Hydrogen Storage In Caverns – "Pilots and Demonstrators".

Report from the 2023 Energy Research Accelerator Event.

1. Executive Summary

- Consensus is growing that hydrogen produced from electrolysis and stored in caverns is the key long-term storage solution to intermittent power sources in net zero grids across North West Europe.
- Demonstration and pilot projects have proliferated and gained momentum in the last year as the industry works towards technical solutions. Several featured in the event are under construction with production and results expected in 2024.
- Further research and development is required urgently if the industry is to be functional and effective at scale in time to meet net zero targets.
- Gaps that need to be addressed by policy makers exist in:
    - Skills, particularly engineering.
    - Establishing appropriate standards for equipment and processes, for safety and environmental parameters.
    - Planning processes, such as DCO, which adds time to the already long process of creating new underground storages.
    - Funding opportunities and options appropriate to promote schemes at growing scale
    - Clear long term policies and business plans that give investors assurance needed to commit to large scale development.

2. Background: output and conclusions from previous events

- Energy stored as hydrogen in salt cavities will be the most cost-effective long duration storage solution to a net zero power grid in Great Britain and should form the backbone of intermittency mitigation (beyond daily cycles and variations).
- Dramatic falls in the cost of renewable generation mean that a combination of intermittent renewables and energy storage appears to be the lowest cost solution to a net zero power grid.
- Requirement for storage is driven more by unpredictable periods of “wind drought”, than the by winter/summer pattern of demand (that has historically driven gas storage provision).
- A diverse base of storage type and assets will prove economically optimal, and necessary for grid operability. Lower round trip efficiency will place hydrogen in the “slow cycle” storage role. Lower capital costs per GWh of output electrical energy means that hydrogen salt cavities will nonetheless provide most of the 40-140 TWh requirement.
- Great Britain’s geology provides sufficient suitable salt layer to accommodate this requirement and is a source of national competitive advantage.
- 2035 is effectively tomorrow. Urgency is required to deliver power-to-hydrogen-to-power (“P-H2-P”) storage assets in a timeframe useful to the 2035 net zero grid target. Technical challenges all appear surmountable – but the requirement to invent a new industry commercially and technically is nonetheless a huge task. The infrastructure and innovations required have significant lead times. We need to begin today – publishing “business models” in 2025 is not soon enough.

3. Acknowledgements

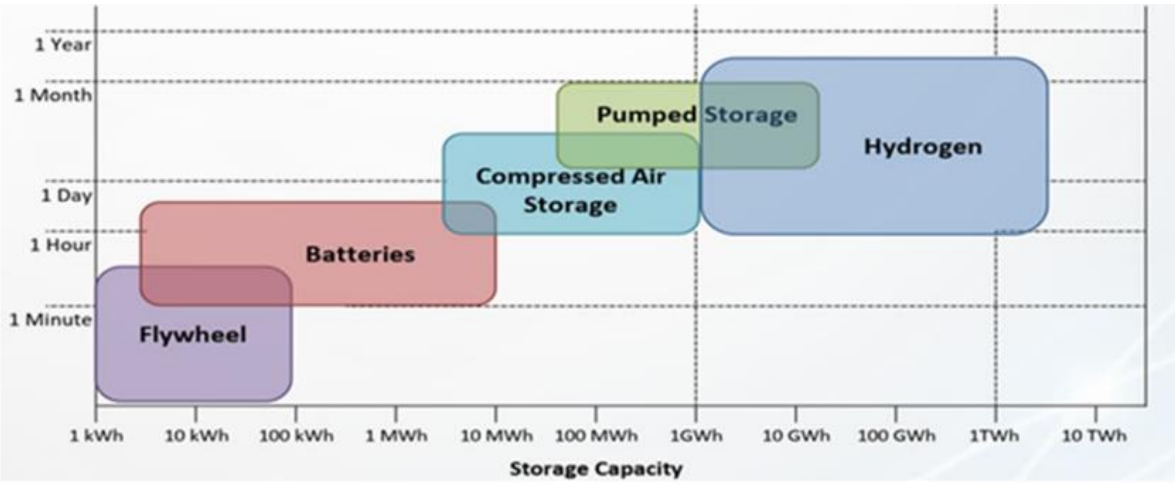
The Hydrogen Storage in Caverns 2023 - ERA Energy Research Accelerator event was run on 29th March 2023 by the University of Nottingham in conjunction with sponsors, the Geological Society, the Supergen Energy Storage Network Plus, The Hydrogen and Fuel Cell Supergen, and the Energy Research Accelerator. It is the third such event, following the successful Hydrogen Storage in Caverns Event 2021 (era.ac.uk) and Hydrogen Storage In Caverns 2022 - ERA Energy Research Accelerator events.

It is also one of a series of similarly funded events held in 2023 to address the overall energy storage requirement and challenges of a “Net Zero” power grid and economy – which commenced in March with the Energy Storage Policy Masterclass - ERA Energy Research Accelerator.

This report summarises the presentations made, and the panels observations, with the intention of providing policy makers and potential participants with a succinct reference source to the event.

We are grateful to all our sponsors and speakers for making the event happen. Attendance – in person and online - and interest proved very high. There were 489 registrations (70 in person, 419 online); as of July 2023, 235 people have also subsequently viewed the video and presentations on catchup.

Figure 1:



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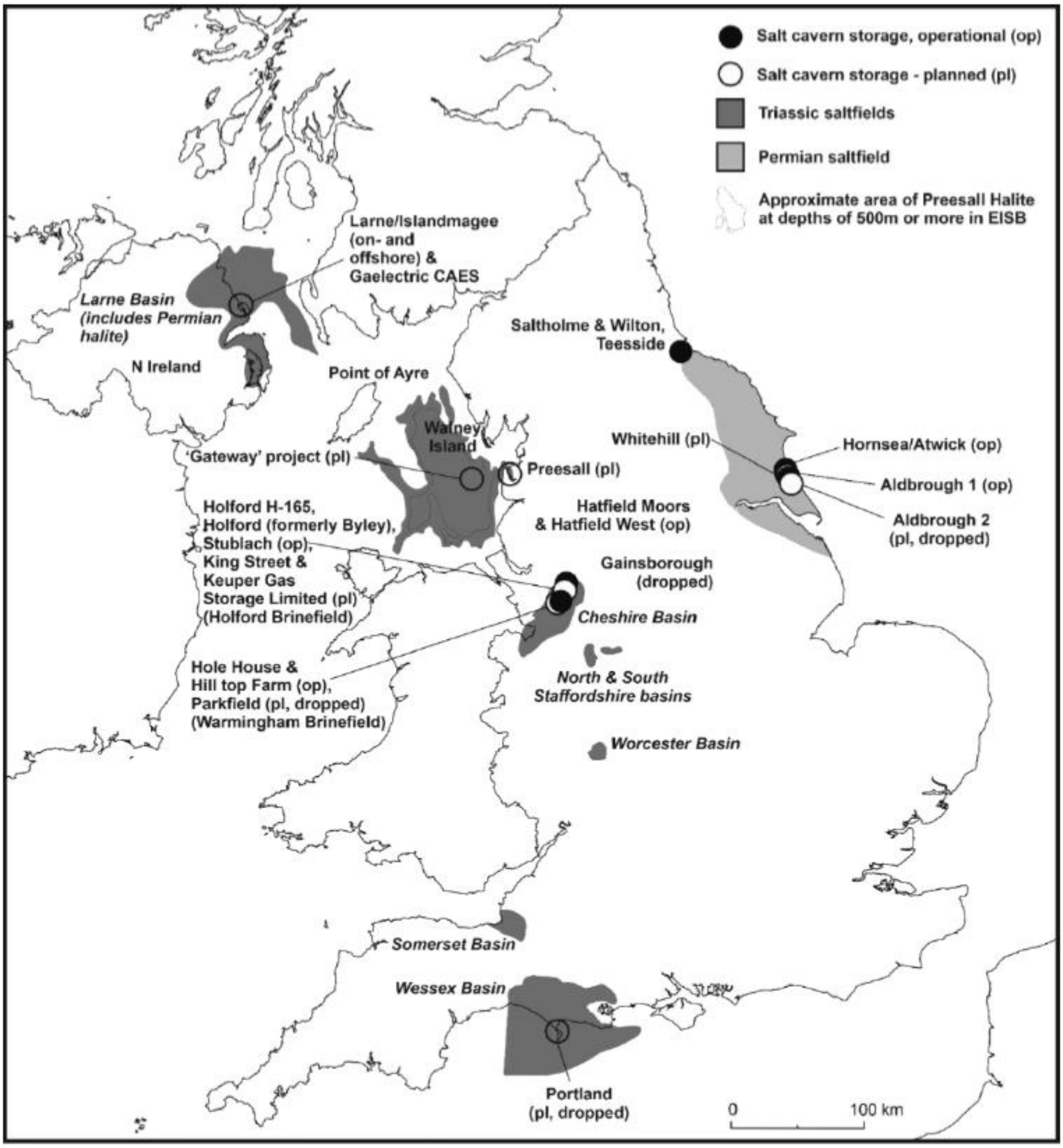

Figure 2: Map of saltfield resource in the UK

4. Summary of Presentations

There were ten presentations made, featuring 12 research and commercial organisations.

i. "The impact of hydrogen blending on existing gas storage infrastructure" - Rene Schneider - Uniper:
   - Hydrogen is the smallest molecule known; diffusion cannot be avoided, only slowed down.
   - Diffusion into materials can possibly result in change of mechanical properties; e.g. embrittlement.
   - A clear picture of the capabilities of installed equipment is essential.
   - Integrity of detachable connections and with instrumentation particularly important.
   - Limited standards only exist so far: EIGA* standard IGC Doc 121/14 "Hydrogen Pipeline Systems" sets material requirements for equipment used in H2 atmosphere.
   - Uniper is investigating a concept of "collect – limit – analyze – test – certify" to set wider standards and validate equipment.
     - Collect data and analyse critical aspects
     - Set tolerance limits (or apply existing ones)
     - Analyse material and equipment in relation to limits
     - Test existing equipment (with feedback loop)
     - Develop certified standard approach to all components used in injection, withdrawal, and generation process.
   - Rules and standards are the key to a safe and effective sector.
   - There are gaps and challenges; more research and validation is required urgently to address proposed transition timetables.

ii. "Hypster project – Large scale hydrogen underground storage in France" – Alan Leadbetter - Storengy
   - Storengy is the 4th largest underground storage operator in the world with 12 bcm of storage assets across France, Germany and UK.
   - HyPSTER stands for "Hydrogen Pilot STorage for large Ecosystem Replication"
   - The pilot project at a repurposed cavern in Etrez, France features:
     - 1MW Electrolyser
     - 3 Tonne of H2 Storage in Pilot Phase
     - Potential to increase to 44 Tonnes in Phase II.
     - €13m budget, including €5m funded by EU's Horizon 2020 programme.
     - Export of H2 in trailers to consumption sites.
   - Purpose of the pilot project is:
     - Test suitability of materials of construction
     - Test leak tightness of completion equipment
     - Characterise behaviour of the equipment during pressure cycling
     - Measure the interaction of hydrogen inside the cavern

        - Hydrogen dissolution in brine (in-situ)
        - Chemical and bacteriological reaction (in-situ)
    - Design phase commenced Jan 2021; construction phase commenced July/Aug 2022. Production expected to commence August 2023.
    - Initial results are expected H2 2024.

iii. “An overview of Corre Energy’s ongoing projects in Denmark and the Netherlands” – Hans-Age Nielsen - Corre Energy
    - Corre Energy is:
        - Working on a Compressed Air Energy Storage (CAES) project in Groningen, Netherlands.
        - Collaborating with Gas Storage Denmark A/S and Eurowind Energy A/S on a Green Hydrogen Hub which features both H2 and CAES storage in €1bn scheme
    - Co-located combination of H2 and CAES provides efficiency and flexibility.

iv. “Hydrogen pilot cavern development at Krummhorn, Germany” – Sebastian Boor - Uniper
    - Uniper operates 80TWh of gas storage at 9 facilities in 4 countries, making it a market leader in gas storage.
    - Uniper is developing a pilot project at Krummhorn featuring:
        - 1000m3 cavern operating in 70-270 bar pressure regime.
        - Total capacity of 700MWh, working capacity 500WMh of H2.
        - Connected electrolyser, import/export of H2 by trailer, filling station for H2 vehicles, export to transportation grid, power generation.
    - Purpose of the pilot project is:
        - Testing of H2 storage operation and technology in a real environment at a demonstration plant
        - Understanding of permitting process and requirements
        - Investigation of materials, subsurface and surface installations and the functionality of individual components in H2 storage operation
        - Development of a storage solution for green hydrogen on a commercial scale.
    - Construction is expected to start and complete in 2023, with first production and filling test early in 2024.

v. “The HyKeuper Project – Planning a large H2 storage in the UK” - Richard Applewhite -Inovyn
    - Ineos Inovyn is a €3.5bn turnover chemical sector leader. It is Europe’s largest electrolyser operator (for chlorine with co-produced hydrogen) and has in the past solution-mined 200 caverns in the Holford Brinefield, and been involved in the construction of 28 caverns now used for natural gas storage.

- Hykeuper is a project to convert existing planning permission for 19 new salt caverns from gas storage to hydrogen storage in Cheshire, UK. This would provide up to 1.3TWh of hydrogen storage.
- Front End Engineering Design (FEED) is currently being carried out on the surface and subsurface facility and safety case.
- Technical components researched include compression, dehydration, and multi-stage expander-generator.
- Hykeuper is collaborating with the Hynet project on potential integration into a regional hydrogen network.
- From Final Investment Decision (FID) the timeline would be approximately 11 years to commercial operation.

vi. “Business and commercial aspects of H2 storage in caverns” - Felicia Chang & Louis Day - Element Energy

- Element Energy is an economic consultancy, and part of the ERM Group. ERM is a major global sustainability, health, safety, risk and sustainability consultancy, which participates in low carbon projects from concept to design.
- There is a clear need for large scale, long duration storage in the future energy system: managing variation in renewable supply and energy demands.
- Hydrogen storage in caverns can be cost competitive with counterfactuals on a per capacity basis.
- There is a need to assess the counterfactual to hydrogen storage in caverns and understand customers’ willingness to pay, particularly for resilience space which is not heavily or frequently utilised.
- Large scale cavern costs are not high within the context of hydrogen supply chain. A hydrogen salt cavern could result in an increase of c. €0.50 for the levelised cost of hydrogen (LCOH), when fully utilised – compared to current H2 production costs 3.70-5.50 €/kg.
- By 2030, salt cavern storage will be valuable to the hydrogen sector based on projections for hydrogen demand and supply. If storage operators and governments act now, this work will support the next generation of projects, in turn enabling future projects to benefit from technical and commercial learnings.

vii. “Reducing Microbial Risk During Underground Hydrogen Storage” - Tim Armitage - Arup

- Arup Group Limited is a multinational professional services firm headquartered in London that provides design, engineering, architecture, planning, and advisory services across every aspect of the built environment; and for GeoEnergy and GeoStorage from concept and design to operation and decommissioning.
- Hydrogen storage requirement estimates for the UK vary from 7TWh to 150TWh.

- A typical salt cavity at 500m may hold 0.1TWh; where a large individual depleted gas field may hold 1000TWh. This makes investigation of porous media and depleted gas fields compelling.
- A key area of risk/concern is presence of H2-eating microbes, which create hydrogen sulphide (H2S).
- Key parameters that control microbial growth include Temperature and Salinity.
- 75 out of 173 existing depleted fields were analysed for suitability and categorised:
    - 9 No Risk/Sterile
    - 35 Low Risk
    - 22 Medium Risk
    - 9 High Risk
- Overlay of GIS maps shows that the Southern North Sea looks most promising for suitable No or Low Risk fields potentially accessible by repurposed infrastructure.
- Acknowledgement: Research presented by Tim into the field survey originated primarily from his PhD research while at the University of Edinburgh.

viii. <u>"Different ways to store H2 underground with a focus on lined rock cavern project from a business development standpoint" - Elodie Zausa - Geostock</u>
- Geostock is part of Vinci Construction Group, Grand Projets (Major Projects) Division; it is a global Consulting, Engineering, Construction management, Operation & Maintenance business focussed on all underground storage techniques.
- Massive storage infrastructure will be required to meet UK, EU and global targets and ambitions for H2 production; between 200 and 400 medium size underground storage might be needed by 2030-2035 to store hydrogen worldwide.
    - Salt caverns are a proven technology commercially available today where there is suitable salt layer.
    - Lined mined rock caverns is a solution to be considered for large scale storage of hydrogen where there is no salt. Marseille-Fos H2 Cluster's GEOGAZ Lavéra Project is an example study for 400-800 Tes of H2 on a site where LPG is currently stored in lined rock caverns.
    - Porous rock reservoirs research continues, getting ready for commercialisation as well: demonstrators may be required. Geostock is involved in the HYSTORIES (Project Leader).

ix. <u>"Towards demonstration and implementation of underground hydrogen storage" - Serge van Gessel - IEA Hydrogen TCP.</u>
- IEA are working to establish the "DNA" for safe and responsible demonstration and implementation of H2 storage underground.

- Approach breaks down to 4 dimensions:
  - Geological: screening, geological integrity, chemical/microbial effects, hydrology.
  - Technical: engineering of the facility, drilling, completion, operational parameters.
  - System: integration into the wider energy complex
  - Social: assess and promote cost, benefit, and environmental cases; societal acceptance.
- Covers lined rock caverns (shallow 10-30GWh), salt caverns (100-250GWh) and depleted gas fields and aquifers (100GWh – 20TWh).
- TRL implies 10 Years + lead time is required for commercial schemes.
- Significant work and successful pilot and demonstrators are required urgently to meet timescales.
- Most European demonstrator schemes are in feasibility and FEED stage; most are in salt caverns, some in porous media.
- Salt layer across Europe has a large theoretical potential far exceeding system requirement; however translation/filtering to feasible and effective sites is yet to be proven.
- At the current status work is required on all fronts to progress the feasibility and reduce the risk and uncertainties of underground hydrogen storage:
  - Industrial and Research communities: to reduce technical risks and uncertainties through experiment and pilot/demonstration schemes, with shared learning.
  - Energy sector and market design authorities: to reduce uncertainty with clear policy instruments and feasible business models
  - Industrial and safety regulators: improve and validate methodologies, establish best practice, standards.
  - Societal and governmental bodies: implement a structural approach to societal aspects; to improve and facilitate societal acceptance.

x. <u>"The State of Hydrogen Underground Storage Projects. A Real Sample under development in Utah" - Andres Fernandez and Tasos Stavrou (WSP):</u>
- WSP are a major global consultancy and professional services company based in Canada who work significantly in engineering and infrastructure.
- WSP see market trends alignment in favour of hydrogen and salt caverns:
  - Optimal complementary technology to intermittent sources, which have decreased in cost relative to firm generation (nuclear, CCS)
  - Optimal economically for longer durations (>1 day) and greater scale (>1GWh) storage deployments.
  - Significant end-to-end improvements in cost and efficiency are emerging from electrolysis production to H2 generation turbines.
  - Salt cavern storage is the most cost-efficient solution, with potential "LCOS" 0.30-0.60 $/Kg H2.

- ACES Delta Project in Utah is the world's largest green hydrogen storage project. Total storage capacity of ~ 20,000 metric tonnes = 6600 GWh (LHV) = 300GWh of dispatchable hydrogen-sourced electricity.
- Project is in the construction phase:
    - Engineering initiated 2021; field work started June 2022
    - Both wells currently drilled to a depth of 1.700m.
    - 41cm production casing set at ~1.300m.
    - Total of 120 drilling days per well.
    - Solution mining to start April 2023 @ 19.000 litres/min; cavern #1 to be completed July 2025 #2 by Dec 2026

Figures 3 & 4: Photographs of the ACES Delta project in Utah, currently under construction.

5. Panel Session:

Panel members and some of the points made by them during the Q&A were:

- Shabana Jamil (Head of Hydrogen Storage Business Model, Department for Energy Security & Net Zero)
  - The government is in listening mode currently, and hopes to put out "minded to" position on storage and transport business models later this year (published in August: Hydrogen transport and storage infrastructure: minded to positions (publishing.service.gov.uk))
  - The key priority is to lower market barriers which are considered to be:
    - Long lead-in time.
    - High cost.
    - Nascency of the market, causing developers uncertainty on demand risk.
  - A floor and potential profit share model is likely to be preferred.
  - A merchant market model is also preferred; albeit that strategic storage reserve may also develop.
  - The gas act inadvertly applies to hydrogen and adaptation is needed to create a suitable legal and regulatory framework.
- Frances Buckingham (Energy Engineer, Department for Energy Security & Net Zero)
  - Technical readiness level is far higher for salt cavity storage; porous reservoirs have enormous capacity potential, but the technical and standards readiness is far lower.
- Susannah Ferris – (Hydrogen Market Strategy Lead, National Gas Transmission)
  - National Grid Transmission (NGT) is now separated from National Grid plc, and owns and operates the high-pressure National Transmission System.
  - Project Union is NGTs lead initiative for hydrogen, developing a concept and plan to convert 2000km, or 25% of the existing gas transmission system to form a new 100% hydrogen backbone. The target is to begin conversion work in 2026.
  - NGT have a £10m project underway testing the integrity of legacy pipes at various blend levels from 2% to 100% hydrogen. Early results show that pipes that do not leak for methane do not leak for hydrogen; but those pipes that do leak, leak worse with hydrogen.
- Michael Wagner – (Hydrogen Advisor, AFRY).
  - Hydrogen storage caverns have a key double role in underpinning energy security, and making net zero affordable.
  - Broad connection of storage, production, and demand centres will play key role in security of supply.
  - In a net zero grid hydrogen storage cycling patterns will be determined by wind events rather than summer/winter seasonality; and so around five cycles a year are likely – much more than the one-to-two cycles that natural gas storage facilities have performed. This will create new technical challenges.

6. Links To Further Reading and Resources.

- Net Zero Power and Hydrogen: Capacity Requirements for Flexibility (AFRY report for the Climate Change Commission)
  - https://www.theccc.org.uk/wp-content/uploads/2023/03/Net-Zero-Power-and-Hydrogen-Capacity-Requirements-for-Flexibility-AFRY.pdf
  - https://www.theccc.org.uk/wp-content/uploads/2023/03/Net-Zero-Power-and-Hydrogen-Capacity-Requirements-for-Flexibility-Additional-Sensitivities-AFRY.pdf

- Large-scale electricity storage briefing (Royal Society Report by Professor Sir Chris Llewellyn Smith FRS, University of Oxford)
  - https://royalsociety.org/-/media/policy/projects/large-scale-electricity-storage/large-scale-electricity-storage-policy-briefing.pdf
  - https://royalsociety.org/-/media/policy/projects/large-scale-electricity-storage/large-scale-electricity-storage-report.pdf

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