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Enabling large scale offshore wind with underground hydrogen storage

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Introduction

The recent commitments to achieve Net Zero by 2050 imply stringent reductions in greenhouse gas emissions (GHG) in the UK (UK Government, 2019). These commitments have led to a renewed push to decarbonise the energy system. Primarily by increasing renewable energy sources in the UK energy mix. This comes at the cost of more variability and intermittency in power generation, a greater stress on the electricity grid and a reduction in the energy system's resilience to extreme weather events.

To mitigate against this variability, energy storage can be used by storing excess renewable energy, or cheap imported energy, to be able to meet demand when the renewable energy generation capacity is insufficient. The challenge of variability in demand and supply is one which occurs on a multitude of spatial and temporal scales, from computer chips to regions and from seconds to years (Mouli-Castillo et al., 2019).

In addition, the consumption of energy uses a range of fuel. To help address this challenge, and avoid massive conversion of infrastructure for electrification, hydrogen has been proposed as an energy vector (Orecchini, 2006). Hydrogen is a gas which could be cheaper to transport than electricity (Dodds & Mcdowall, 2013) and easier to store (Tarkowski, 2019). It can be either combusted in boilers for heat, or converted back to electricity using fuel cells. Hydrogen can be produced from natural gas (with CO_2 as a by-product to be stored) or from electrolysis powered by curtailed or dedicated renewable electricity, to split water molecules in high purity hydrogen and oxygen. As such hydrogen is considered as a versatile tool to mitigate the need to install electrification infrastructure, reuse the existing gas grid and minimise disruptions to end users.

In this article we present recent findings addressing the challenges of achieving large-scale seasonal storage of energy using underground hydrogen storage (UHS).

Storage Need

In order to better evaluate the storage capacity required to enable the seasonal balancing of energy in the UK we first need to estimate the storage need (Mouli-Castillo, Heinemann, et al., 2021). This is quite challenging due to uncertainties in the future energy system, such as the generation mix, the end-use, and key policy decisions. Here we present an approached based on historical supply and consumption data to paint a picture of the potential storage needed at inter-seasonal scales. We present the methods used in two distinct publications, one aiming to understand the need at a system level, the other focusing on the need for seasonal domestic heating. The former uses monthly supply and consumption data, whilst the latter uses daily supply data from the Local Distribution Zones.

The seasonal storage capacity needed to replace the entire UK annual gas demand with hydrogen is between 135 – 150 TWh (Scafidi et al., 2021). This was calculated using a decade of monthly gas demand data and is taken as the difference above the average for each October to October yearly period. This figure includes gas demand for heating, power generation, industrial, and all other uses. It should therefore be treated as a maximum figure for the UK's potential hydrogen storage need.

The storage need required for domestic heat in the UK is evaluated as half the sum of the cumulative difference in consumed natural gas between winter and summer days. The data used for this evaluation is the gas consumption as Non-daily Metered Gas Demand, which is a reasonable proxy for domestic heat consumption from natural gas (Wilson et al., 2013). It should be noted that this metric does not account for electric heating, which may require hydrogen storage and conversion to electricity, in the winter and accounts for less than 15% of domestic heat in the UK. The storage need is computed for 5 years and the maximum value is used as the storage target representing a conservative value. The total storage need for the UK was found to be 78 TWh. With the following regional split (Figure 1).

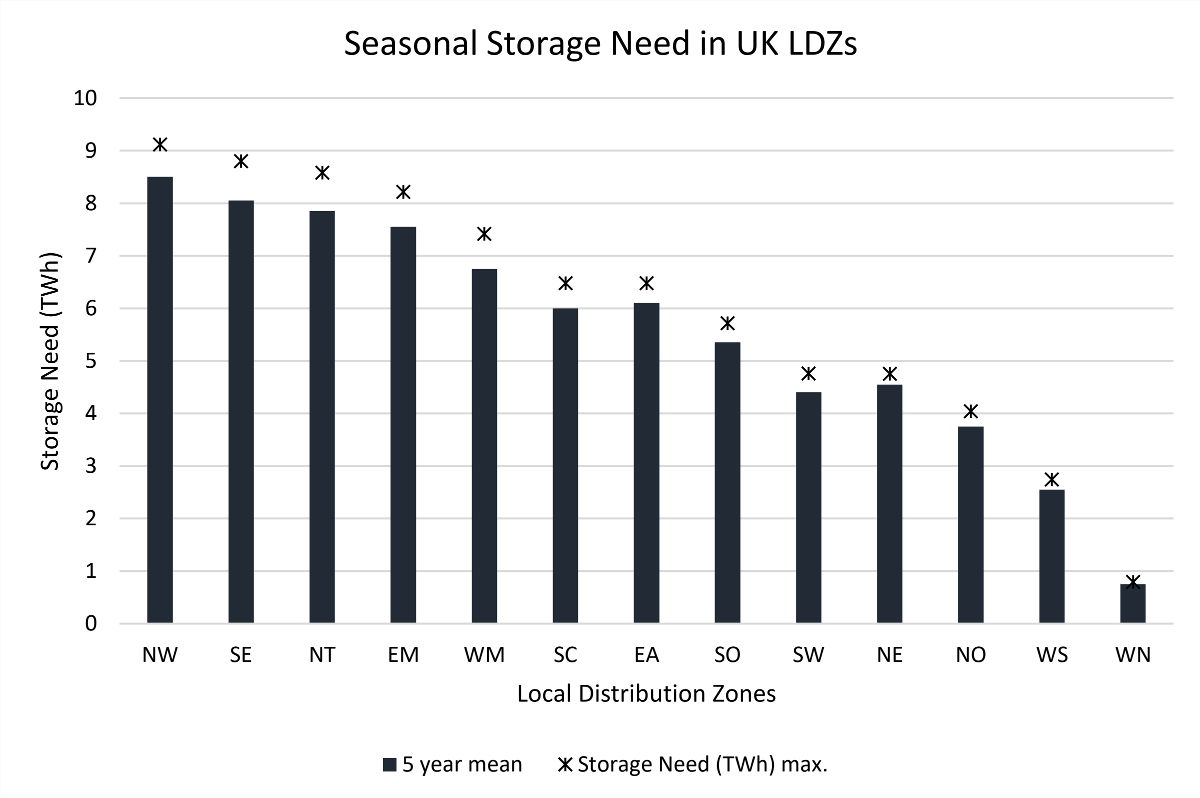

Figure 1: Seasonal energy storage need for domestic heat demand from natural gas users. SC: Scotland, NO: Northern England, NE: North East England, NW: North West, EM: East Midlands, WM: West Midlands, WN: Wales North, WS: Wales South, SW: South West, SO: Southern England, SE: South East, NT: North Thames, EA: East Anglia.

Storage Capacity Estimates

It is possible to estimate the UHS potential of depleted gas fields based on existing data from decades of Oil and Gas production. Here we present and characterise the uncertainty in early estimates. Two distinct approaches were implemented, the first using pore volumes of depleted gas fields (Scafidi et al., 2021)**,** the second using gas initially in place and recoverable gas values from the literature (Mouli-Castillo, Heinemann, et al., 2021).

The first method (Scafidi et al., 2021) uses the CO2Stored database (Bentham et al., 2014) a collection of oil and gas data for fields and rock formations on the UK continental shelf (UKCS). It was developed to estimate the CO_2 storage capacity of the UKCS, but it is also possible to make an estimate of the hydrogen storage capacity in fields using the same data. The total hydrogen storage estimate using this method was 6900 TWh of working gas capacity in 95 gas fields of the UKCS. 85% of this capacity is in the Southern North Sea.

The second method (Mouli-Castillo, Heinemann, et al., 2021) identified 41 gas fields with direct pipeline connections to UK gas terminals. The method assumed that the cushion gas in the store, that is the gas permanently remaining in the store to provide pressure support and avoid water infiltration at the well, was set to follow two rules, the first that the cushion gas should be at least equal to the working gas volume (that is the volume of gas actually used for storage operations) (Amid et al., 2016; Flanigan, 1995), the second was that at least 20% of the cushion gas should be hydrogen (Misra et al., 1988). This second rule was applied to mitigate the mixing effects between the hydrogen and the *in situ* hydrocarbons in the store. The hydrogen storage found in 41 fields directly connected to gas terminals is about 2662 TWh, with the greatest capacity also found in the Southern North Sea.

Both method yield comparable results. UHS potential in the UKCS can be found at fields connected to all the main gas terminals providing seasonal storage opportunities to be spread across the country depending on the need and the gas transmission network capacity (Figure 2).

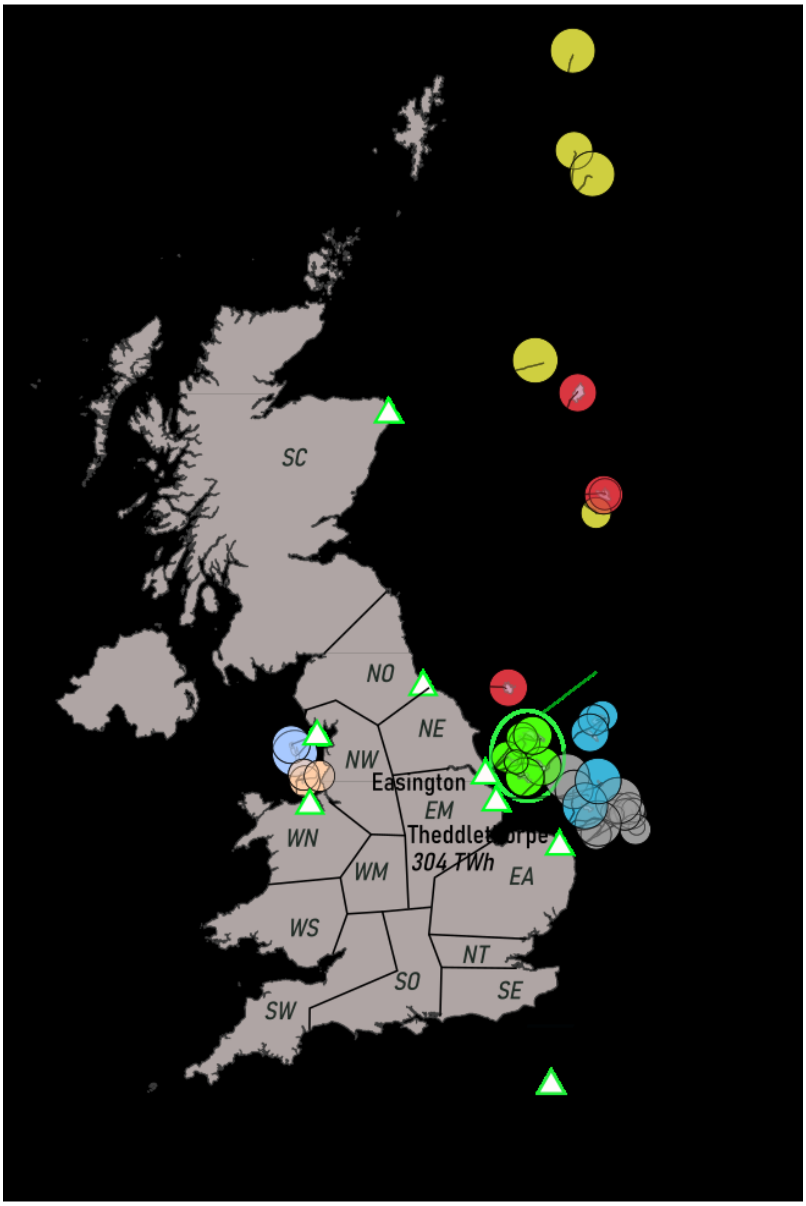

Figure 2: Capacity estimates using the Gas Initially in Place and Recoverable Gas method. Local Distribution Zones boundaries are approximate.

HyStorPor – Characterising UHS

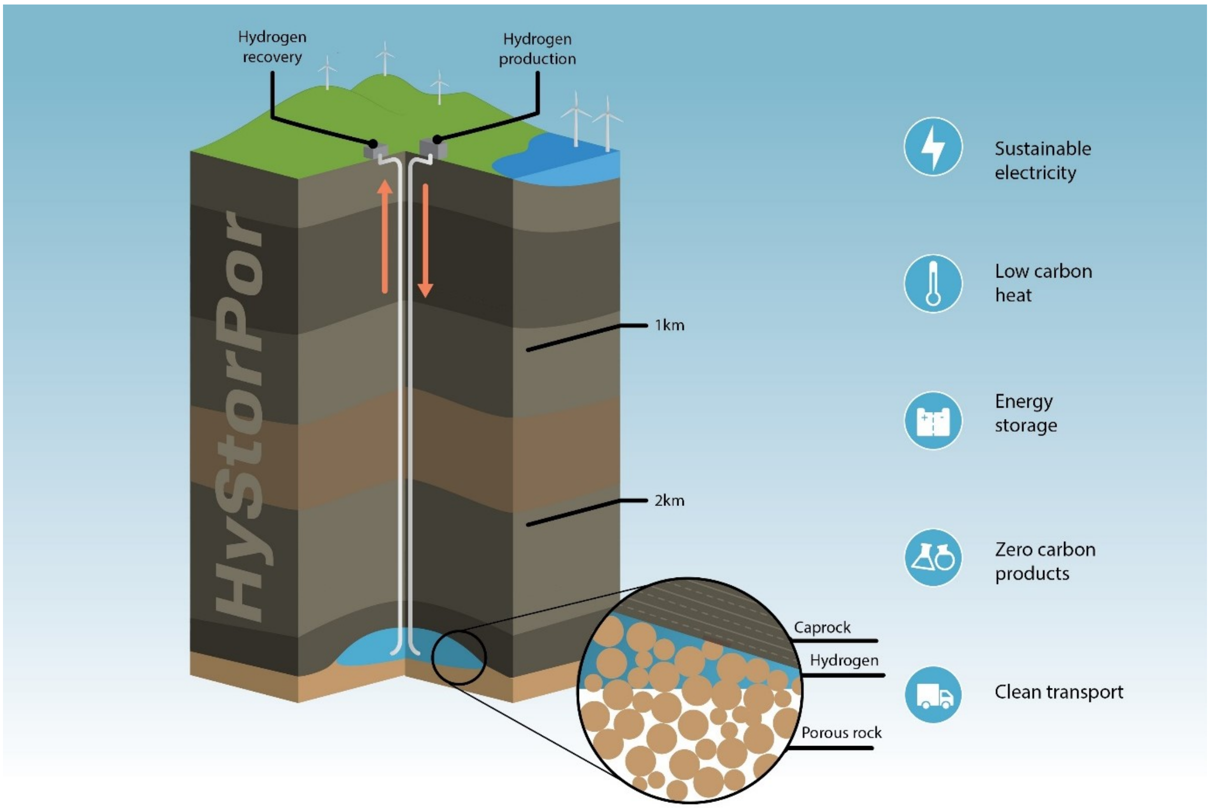

Figure 3: HyStorPor and principles and applications of UHS.

To ensure the delivery of UHS in the next decade it is important to better understand the behaviour of hydrogen in the subsurface The University of Edinburgh's, EPSRC funded, HyStorPor (hydrogen storage in porous media) project is undertaking a comprehensive research investigation into the processes underpinning UHS (Figure 3). The project has 4 primary goals: (1) To identify if any biological and chemical reactions between the rock, fluids, cushion gas and hydrogen could compromise storage. (2) Determine what flow processes will influence hydrogen migration and trapping during injection and withdrawal. (3) Undertake reservoir simulations to estimate what volumes of hydrogen can be stored and recovered from storage sites of varying scales. (4) Clarify what citizens and opinion shapers think about hydrogen storage.

Understanding the likelihood and impact of geochemical reactions between the stored hydrogen and the storage reservoir rocks, caprock, well cements/casing and fluids to reduce the feasibility of a hydrogen store through hydrogen loss, contamination, pore blocking and permeability reduction, degradation of operational equipment and potential environmental risks is extremely important. An extensive program of laboratory experiments reacting hydrogen and formation brine with representative samples of reservoir and seal rock along with well cements under reservoir conditions of temperature and pressure have been undertaken. While some geochemical reactions with hydrogen have been observed, none are severe enough to reduce the feasibility of hydrogen storage (Flesch et al., 2018).

Another important consideration for hydrogen storage in the subsurface is whether microbial activity will consume or contaminate the stored hydrogen, reduce well and casing integrity or impact permeability through biofilm formation and mineral precipitation. A review on the microbial reactions with hydrogen in the subsurface has been undertaken by the HyStorPor project team and shows that in addition to nutrients and water, temperature and salinity are the key environmental controls on the growth of the three most important groups of hydrogen oxidizing microorganisms – methanogens, homocacetogens and sulphur species reducing microorganisms (Thaysen et al., n.d.). The study reveals that several depleted or close to depleted gas fields in the North Sea and Irish Sea have temperature and salinity conditions that are beyond the tolerance limits of these microorganisms. This research effectively provides a site screening tool to identify storage sites that will be unfavourable to microbial growth and as such minimise the risk of microbial hydrogen consumption (Thaysen et al., n.d.).

The low density of hydrogen implies that that capillary sealing within reservoir caprocks, which are secure for hydrocarbons, may not necessarily be secure for hydrogen. The HyStorPor team has developed a methodology to convert established pre-production natural gas column heights into hydrogen column heights to estimate caprock sealing security. The calculations are based on highly accurate thermodynamic models which have been tuned using experimental data for both methane and hydrogen (Hassanpouryouzband et al., 2020).

Public Acceptance

One of the essential aspects of any future energy strategy is that it is developed in a way that respects and is responsive to social concern. Despite strong policy interest in hydrogen as a means of meeting NetZero emission obligations, there are questions over the necessity or viability of hydrogen. These questions focus on safety, cost, impact on consumers, fuel poverty risks, and the role of fossil fuel corporations. The HyStorPor project is investigating the social perception of hydrogen storage, engaging with citizens to understand what shapes perceptions of alternative energy options. This is a critical aspect of supporting hydrogen acceptance and has to be achieved for all aspects of the value chain. Recent work has been undertaken to assess the safety of the distribution and use of hydrogen in the domestic setting. The work focused on establishing a comparative evaluations of 100% hydrogen against the current natural gas network. Areas which were investigated included the use and efficiency of odorants (Mouli-Castillo et al., 2020; Mouli-Castillo, Orr, et al., 2021), and the development of quantitative risk assessments for domestic properties (Mouli-Castillo, Haszeldine, et al., 2021). These complement the work done on refuelling infrastructure critical for the uptake of hydrogen for road transportation (Tsunemi et al., 2019).

Cost estimates

Current levelised costs of hydrogen storage, in all forms, range from 2-15 USD/KWh, which compares favourably to pumped hydro (5-136 USD/KWh) and is lower than Li-ion batteries (282-4104 USD/KWh) (Rahman et al., 2020). It is anticipated that the cost of green hydrogen production in particular will follow the same cost reduction trends as seen in renewable energy sources and fall from $6/kg to the goal of "$H_2$ under 2" reaching $2/kg over the next 10 years, becoming cost competitive with renewable and heat pumps by 2030 and is commercially competitive for space heating and commercial transport at $3/kg (Council, 2021). Work by Lord et al found that geological limitations are likely to control the economic drivers for hydrogen storage, for example they looked at the cost of hydrogen for Detroit and Los Angeles and found the cost to supply Detroit with hydrogen is three times higher, because Detroit is located by thinly bedded salt formations, whereas Los Angeles has access to massive salt formations and as such can develop fewer larger caverns at lower costs (Lord et al., 2014). This is the first indication that hydrogen storage in fewer larger storage locations may be the most economically viable option. Since, UHS in porous rocks is the next step up from large salt caverns these early findings indicate that such stores could be economically advantageous compared to their smaller salt based counterparts. Further economic studies are required to characterise the cost of hydrogen storage.

Conclusion

In this article we highlight recent findings which indicate that currently, no show stoppers for the large-scale storage of hydrogen in porous formations have been identified. That more than enough storage sites are present in the UK continental shelf to support the national seasonal storage need generally, and for domestic heat specifically. Research highlights that the underground storage option appears to be lower cost option than other surface alternatives or buried pipes. In addition, hydrogen storage offers the possibility of shifting vast amount of energy between summer and winter, which remains a storage challenge with no proven solution. In addition to being technically feasible, we indicate that progress is being made in characterising the safety aspects of the hydrogen supply chain for domestic heat and road transport. Finally, the colocation of offshore storage potential with offshore wind resources could contribute to supporting the development of offshore wind without the downside of its variability.

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