for reservoirs to have higher cell numbers, greater microbial diversity and thus activity. Here new studies could show that sulphate-reducing organisms from original samples brine from both a gas reservoir (Dohrmann and Krüger 2023) and an aquifer (Haddad et al. 2022) will be instantly stimulated by H₂ and will convert it to H₂S. However, the results of these two studies are difficult to compare because they used vastly different methods for sampling, growth, and community analysis. Every reservoir exhibits different conditions regarding mineralogy, organic content, etc. and such heterogeneity might have direct impact on the extent of microbial H₂ consumption. As only a few studies have been published so far, no general conclusions can be drawn.

Methods

We will apply a variety of different microbiological methods to our obtained field samples, which are provided by different operators in Europe. This includes anaerobic cultivation techniques to obtain growth rates, gas conversion rates and get an insight into the microbial metabolic potential. We will use gas- and liquid analytics to analyse all major compounds and products. Further we will apply DNA-based methods to obtain information on the microbial community structure both from the original brines and the grown samples to identify key microbial families and groups. All data, along with corresponding metadata, will be categorized to allow for a database design that would fit the data storage and organization needs in its entirety. Using established hydrogen consuming cultures, we will develop a novel microbial control assessment program to provide insights on the inhibitory effects of common 'natural' (such as nitrate - and/or plant-based biocides) and common chemical biocides. All the mentioned data will be essential for predicting the metabolic function of the microbes. For this the metabolic network of the microbial communities will be reconstructed for each environmental sample, by inferring the presence of metabolic reactions based on the genomic content of the associated

organisms. A 3D model based on a specific kinetic model in CMG-STARS will also be developed in the frame of this project. For the business case including microbial risk factors an economic feasibility study will be conducted. An economic feasibility study focuses on the expected costs of the storage site and possible mitigation strategies. The study benefits from applying investment analysis underpinned by data from the storage site and strategies as well as the market.

Results and Outlook

For Europe to reach climate neutrality by 2050, we will need large-scale, safe, and economically viable H₂ storage systems. To achieve this, microbial risks must be well understood. Thus, we are generating high level knowledge and competence on this topic as fast and as broadly as possible by involving four microbiological labs across four different countries. A big advantage of HyLife is that we aligned and develop best-practice protocols, methods, and standards across our labs, thus forming a microbiological network on this topic. This ensures that all results are as comparable as possible and clear, feasible guidelines to assess microbiological risks will be developed for industry and operators for future practices. Furthermore, the uncertainty of geological variations of the storage sites are high and it is essential to investigate as many sites as possible to gain a holistic understanding on the overall impact of microorganisms. This cannot be achieved by one single lab due to the sheer number of samples and the necessary analytics. In the beginning we worked to align different methods between the four microbiological labs involved in analysis located in Germany, France, Norway and Czech Republic. We designed sampling protocols to be used by operators to sample for microbiological and DNA analysis. Here important points are sterility, anoxic conditions, safe handling and stabilization for shipping (Fig. 2). All work is available online and supported by videos on Youtube. The sampled brine will be analysed and used for microbial enrichments to assess activity of the most concerning microbial groups which are sulphate reduction, methanogenesis and acetogenesis. Our project is closely working with industry operators. At the current state we are in contact with 21 storage operators in 8 countries, which will provide us samples over 2023 and 2025. We will continuously look for more operators to join the project to get a good coverage of different storages in different geological locations with different chemo-physical properties.



Figure 2: Sampling overview: (A) Wear gloves and sterilize them before you start. (B) Flush the provided glass bottle with the nitrogen. (C) Flush the pipes properly before sampling. (D) Connect the tubing to the tap. (E) Sample the water while continuously flushing the bottle with nitrogen. (F) Fill the bottle to 2/3 volume and continue flushing with nitrogen. (G) Close the bottle and write the label. (H) Pack the bottle into a styrofoam box.

Conclusions

Within our HyLife project we are able to significantly improve the current knowledge on microbial effects during hydrogen underground storage in all different storage types. One asset of HyLife is that four microbiological labs will work closely together on the many samples gathered in Europe using the same methodologies to generate compare results and therefore obtain a much higher data output in a short amount of time. As the need for H₂ storage rises, site selection is a major point of concern for the energy sector. Our project is tackling challenges faced by the energy industry (reservoir operators, cavern owners and operators, H₂ producers) by providing selection criteria for most favourable storage sites minimizing microbiological risks to the business. There are many storage options within Europe either within newly leached or legacy salt caverns (previously used for storage of natural gas or oil), in deep saline aquifers or within the abundant old hydrocarbon reservoirs. Due to the geological differences and biogeochemical heterogeneity, microbial H₂ consumption factors are not well understood. Our output in form of published guidelines, publications, close communication with our industry stakeholders and the open database will permit a fact-based decision-making capacity on suitable storage locations by delivering important baseline knowledge on on-site biological processes from our sampled locations in Europe and contextualize this knowledge with associated economic costs. We will pioneer in this broad-scale microbial evaluation process and enable the development of a microbiological-risk specific business case containing the costs of possible mitigation and H₂S treatment routines to avoid unexpected failures, which increase costs while reducing faith in the safety of renewable storage sites. Our project will enable development of new and targeted mitigation/biocide strategies that directly aid to accelerate safe, long-term H₂ storage and therefore enable a faster and more secure energy transition in Europe.

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