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UNDERGROUND HYDROGEN STORAGE: INSIGHTS AND ACTIONS TO SUPPORT THE ENERGY TRANSITION

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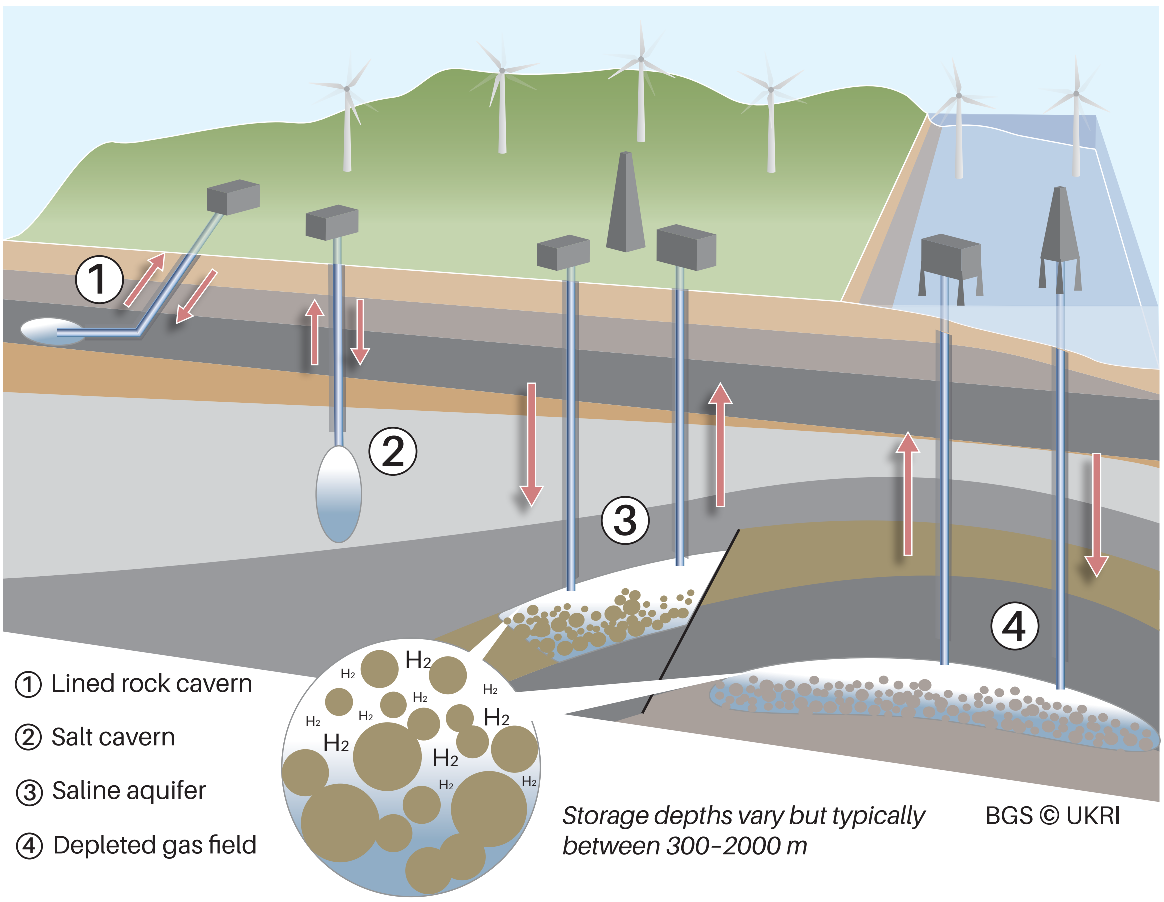
Underground hydrogen storage is a fundamental requirement of any net zero energy system, which is likely to rely on the use of hydrogen as both an energy carrier for storing excess energy from renewable sources (e.g. solar, wind) and alternative fuel to decarbonise hard to abate sectors (e.g. shipping, freight, heavy industry). With the increasing penetration of renewable energy sources and as demand for hydrogen increases, the intermittency of supply poses significant challenges to balancing the energy system. Hydrogen, as a versatile energy carrier, offers a viable pathway to mitigate these challenges.

Various underground storage technologies such as salt caverns, lined rock caverns and depleted hydrocarbon fields provide scalable and long-duration hydrogen storage options. These technologies, while requiring significant initial investment and specific geological conditions, offer the potential for large-scale long duration storage capacities. However, there are still considerable knowledge gaps in how and where such large-scale storage can be achieved.

> **'Hydrogen storage will be crucial** for the stability and reliability of the energy grid and will ensure that hydrogen **is available for use as a low-carbon fuel'**

Recommendations:

- Implement more demonstration projects to build in-situ technical capability, address market barriers, and promote wider hydrogen adoption.
- Integrate hydrogen storage into the UK's energy strategy through comprehensive planning and supportive regulatory frameworks. Currently, there is little regulatory clarity, which might be regarded by industry as a potential risk to adoption and roll out.
- Invest in research and development to rapidly expand knowledge in the hydrogen storage technologies essential for meeting clean energy targets.



Background

Solar and wind are essential renewable energy sources for a future low-carbon world. As sun and wind outputs are variable, availability of the resource is intermittent and unpredictable. This uncertainty, compounded by variability in demand, makes it challenging to provide reliable and adequate energy supplies from renewable sources alone and to balance periods of over- and under-supply of energy. As the contribution of intermittent renewable energy to the UK energy mix increases, balancing supply and demand will become increasingly important, requiring energy carrier and storage technologies that permit conversion, storage and release or redistribution of energy during times of over and under supply, respectively[1]. In addition, low carbon fuels will be needed to decarbonise difficult to abate sectors.

Box 1: Low-carbon hydrogen production

There are two established methods of producing low-carbon hydrogen: **steam methane reforming** (**SMR**) with carbon capture, utilization, and storage (CCUS), and **electrolysis** powered by renewable energy sources[2]. SMR utilises natural gas but captures the resulting CO_2 emissions, minimising its environmental impact and termed **'Blue' hydrogen**. Electrolysis directly splits water molecules into oxygen and hydrogen in an electrolyser using electricity, termed **'Green' hydrogen**. For electrolytic hydrogen to be truly low-carbon, electricity must come from low-carbon sources such as solar or wind power.

Hydrogen has been suggested as an energy carrier for storing excess energy from renewable sources to help balance supply and demand[3,4] and as fuel to decarbonise difficult to abate sectors which presently rely on hydrocarbons, including heavy industry, chemical refining and transport such as shipping or aviation[5,6,7]. The two are linked in that large amounts of hydrogen will be needed to meet the UK's 2035 and 2050 climate targets[8,9]. Most of the hydrogen will have to be produced, although there are some natural sources[10]. Hydrogen production can use different methods and sources (see Box 1), and different colours are being used to differentiate between the various origins of hydrogen. The produced hydrogen acts as the energy carrier. It does not emit carbon dioxide when used and provides a low-carbon energy source for transport or industry. However, it should be noted that hydrogen does have a greenhouse gas effect when leaked[11]. To help meet the fluctuations in demand for hydrogen between production and end use, the produced hydrogen will need to be stored at a large scale[12].

Hydrogen storage options

A gas storage facility may be in natural or man-made settings and below or above ground. Hydrogen storage does not differ significantly from the storage of natural gas. A limited number of geological stores for hydrogen have been operated since the 1960's

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(US) and 1970s (UK), with numerous demonstrator sites currently being developed. Using prior knowledge of hydrogen and hydrocarbon (gas) storage, lessons may be taken for application to storing hydrogen at-scale.

	Storage technology	Technology Readiness Level (TRL)	Storage capacity	Notes
Above ground storage	Pressure vessels	9	Low MWh-GWh	Suitable for short term, limited for long term.
Above ground storage	Pipe storage	9	Low MWh-GWh	Suitable for short term, limited for long term.
Above ground storage	Horton sphere	9	Medium GWh	Expensive due to cryogenic storage.
Above ground storage	Liquified hydrogen	9	Medium MWh-GWh	Expensive due to cryogenic storage.
Below ground storage	Lined rock caverns	5 for pure hydrogen	Medium MWh-GWh	Lower capacity, independent of geology.
Below ground storage	Salt caverns	5–6 (pure hydrogen in fast-cyclic energy system setting) 9 for static or low-cyclic feedstock applications based on pure hydrogen	Medium GWh	Most TRL mature underground technology, highly dependent on geology.
Below ground storage	Saline aquifers	2–3 for pure hydrogen 9 for town gas blends	High GWh-TWh	Low TRL, dependent on geology, offers vast capacities.
Below ground storage	Depleted gas fields	3–4 for pure hydrogen 5 for hydrogen natural gas blends (10–20%)	High GWh-TWh	Low TRL, dependent on geology, offers vast capacities.

Above ground storage

Options for above ground hydrogen storage include compressed gas, stored within pressurised vessels such as pipes or Horton Spheres, and liquified storage options[14]. Both technologies are readily applied and are commercially developed (technology readiness level, TRL ~9). Above-ground storage is independent of geological conditions, have lower initial capital expenditure (CAPEX) compared to underground options and faster deployment times due to lower engineering requirements. However, these are traded for drawbacks including limited capacities (kWh -MWh scale) compared to subsurface storage and large aboveground footprint with greater visual impact. For liquefied hydrogen, although stored hydrogen may be of a much greater density than pressurised vessels, hydrogen evaporation is unavoidable even within a contained system and certain boil-off losses are inevitable. Combined with this, liquefaction requires a significant amount of energy leading to high operational expenditure (OPEX) costs.

Below ground storage

Underground technologies offer orders of magnitude greater capacity (MWh-TWh scale) than above ground options[15,16], improved safety case for hydrogen leakage[17], reduced footprint meaning storage requires less land space on the surface, and overall reduced OPEX per unit of energy stored with the potential for economies of scale[18,19]. Conversely, underground storage typically involves higher CAPEX, specific geological requirements with suitable geology, relatively lower TRL[20], and slower hydrogen retrieval and responsiveness compared to above ground tanks.

1. Lined cavern storage

Lined rock caverns (LRC) are an excavated subterranean chamber in hard rock formations sealed with a lining system. Lined rock caverns can be accommodated in a wide range of geological formations that are geographically widespread[21], but may be limited in spatial extent. This versatility allows storage in areas where other storage options are limited by geological factors. The storage capacity that may be held within a lined rock cavern may be 10's of GWh.

2. Salt caverns

Solution-mined caverns in salt structures are already in widespread use as subsurface energy storage facilities for natural gas and other products onshore in many parts of the world, and as hydrogen storage onshore in a limited number of facilities in the UK and US[22,23]. The storage capacity that may be held within a salt cavern may be on the order of 10–100's of GWh, discharged and refilled over a course of days[24]. Salt caverns are being explored as a medium-scale storage option addressing local/regional storage demand.

Currently, only a few sites exist for hydrogen storage (>95% hydrogen) in salt caverns, including Teesside (UK). Teesside has been storing hydrogen since 1970 in three elliptical shaped caverns[25]. Teesside has operated under a long duration storage model and rarely cycle the gas frequently through the cavern, i.e. steady cavern pressure is maintained over long periods of time. This has unequivocally demonstrated for decades that underground hydrogen storage is a technically feasible option for long duration storage. Questions do remain, however, regarding different operational modes (e.g., the frequency of cycling and impact of quickly removing and replenishing gas over short periods of time in a salt cavern[26]).

3. Porous media — hydrocarbon fields and saline aquifers

Porous media are rocks which have a pore space that may fill with liquids or gasses, including water, oil, natural gas or hydrogen. Where occurring with hydrocarbons, these may be referred to as fields, while where water filled are termed aquifers. Two geological conditions must be met: **1)** the rocks selected for injection have good porosity and permeability and **2)** they are overlain by an impermeable seal (caprock).

Depleted hydrocarbon fields are typically well-characterised during their exploration and exploitation and have demonstrated storage and sealing for methane. Depleted oil fields are not typically converted to underground gas storage facilities. This is because hydrogen may react with residual hydrocarbons or dissolve in the oil, forming methane, and become irreversibly lost[27]. Porous media may also face problems with microbial consumption of hydrogen[28] and hydrogen reacting with the host rock[29].

Deep aquifers (~400 m or deeper) hold brine water that are not generally exploited. Many aquifers are situated close to major energy consumers or large cities and urban agglomerations and have been safely used as natural gas storage sites for decades.

Depleted gas fields and aquifers are typically far greater in size to other storage options, with even the smallest deposit potentially hosting TWh-scale hydrogen storage capacities that could be discharged over a course of weeks to months. Depleted gas fields are often viewed as a seasonal storage facility that may be used for strategic national storage.

Scale of hydrogen storage required

The current UK energy storage system (Box 2) holds some of the lowest levels of gas storage in Europe at 12 days average or 7.5 peak winter days. The requirement for storage is intrinsically linked to demand for hydrogen, and schedules of planned implementation of transport networks, linking supply to demand, and how hydrogen is likely to be used.

As parts of the transmission system become more congested with renewable electricity/hydrogen suppliers and offtakes, the location and connectivity for storage will become increasingly critical[31]. Some industrial clusters are fortunate to have access to readily available salt for cavern development (e.g., Humberside and Teesside, HyNet NW England). However, other regions may require porous media or lined rock caverns for local storage.

'Estimates for hydrogen storage required by 2050 range from 19–100 TWh[10,30], up to 5 times greater than the **current UK gas storage capacity.'**

Box 2: How much energy storage does the UK currently hold?

The current UK energy system, minus transportation fuels, held the average following capacity in 2019 [32,33]:

Fossil fuels on average stored:

- 35 TWh – coal (falling)
- 18 TWh – gas (12 average days' supply)

Supported by:

- Pumped hydro – 30 GWh capacity
- Hot water tanks – 40 GWh
- Grid connected batteries – 1.8 GWh
- 320 Kt biomass at Drax power station →560 GWh electricity

Total: c. 53.6 TWh

Commercial and regulatory challenges

Hydrogen storage facilities can take significant timescales to build (e.g. 7–10 years for a salt cavern) and require substantial up-front capital investment[34]. Therefore, developers need a clear business case and return on investment to justify the inherent project risk (Box 3). Better articulation of the business case is seen as one of the most prominent barriers for hydrogen storage[35]. To assist with the business case, the Hydrogen Storage Business Model (HSBM) provides a revenue support mechanism for operators. However, projects are only eligible for support if they meet a TRL of ≥7. To overcome this, active research programmes and demonstrators have been identified as 'low regret' options that could advance our technical understanding and prove commercial viability[36].

Box 3: Barriers to hydrogen storage development

1. **Environment & Social**: The support of local communities and stakeholders is essential. Public concerns about safety and environmental impact can lead to opposition and delays, as seen in Whitby and Redcar hydrogen village trials[37,38,39].
2. **Technical**: There are key technical questions that exist. Developing pilot studies and testing uncertainties in situ, especially for porous storage, could greatly improve design, commissioning and operation of hydrogen storage.
3. **Cost & Programme**: Projects are CAPEX intensive and take a long time to build with uncertain payback periods.
4. **Supply Chain Readiness**: Limited availability of key skills and equipment within the market is impacting project schedules which in turn increase costs.
5. **Planning & Regulation**: Regulation is multi-agency with no clear pathway, and schemes can take years to pass through the planning process.
6. **Demand Certainty**: Uncertainty over what/where/when storage will be required, impacting the investment case of projects.

Conclusion

Underground hydrogen storage in salt caverns, lined rock caverns, and porous media such as depleted hydrocarbon fields, offer scalable, long-duration storage options that are essential for ensuring the stability and reliability of a renewable-based energy system.

While expertise in hydrocarbon gas storage exists, further research is needed to advance technical expertise, enhance capabilities, and expand knowledge specific to underground hydrogen storage. Specifically, at-scale demonstrators and pilot projects will help to define the business case and overcome market barriers, thereby encouraging wider uptake of the technology.

Furthermore, hydrogen storage is currently not sufficiently represented in the UK's energy strategy and this represents a potential risk for technology adoption and roll out. More detailed planning, a supportive regulatory framework along with increased investment in research and development would ensure that underground storage technology and markets are ready to support hydrogen rollout in time for meeting the UK climate targets.

References

1. Cardenas, B, Swinfen-Styles, L, Rouse, J, Hoskin, A, Xu, W, and Garvey, S D. 2021. Energy storage capacity vs. renewable penetration: A study for the UK. *Renewable energy*, 171, pp.849–867. https://doi.org/10.1016/j.renene.2021.02.149
2. The Royal Society. 2018. Options for producing low-carbon hydrogen at scale: Policy briefing. https://royalsociety.org/-/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf
3. Gabrielli, P, Poluzzi, A, Kramer, G J, Spiers, C, Mazzotti, M, and Gazzani, M. 2020. Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage. *Renewable and Sustainable Energy Reviews*, 121, p.109–629. https://doi.org/10.1016/j.rser.2019.109629
4. Scafidi, J, Wilkinson, M, Gilfillan, S M, Heinemann, N, and Haszeldine, R S. 2021. A quantitative assessment of the hydrogen storage capacity of the UK continental shelf. *International Journal of Hydrogen Energy*, 46(12), pp.8629–8639. https://doi.org/10.1016/j.ijhydene.2020.12.106
5. Griffiths, S, Sovacool, B K, Kim, J, Bazilian, M, and Uratani, J M. 2021. Industrial decarbonization via Hydrogen: A critical and systematic review of developments, socio-technical systems and policy options. *Energy Research & Social Science*, 80, p.102–208. https://doi.org/10.1016/j.erss.2021.102208
6. Shahabuddin, M, Brooks, G, and Rhamdhani, M A. 2023. Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis. *Journal of Cleaner Production*, 395, p.136–391. https://doi.org/10.1016/j.jclepro.2023.136391
7. Climate Change Committee. 2019. Hydrogen in a low-carbon economy. https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/
8. AFRY, Climate Change Committee. 2023. Net Zero Power and Hydrogen: Capacity Requirements for Flexibility. https://www.theccc.org.uk/publication/net-zero-power-and-hydrogen-capacity-requirements-for-flexibility-afry/
9. National Energy System Operator. 2024. Future Energy Scenarios: ESO Pathway to Net Zero. https://www.neso.energy/document/321041/download
10. Royal Society. 2023. Large-scale electricity storage. https://royalsociety.org/-/media/policy/projects/large-scale-electricity-storage/large-scale-electricity-storage-report.pdf
11. Zgonnik, V. 2020. The occurrence and geoscience of natural hydrogen: A comprehensive review. *Earth-Science Reviews*, 203, p.103–140. https://doi.org/10.1016/j.earscirev.2020.103140
12. Ocko, I B, and Hamburg, S P. 2022. Climate consequences of hydrogen emissions. *Atmospheric Chemistry and Physics*, 22(14), pp.9349–9368. https://doi.org/10.5194/acp-22-9349-2022
13. Cardenas, B, Swinfen-Styles, L, Rouse, J, and Garvey, S D. 2021. Short-, medium-, and long-duration energy storage in a 100% renewable electricity grid: A UK case study. *Energies*, 14(24), p.8524. https://doi.org/10.3390/en14248524
14. International Energy Agency. 2023. Task 42: Underground Hydrogen Storage Technology Monitoring Report. https://www.ieahydrogen.org/tasks-reports/
15. IEA. 2022. Global hydrogen review. https://www.iea.org/reports/global-hydrogen-review-2022
16. Caglayan, D G, Weber, N, Heinrichs, H U, Linsen, J, Robinius, M, Kukla, P A, and Stolten, D. 2020. Technical potential of salt caverns for hydrogen storage in Europe. *International Journal of Hydrogen Energy*, 45(11), pp.6793–6805. https://doi.org/10.1016/j.ijhydene.2019.12.161
17. Tarkowski, R, and Uliasz-Misiak, B. 2022. Towards underground hydrogen storage: A review of barriers. *Renewable and Sustainable Energy Reviews*, 162, p.112–451. https://doi.org/10.1016/j.rser.2022.112451

British Geological Survey

18. Heinemann, N, Alcalde, J, Miocic, J M, Hangx, S J, Kallmeyer, J, Ostertag-Henning, C, Hassanpouryouzband, A, Thaysen, E M, Strobel, G J, Schmidt-Hattenberger, C, and Edlmann, K. 2021. Enabling large-scale hydrogen storage in porous media–the scientific challenges. *Energy & Environmental Science*, 14(2), pp.853–864. https://doi.org/10.1039/D0EE03536J

19. Lord, A S, Kobos, P H, and Borns, D J. 2014. Geologic storage of hydrogen: Scaling up to meet city transportation demands. *International journal of hydrogen energy*, 39(28), pp.15570–15582. https://doi.org/10.1016/j.ijhydene.2014.07.121

20. 20. James, B D, Houchins, C, Huya-Kouadio, J M, and DeSantis, D. 2022. Hydrogen storage system cost analysis. *Strategic Analysis Inc., Arlington, VA (United States)*. https://doi.org/10.2172/1975554

21. Thiyagarajan, S R, Emadi, H, Hussain, A, Patange, P, and Watson, M. 2022. A comprehensive review of the mechanisms and efficiency of underground hydrogen storage. *Journal of Energy Storage*, 51, p.104–490. https://doi.org/10.1016/j.est.2022.104490

22. Masoudi, M, Hassanpouryouzband, A, Hellevang, H, and Haszeldine, R S. 2024. Lined rock caverns: A hydrogen storage solution. *Journal of Energy Storage*, 84, p.110–927. https://doi.org/10.1016/j.est.2024.110927

23. Evans, D J, and Holloway, S. 2009. A review of onshore UK salt deposits and their potential for underground gas storage. *Geological Society, London, Special Publications*, 313(1), pp.39–80. https://doi.org/10.1144/SP313.5

24. Miocic, J M, Heinemann, N, Edlmann, K, Alcalde, J. and Schultz, R A. 2023. Enabling Secure Subsurface Storage in Future Energy Systems. *Geological Society, London, Special Publications*, 528,73–86. https://doi.org/10.1144/SP528-2022-88

25. Williams, J D, Williamson, J P, Parkes, D, Evans, D J, Kirk, K L, Sunny, N, Hough, E, Vosper, H, and Akhurst, M C. 2022. Does the United Kingdom have sufficient geological storage capacity to support a hydrogen economy? Estimating the salt cavern storage potential of bedded halite formations. *Journal of Energy Storage*, 53, p.105–109. https://doi.org/10.1144/SP528-2022-88

26. Kumar, K R, Honorio, H, Chandra, D, Lesueur, M, and Hajibeygi, H. 2023. Comprehensive review of geomechanics of underground hydrogen storage in depleted reservoirs and salt caverns. *Journal of Energy Storage*, 73, p.108–912. https://doi.org/10.1016/j.est.2023.108912

27. Zivar, D, Kumar, S, and Foroozesh, J. 2021. Underground hydrogen storage: A comprehensive review. *International journal of hydrogen energy*, 46(45), pp.23436–23462. https://doi.org/10.1016/j.ijhydene.2020.08.138

28. Thaysen, E M, McMahon, S, Strobel, G J, Butler, I B, Ngwenya, B T, Heinemann, N, Wilkinson, M, Hassanpouryouzband, A, McDermott, C I, and Edlmann, K. 2021. Estimating microbial growth and hydrogen consumption in hydrogen storage in porous media. *Renewable and Sustainable Energy Reviews*, 151, p.111–481. https://doi.org/10.1016/j.rser.2021.111481

29. Braid, H, Taylor, K, Hough, E, Rochelle, C, Niasar, V, and Ma, L. 2024. Hydrogen-induced mineral alteration: A review in the context of underground hydrogen storage (UHS) in saline aquifers. *Earth-Science Reviews*, p.104–975. https://doi.org/10.1016/j.earscirev.2024.104975

30. NESO. 2024. NESO Pathways to Net Zero, Accessed 19/11/2024. https://www.neso.energy/publications/future-energy-scenarios-fes/fes-documents

31. Aurora Energy Research (2023). Prioritising grid expansion is crucial to achieving Net Zero in Britain. https://auroraer.com/media/prioritising-grid-expansion-is-crucial-to-achieving-net-zero-in-britain/ [Accessed 15/01/2025].

32. Department for Energy Security and Net Zero. 2023. Hydrogen Storage Business Model: market engagement on the first allocation round. https://www.gov.uk/government/consultations/hydrogen-storage-business-model-market-engagement-on-the-first-allocation-round. [Accessed 19/11/2024].

33. Department for Energy Security and Net Zero. 2023. Energy Security Bill factsheet: Hydrogen transport and storage business models. https://www.gov.uk/government/publications/energy-security-bill-factsheets. [Accessed 19/11/2024].

34. HyNET. 2021. Potential Economic Impacts of the HyNet North West Project. https://hynet.co.uk/wp-content/uploads/2021/06/economic-impacts-report-040518.pdf

35. The Industrial Decarbonisation Research and Innovation Cluster, Arup, British Geological Survey, University of Edinburgh. 2024. Assessing the regional demand for geological hydrogen storage. https://www.arup.com/globalassets/downloads/insights/a/assessing-the-regional-demand-for-geological-hydrogen-storage.pdf

36. House of Lords Science and Technology Committee. 2024. Long-duration energy storage: get on with it. https://publications.parliament.uk/pa/ld5804/ldselect/ldsctech/68/6802.htm

37. DESNEZ. 2023. Energy Security Bill factsheet: Enabling the Hydrogen Village trial. https://www.gov.uk/government/publications/energy-security-bill-factsheets/energy-security-bill-factsheet-enabling-the-hydrogen-village-trial.

38. BBC. 2023. Ellesmere Port hydrogen heating trial scrapped after protests. https://www.bbc.co.uk/news/ukengland-merseyside-66165484 . [Accessed 19/11/2024].

39. BBC. 2023. Redcar hydrogen trial scrapped by government. https://www.bbc.co.uk/news/articles/c842wzn9g35o. [Accessed 19/11/2024].