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PRESENTS

# *Exploring the Geo-Technical Challenges in the development of safe, efficient, and scalable Underground Hydrogen Storage –UK case studies*


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- Research Students
- Teesside University

# The Biggest Challenge –Seasonal Energy

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Natural Gas currently provides Europe with  more than 1500 TWh of inter seasonal flexible energy.

**What is the magnitude of storing 1500 TWh in an energy storage system?**

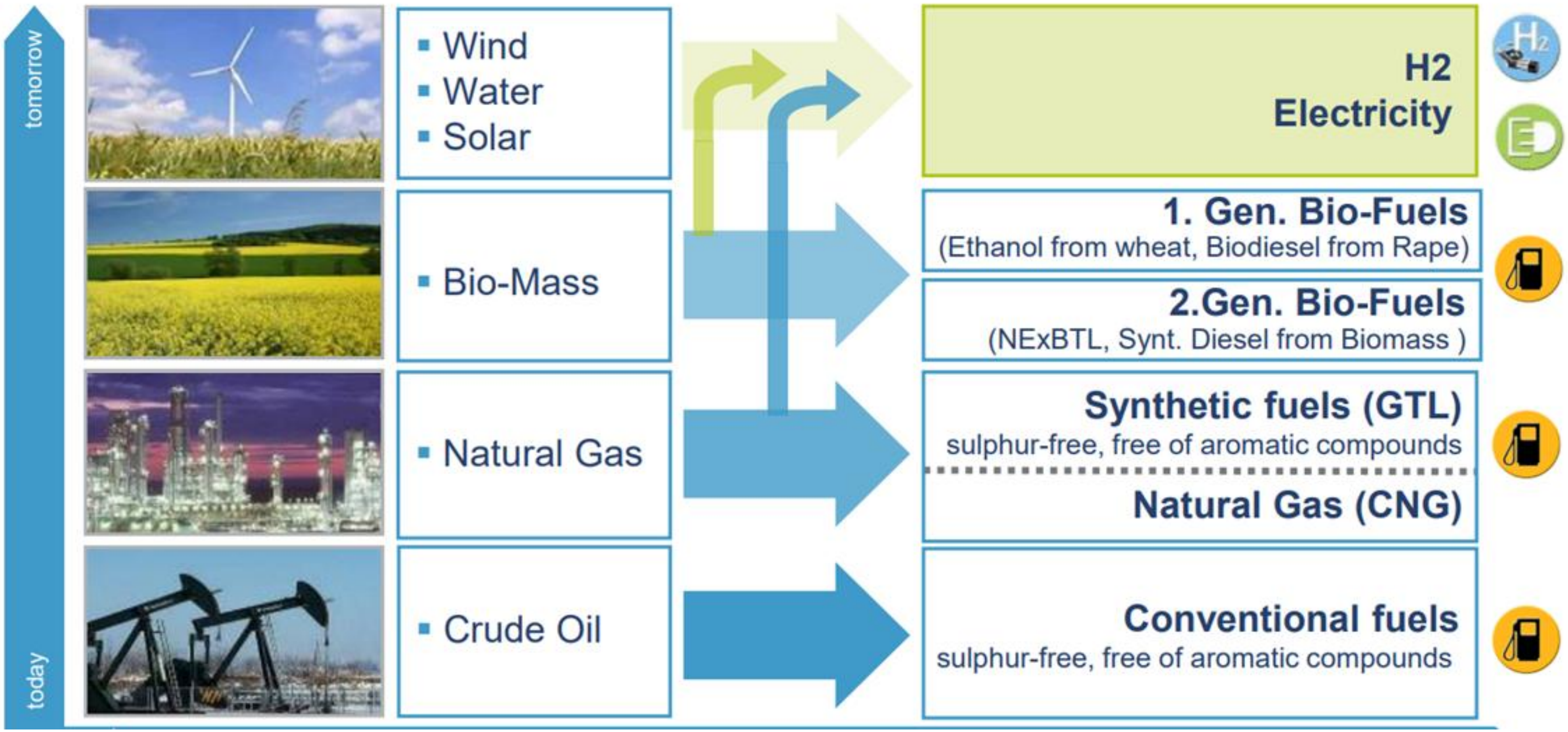
Number of cars:

Number of battery park:

Number of battery hydro power:

| Vehicle | Battery park | Hydro |
|---|---|---|
| 20 000 000 000 X | 11 600 000 X | 200 X |


# Variation of future fuels



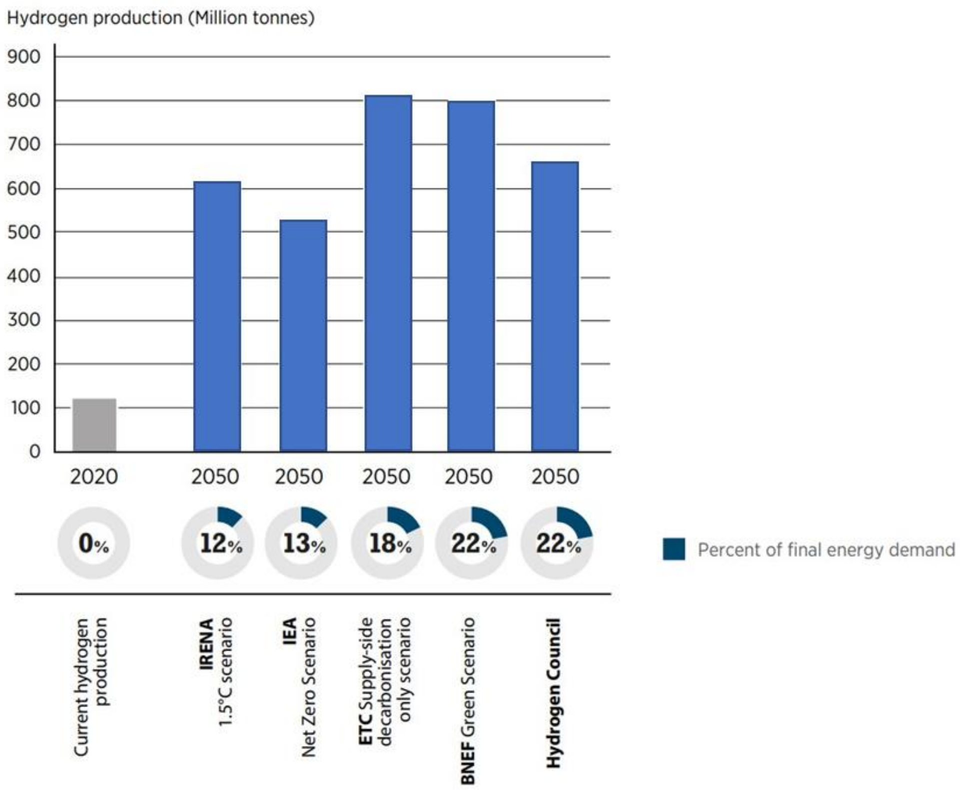
# World-wide hydrogen demand projections

**Factors enabling hydrogen uptake**

Governments worldwide have pledged to limit global temperature rise to 1.5°C by 2050, as laid out in the 2015 Paris Agreement

The increasing share of renewables can provide a significant opportunity to grow clean hydrogen technologies economically at scale

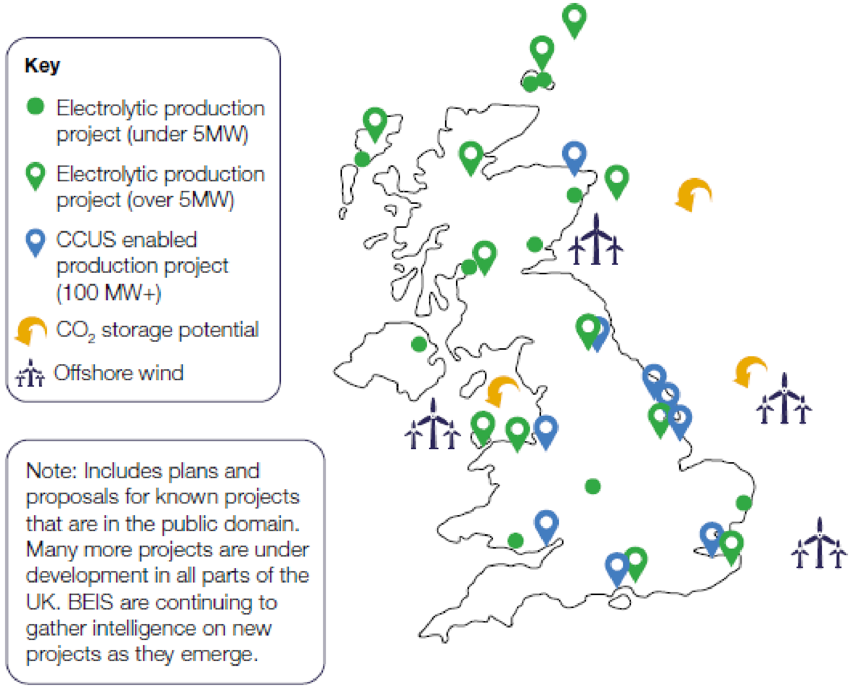
Energy security

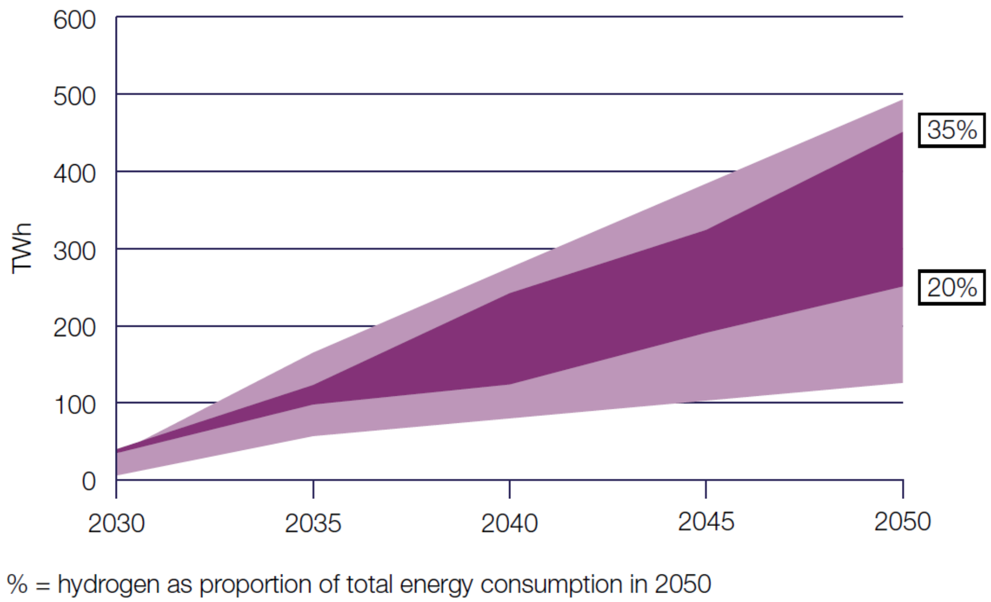



Source: IRENA, Geopolitics of the Energy Transformation

# Hydrogen in the UK

Analysis by the Department of Business, Energy & Industrial Strategy (BEIS) suggests **250-460TWh** of hydrogen could be needed in 2050, making up 20-35 % of UK final energy consumption.




**a million tonnes about 33 terawatt hours (TWh**).

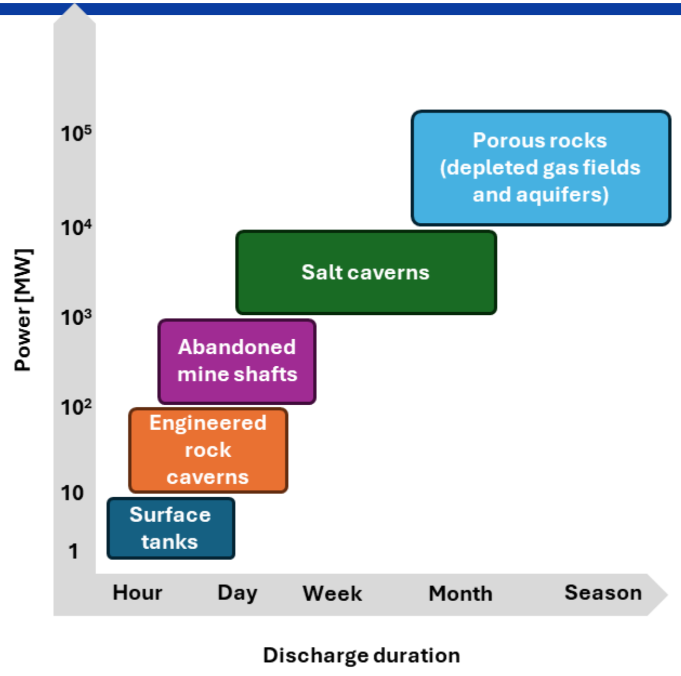
# Underground hydrogen storage

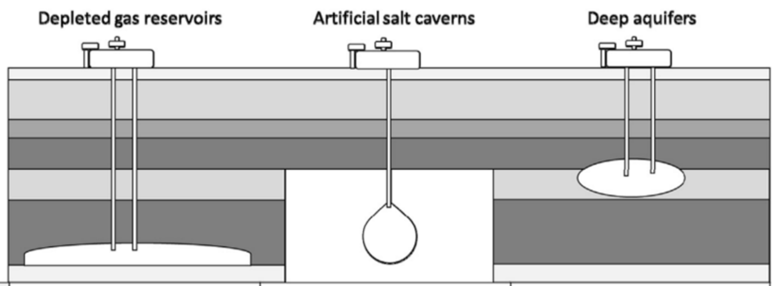
- **Safety of storage:** Underground facilities are less susceptible to fire, terrorist attacks, or military actions.

- **Space management:** Traditional surface tanks would have to cover extensive areas to store the same amounts of gas as in underground facilities; the relatively minor surface installations of the underground facilities are easier to integrate with the landscape and with existing infrastructure.

- **Economy:** The costs are much lower than those of surface facilities with a comparable capacity.

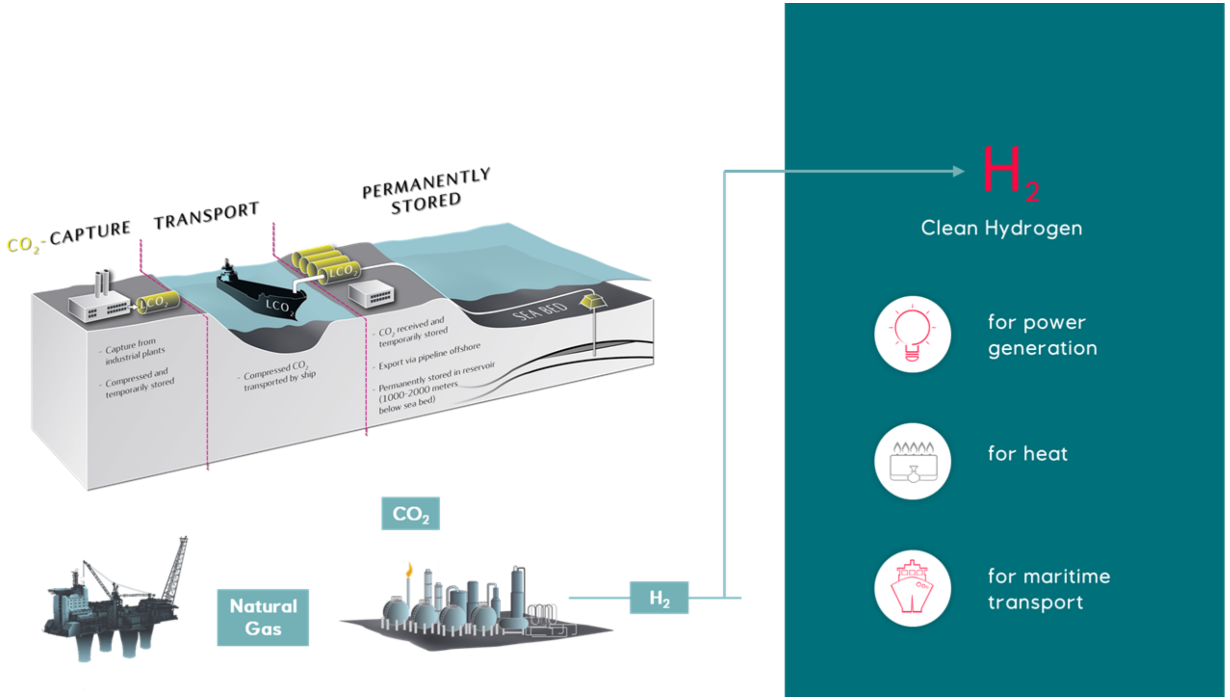
- **Availability of suitable geological structures:** These are common in many countries and over large areas.




| | Depleted gas reservoirs | Artificial salt caverns | Deep aquifers |
|---|---|---|---|
| Temperature range | high range | mostly 20 – 35°C | 7 – 174 °C |
| Salinity | high range | in sump up to saturation | 5 – 52.000 ppm |
| Experience for $H_2$ storage | low | high | very low |
| Knowledge on microbial activity during $H_2$ storage | low | very low | low |

# Hydrogen production and CCS

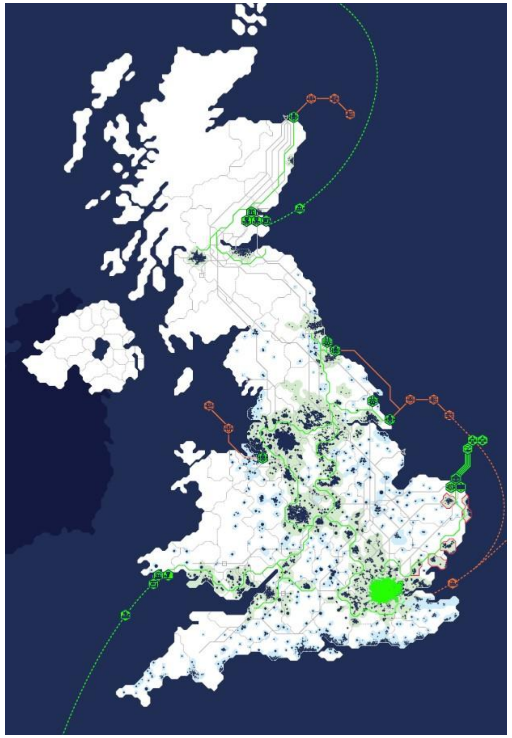



- Proven and referenced technology at scale (TWh-solutions)
- Build and commissioned at mega scale
- 95% CO2 reduction equal to a CO2 footprint of 14-15 g/kWh
- Robust and reliable design to meet customers demand
- Can deliver credible CO2 reductions for 2030 and 2050 targets
- Building upon a strong existing large scale industry

# Hydrogen production and CCS

## Northern Gas Networks and Cadent

H21 North of England – Meeting the Climate Change Act 2008



### Key Features

- Conversion start 2028 with stepwise expansion to 2035 replacing more than 3.7 million appliances
- Resilient design to fulfil security of supply during peak winter (the beast from the east)
- Design capacity of 85 TWh
- 12.5 million $CO_2$ per year avoided
- 12.1 GW hydrogen production in UK based on reforming of natural gas with CCS
- 8 TWh inter seasonal hydrogen storage in salt caverns in UK
- Offshore CO2 storage in either UK or Norway
- CO2 footprint: 14.47 g/kWh

# Hydrogen production and CCS-Case Study

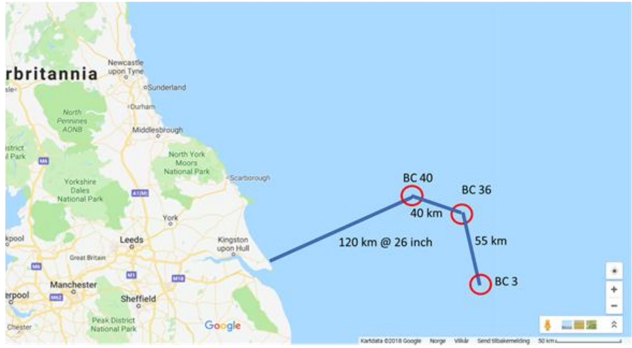
## H21 North of England – Meeting the Climate Change Act 2008


Greenfield Hydrogen Facility

- Location: Easington
- Capacity: 12.15 GW
- Configuration: Modular design and self sufficient with power


Hydrogen Storage

- Location: Aldbrough
- Capacity: 8 TWh
- Configuration : 56 salt caverns at 300,000 m3

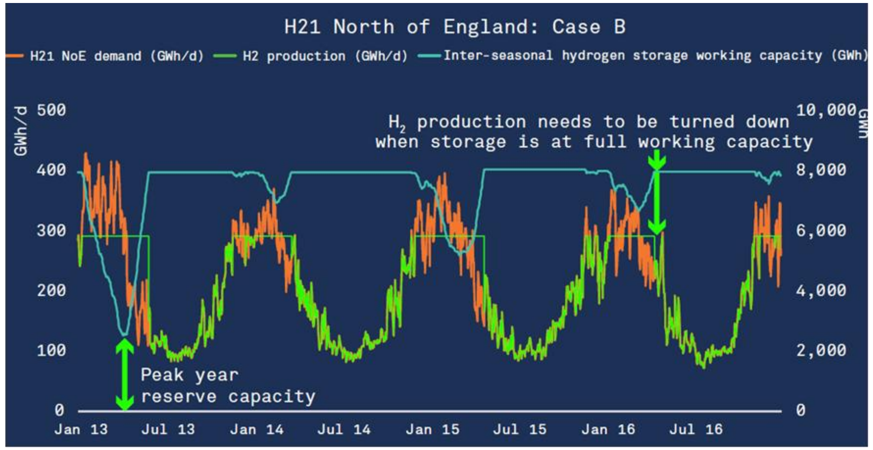



CO2 Storage

- Location: Bundter
- Capacity: +600 Million @ 17 mtpa
- Configuration: Saline aquifers

# Hydrogen production and CCS-Case Study

## Inter-Seasonal hydrogen storage




- Salt caverns – best suited/multiple cycles - proven
- Depleted oil/gas fieds and aquifers: Strategic storage 1-2 annual cycles – not proven
- Allows for optimisation of production and storage capacity

| PARAMETERS | CHESHIRE | TEESSIDE | YORKSHIRE |
|---|---|---|---|
| Type | Triassic | Permian | Permian |
| Depth (m) | 200-500 | 300-400 | 1,000-2,000 |
| Thickness (m) | 250-300 | 30-45 | 75-100 |
| Maximum pressure (bar) | 34-100 | 51-80 | 170-400 |

Table 4.6: Potential areas for hydrogen storage in salt caverns for the NoE

# Storage mechanism in porous rocks

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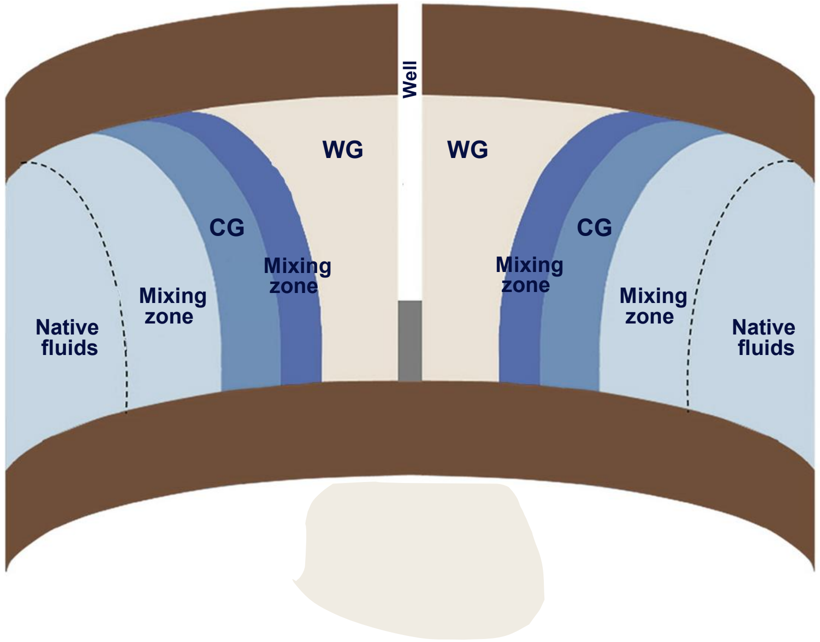
- **Working gas:** is the amount of gas that can be injected, stored and withdrawn during the normal commercial cyclic operation of the storage facility.

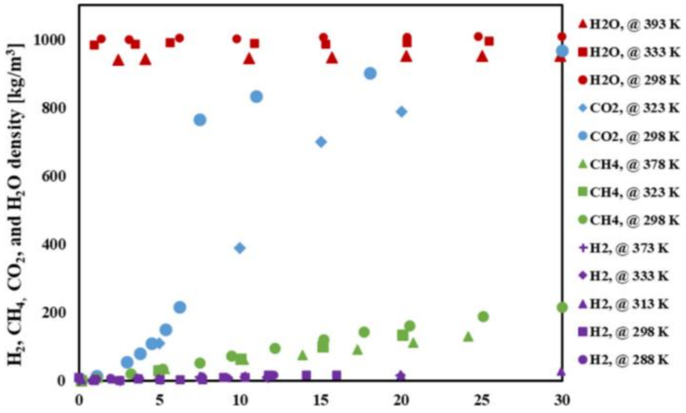
- **Cushion gas**: is the amount of gas that is permanently stored in the system. Its main function is to maintain sufficient pressure in the storage to allow for adequate injection and withdrawal rates at all times. Also, it prevents gas mixing with native reservoir fluids in aquifer or depleted fields. It can be the same type as the working gas, or a different gas.

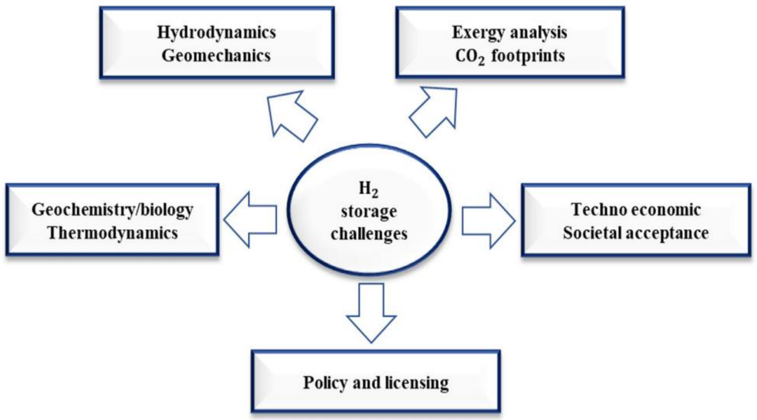


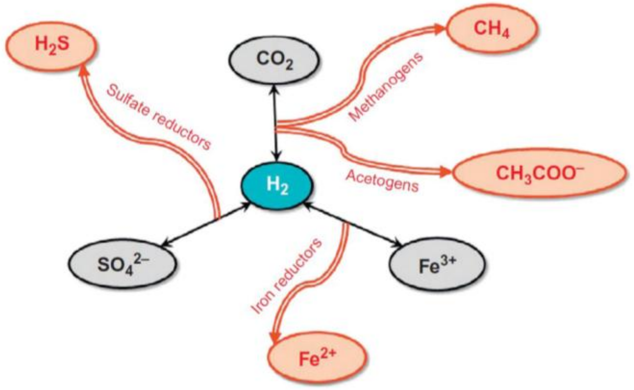
# UHS –Challenges

Scale – Challenges

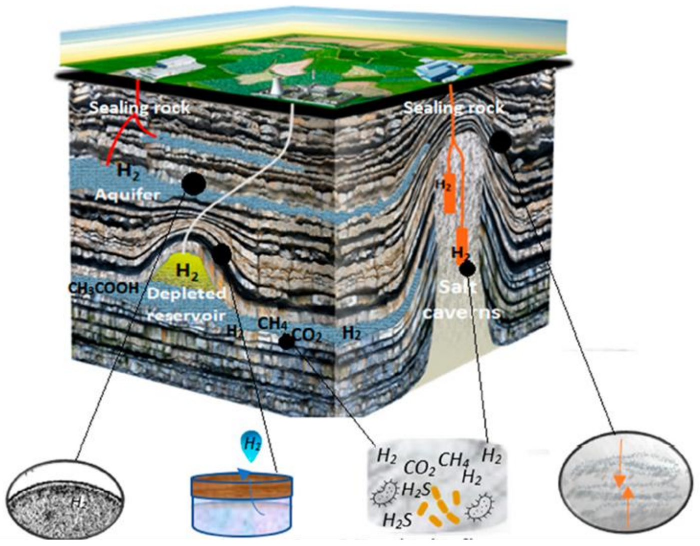
- **Containment** : Salt mines have stable strata and good trap conditions
- **Safety :** impermeable caprock along with a geologic structure to contain and trap gas
- **Storability and Injectivity :** High poro-perm reservoirs
- **Cushion Gas :** To maintain reservoir pressure and adequate withdrawal rate , 30-50% of the reservoir volume must contain cushion gas.
- **Microbiology:** The main microbial H2-utilizing terminal electron-accepting processes expected and identified to occur in UGS sites are **methanogenesis**, **sulphate reduction**, and **acetogenesis**)




N.S. Muhammed, B. Haq, D. Al Shehri et alEnergy Reports 8 (2022) 461–499




1 2 3 4

1. **Mineral dissolution/precipitation**
2. **Caprock integrity, $H_2$ diffusion and dissolution (loss)**
3. **Biotic reactions, $H_2$ consumption and contamination, geochemical reactions, mineral transformation**
4. **In-situ stresses, deformation, cracks**

# Potential Solutions to the Challenges

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## Repurposing depleted gas fields for hydrogen storage

**Benefits:**

- Well characterized due to years of exploration and development.
- Proven reservoir and caprock quality.
- Huge capacities suitable for grid-scale storage.
- Already equipped with necessary surface and subsurface installations.
- Less need for cushion gas.

**Technical Considerations**

- Reservoir tectonic characteristics (trap structure)
- Reservoir rock quality (NTG ratio, porosity, permeability)
- Maximum achievable hydrogen well deliverability rate
- Reservoir working gas capacity
- Risk of microbial activities

# Geo-Technical aspects for UHS

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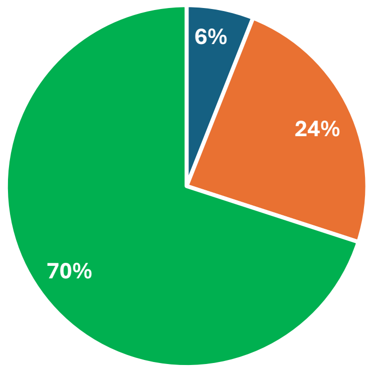
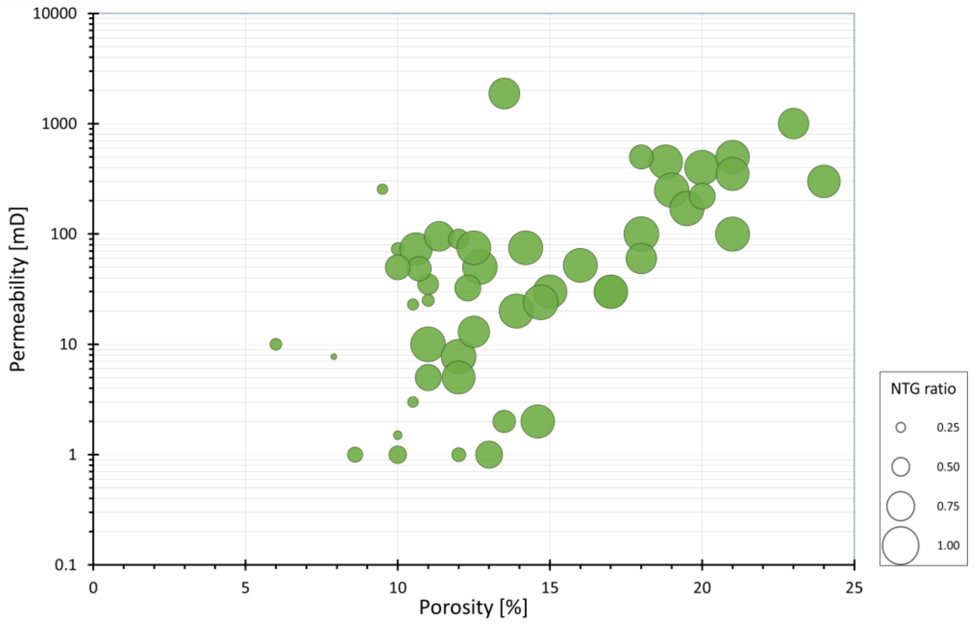
## Reservoir tectonic characteristics (trap structure)

- **Determined by the type of reservoir trap structure:**
  - **Domal anticline**
  - **Fault dependent**
  - **Hybrid, faulted anticline, stratigraphic**




- **Determined by average NTG ratio, porosity, permeability parameters**



# Geo-Technical aspects for UHS

## Maximum achievable hydrogen well deliverability rate

- Determined by calculating single well inflow and outflow performance equations

**Inflow performance**

$$m(P_r) - m(P_{bh}) = aQ + bQ^2$$

$$m(P) = \int_{p_0}^{p} \frac{P}{\mu Z} dp$$

$$a = 108.1762509 \frac{T}{kh}\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]$$

$$b = 0.203867 \frac{\beta\, T \gamma_g}{h^2\, \mu_w r_w}$$

$$\beta = \frac{2.017\times10^{11}}{k^{1.55}}$$

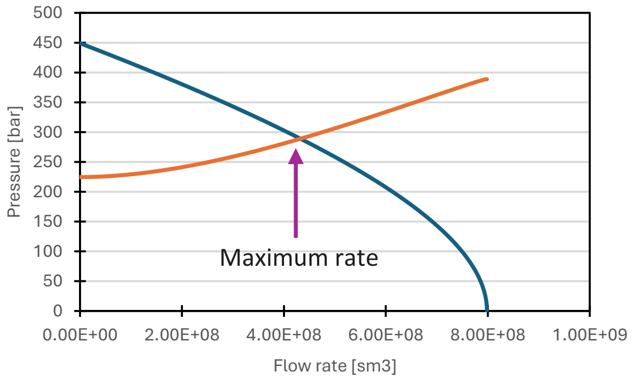
**Outflow performance**

$$P_{bh}^2 = e^s P_{wh}^2 + 93616.81 \frac{f Q^2\, Z_{ave}^2\, T_{ave}^2\, (e^S - 1)}{d_i^5\, \cos\,\theta}$$

$$S = 6.836286\times10^{-4} \frac{\gamma_g L\, \cos\,\theta}{Z_{ave} T_{ave}}$$

$$f = 4\left[2.28 - 4\log\left(\frac{\varepsilon}{d_i} + \frac{21.25}{N_{Re}^{0.9}}\right)\right]^{-2}$$

$$N_{Re} = 0.0150767 \frac{\gamma_g Q}{d_i\, \mu_{ave}}$$




Reservoir and well input parameters for calculation of deliverability rates

| Calculation type | Parameter | Value | Unit |
|---|---|---|---|
| Inflow performance | Tubing inner radius ($r_w$) | 0.125 | m |
| | Drainage area ($r_e$) | 500 | m |
| | Mechanical skin factor ($s$) | 0 | – |
| | Perforated reservoir thickness ($h$) | Equal to total reservoir net thickness above gas-water contact (GWC) | m |
| Outflow performance | Tubing roughness ($\varepsilon$) | $1.5\times10^{-5}$ | m |
| | Tubing length ($L$) | Equal to reservoir depth at mid reservoir thickness | m |
| | Well deviation angle ($\theta$) | 0 | degree |
| | Wellhead pressure ($P_{wh}$) | Half the initial reservoir pressure ($P_i/2$) | bar |

# Geo-Technical aspects for UHS

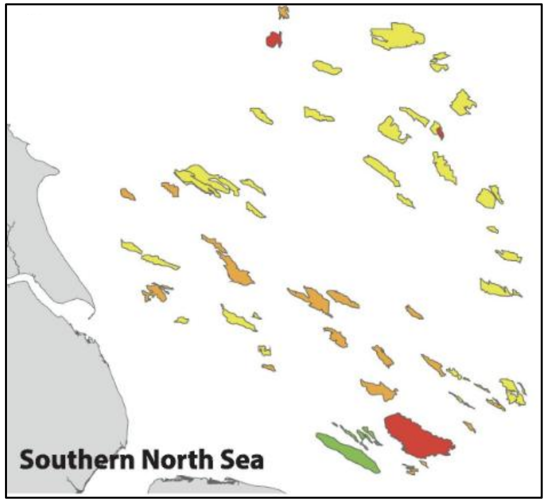


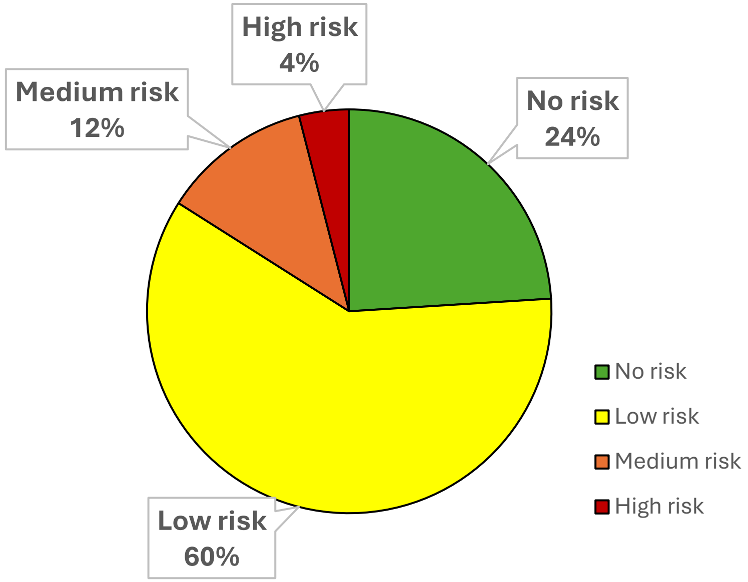
## Risk of microbial activities

- Categorized reservoirs based on microbial growth constraints:
  - Temperature
  - Salinity
  - Sulphate concentration

- **No risk** : Fields with a temperature above 122 °C
- **Low risk** : Fields with a temperature above 90 °C
- **Medium risk** : Fields with temperatures equal to or above 55 °C and salinities above 1.7 M NaCl
- **High risk** : Fields with a temperature below 55 °C

A sulphate concentration interval of 0–1250 mg $L^{-1}$ mark a risk reduction and > 1250 mg $L^{-1}$ sulphate for DGF at increased risk

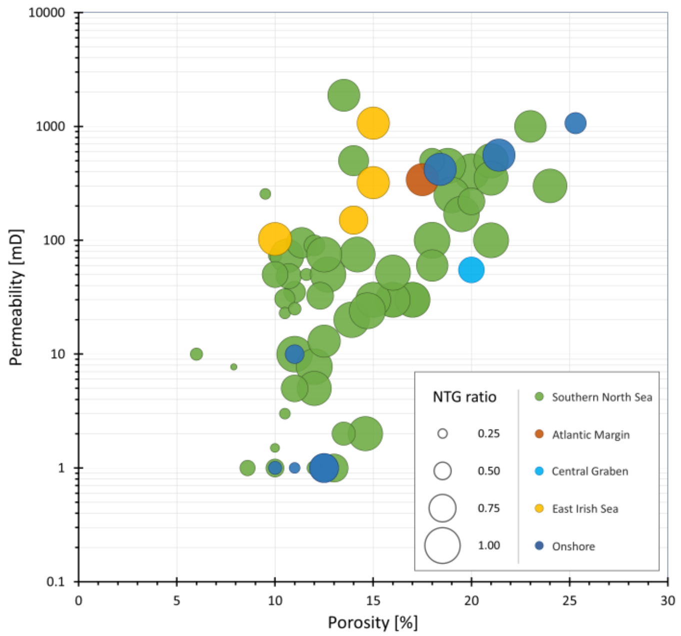


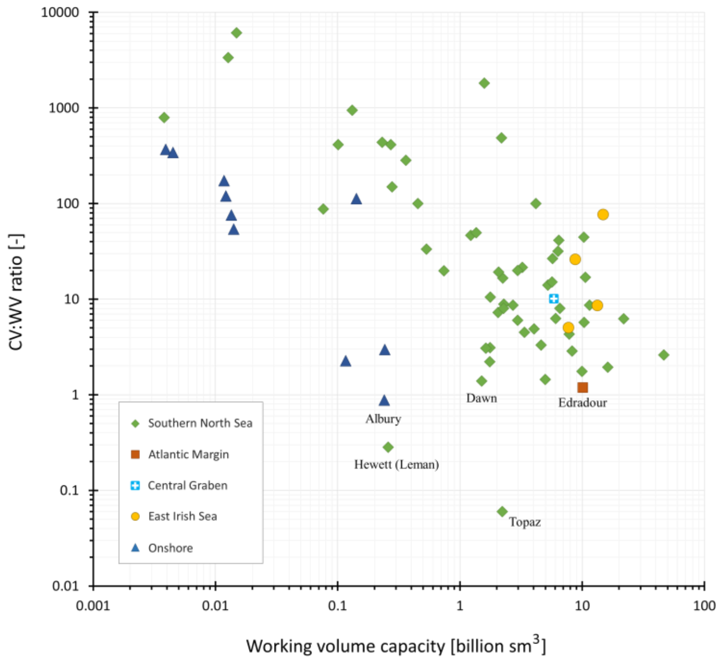

Based on the study of Thaysen et al., 2023

# Geo-Technical aspects for UHS

## Rock quality




## Working/cushion gas



# Case Study : Storage site: Bunter closure 36 – North Sea

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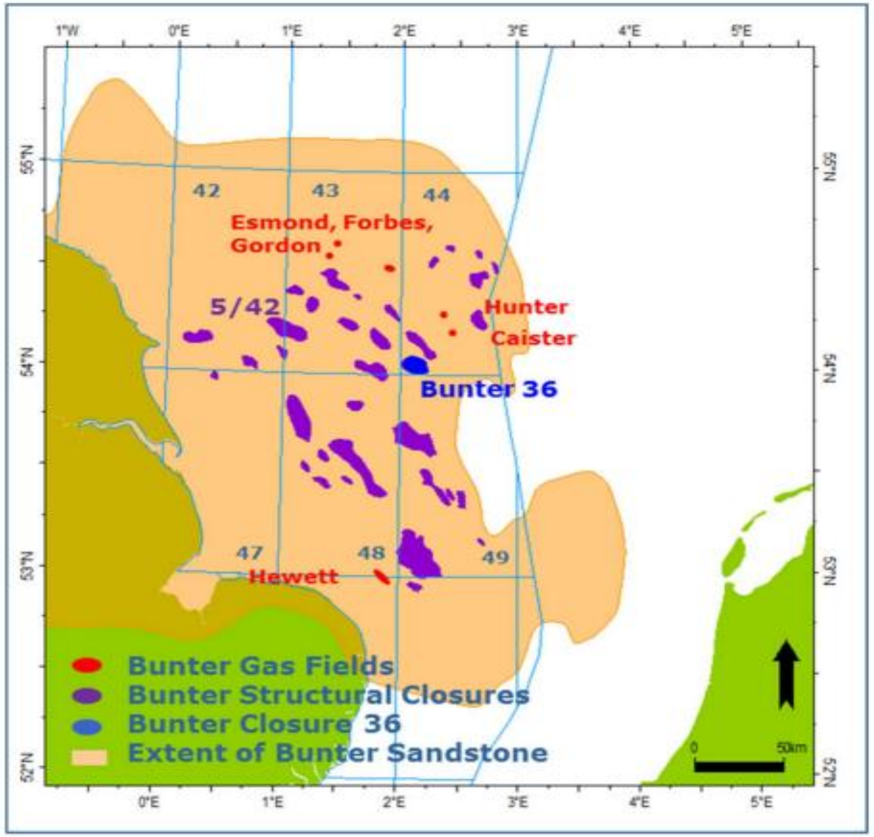
- Dome shaped/ elongate anticline structural closures within the Lower Triassic Bunter Sandstone Formation, Saline Aquifer
- Blocks 44/26 and 44/27 of the UK sector of the Southern North Sea (SNS), 150 Km off the Yorkshire coast
- The geological model of the reservoir was obtained from the Strategic UK CCS Storage Appraisal Project, funded by DECC,

| Reservoir Parameter | Value |
|---|---|
| Dimensions (km) | 25x25 |
| Number of Cells | 603,394 |
| Number of Gridblocks in Each Direction (i, j, k) | 124 x 134 x 41 |
| Average Porosity | 0.23 |
| Average Permeability (md) | 210 |
| Formation Top Depth (m) (DATUM) | 1171 |
| Formation Thickness (m) | 220 |
| Formation Net to Gross Ratio | 0.95 |
| Initial Pressure (bar) @ 1171m TVDSS | 119 |
| Temperature (°C) | 44 |
| Formation Water Salinity (ppm) | 205000 |

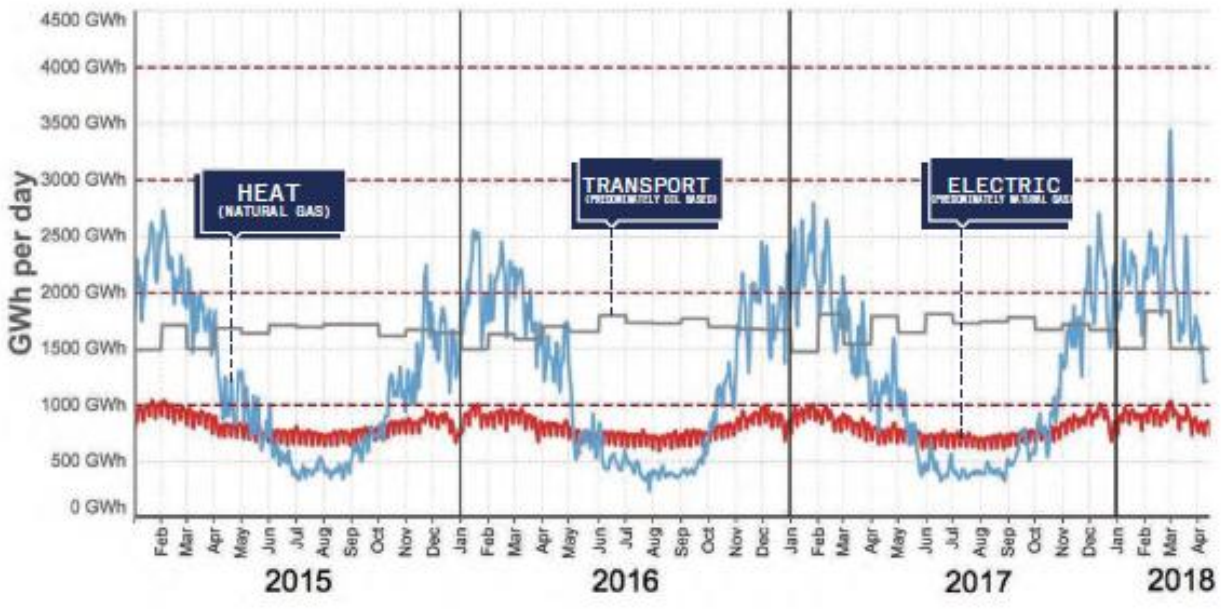



Source: Strategic UK CCS Storage Appraisal Project Report

# Demand Scenario: Decarbonisation of domestic heat by replacing Natural Gas

- Domestic heat accounts for almost a quarter of annual final energy consumption in the UK
- Heating is the greatest seasonal fluctuations
- Heating accounts for 1/5 of total emission
- 80% of building heating from gas network

Seasonal variations in different energy sectors




Source: H21 North O England Report

# Storage scenario based on heating demand

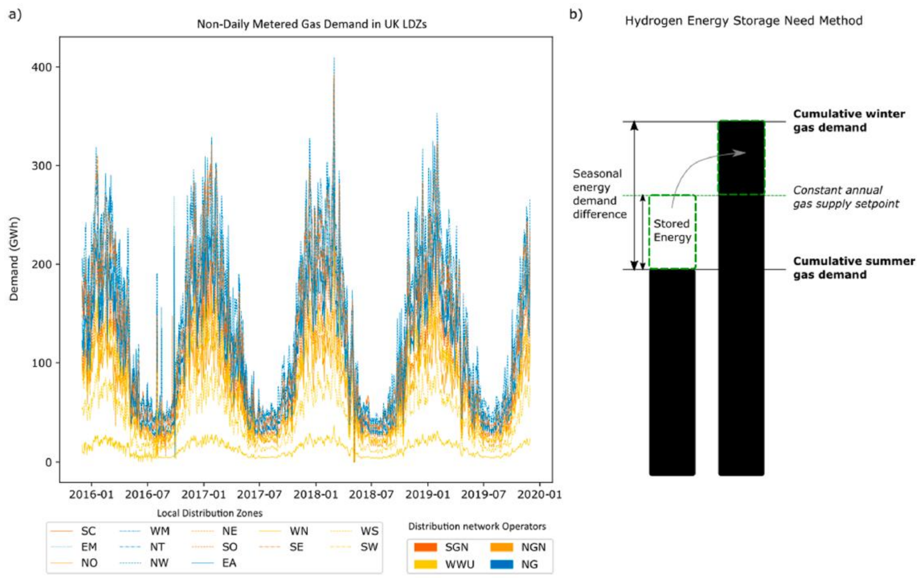
**Assumptions :**

- the hydrogen production facility is operating at a constant load throughout the year,
- surplus hydrogen can be injected during summer when domestic NG demand is lowest,
- Hydrogen withdrawn over cold days of winter when domestic NG demand is significantly higher

- the total hydrogen energy demand of the UK based on this approach would be around 77.9 TWh,

- 4.8 TWh would be needed in the North East area

- Considering the $H_2$ lower calorific value, around 1.6 billion $sm^3$ of $H_2$ is required to meet 100% domestic heat demand of the North East UK



# Research questions

- How much of the domestic heat energy demand of the North East UK can be responded by the selected storage site?

- What are the impacts of well number/placement on overall performance of storage (i.e., Working gas capacity, well injectivity/productivity, purity of produced gas)?

- How will the storage performance change after multiple injection/withdrawal cycles?

# Numerical simulation scenario

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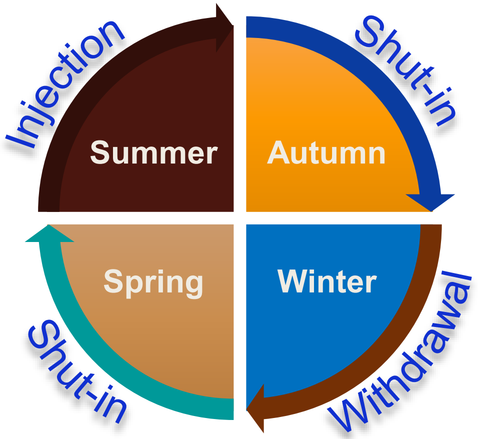
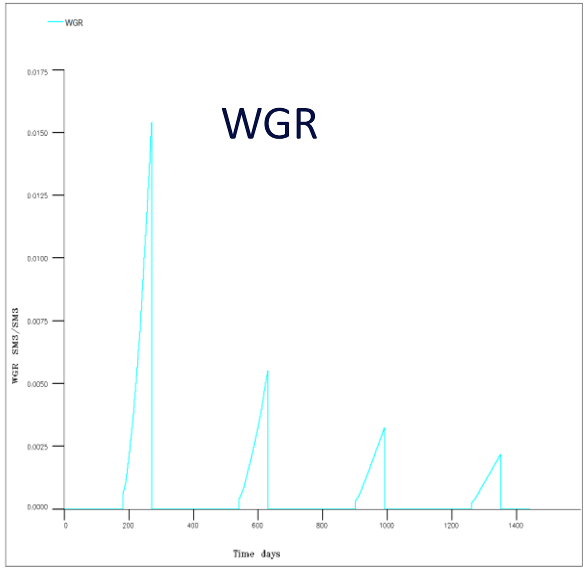
- Numerical simulation was carried out using Eclipse 100 software in a regional-scale reservoir model of the aquifer[5]
- $H_2$ was injected during summer and withdrawn during winter for 4 consecutive annual cycles
- $H_2$ was injected at the highest achievable rate allowed by upper bottom hole pressure (BHP) limit (based on geomechanical constraints)
- $H_2$ was withdrawn at an average daily rate for each well based on the volume of injected gas and lower BHP limit
- $H_2$ storage performance in multiple well pattern scenarios involving 1, 3, 7, and 9 wells with various well spaces from 300m to 1500 m was evaluated

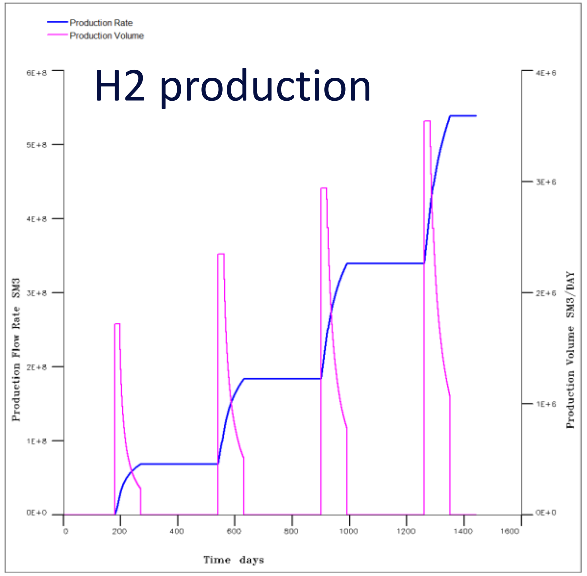


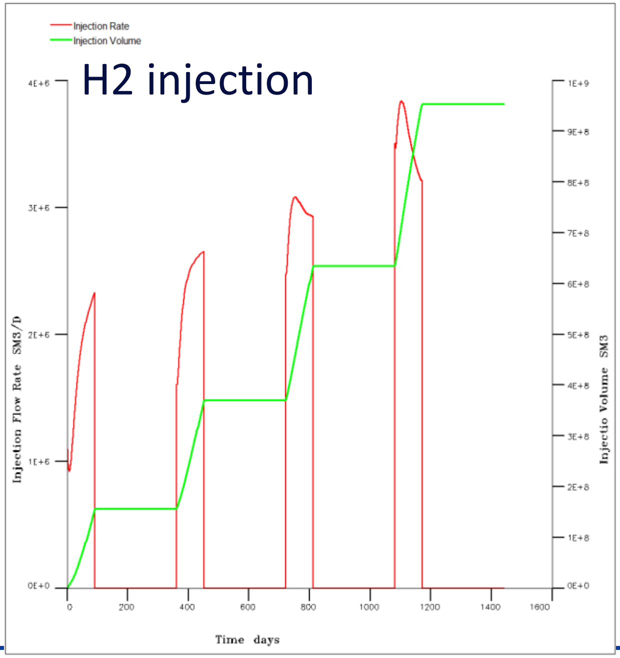

Storage Cycle

# Single injection/withdrawal well placed at the crest of the reservoir

- Well injectivity and productivity increased after each cycle
- The volume of working gas increased after each cycle
- Water/Gas Ratio (WGR) during production decreased after each cycle

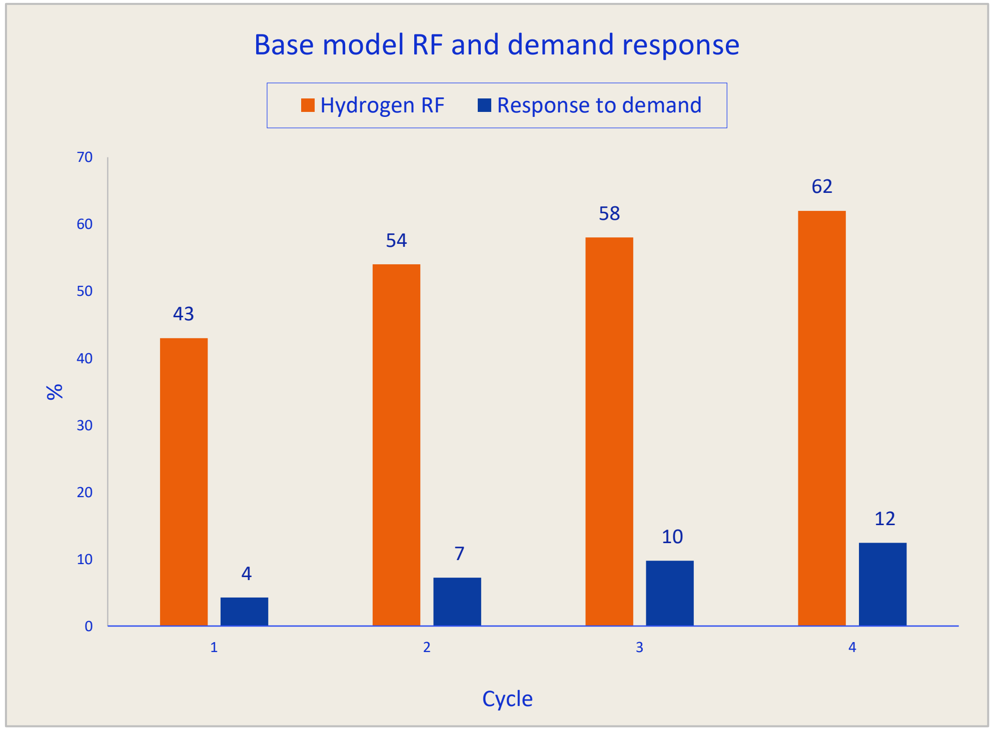


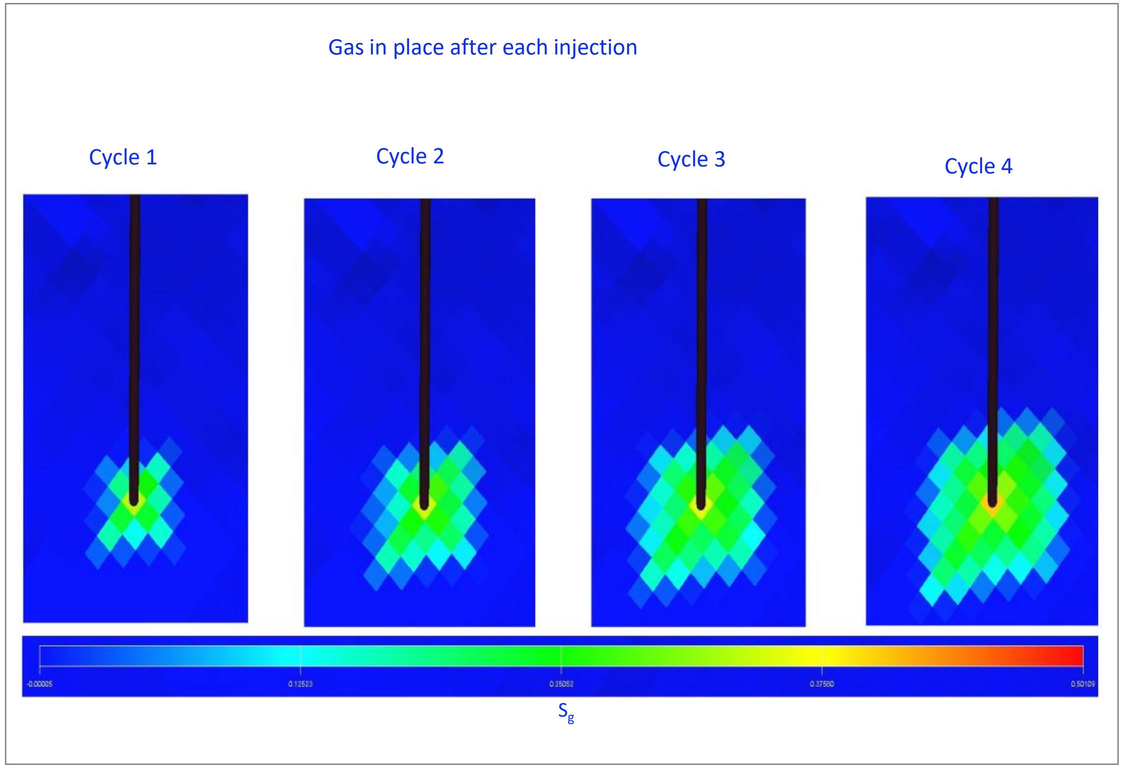




4 Cycles ( 6 months injection and 6 months production)

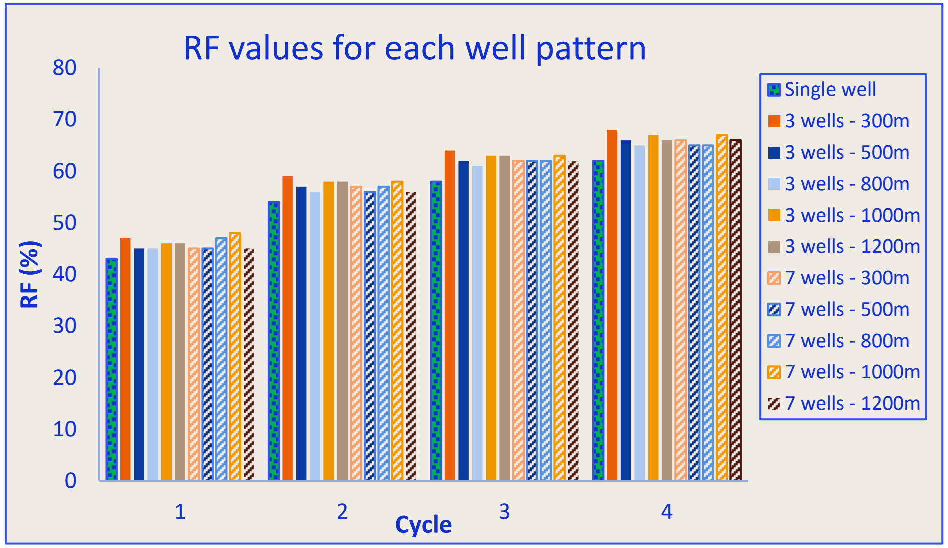
- Hydrogen Recovery Factor (RF) increased after each cycle, leading to a higher response to the demand

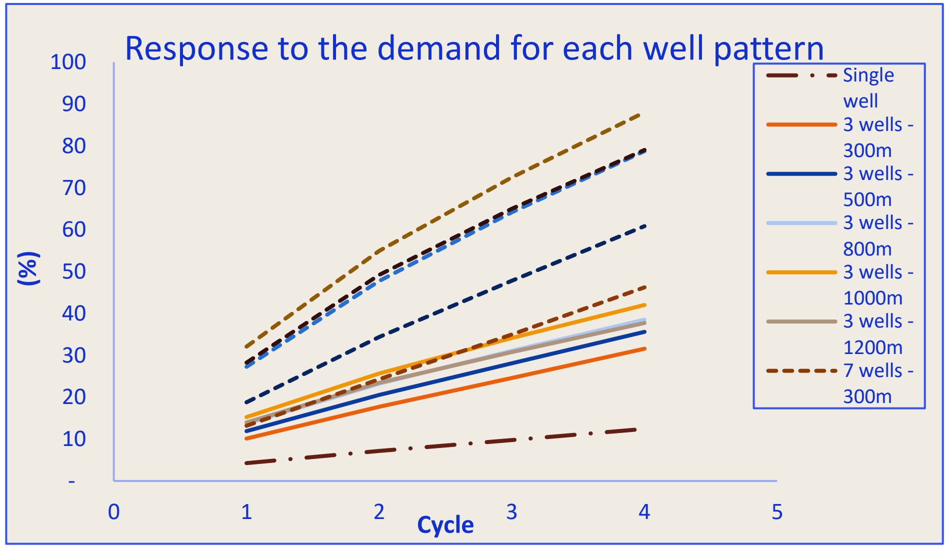


# Well pattern design:
# Well distance and well Number

- Reservoir $H_2$ capacity and well injectivity/productivity increased significantly with number of wells, which led to a higher response to the demand
- Well distance had also a critical role in reservoir $H_2$ capacity and well injectivity/productivity
- However, the impact of well pattern design on RF is insignificant





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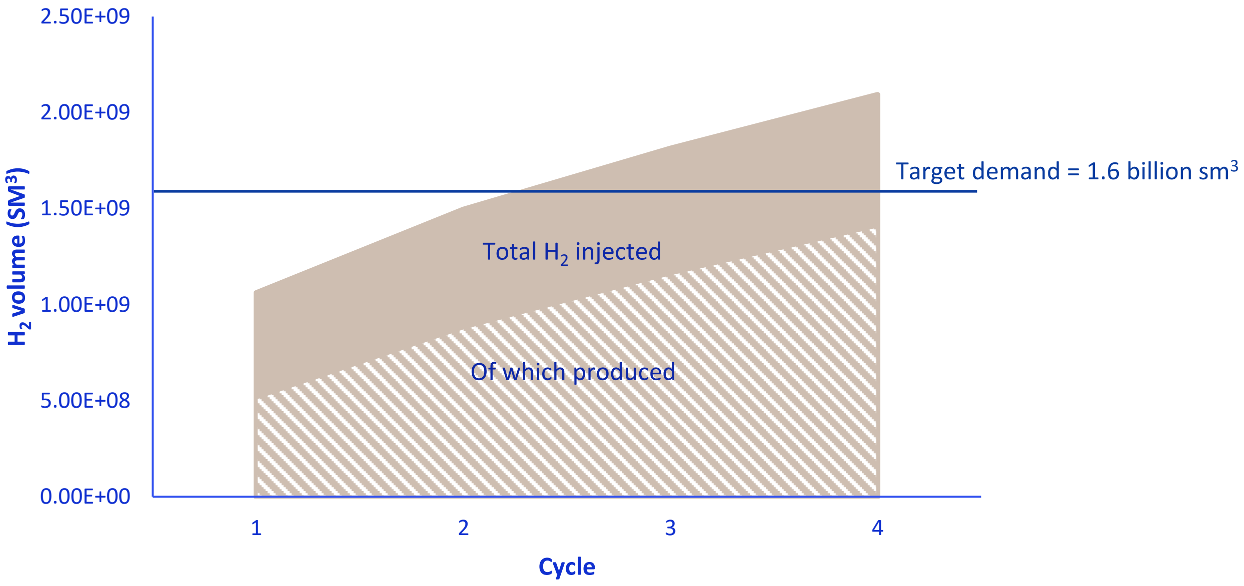
# Optimal well design to respond to the demand

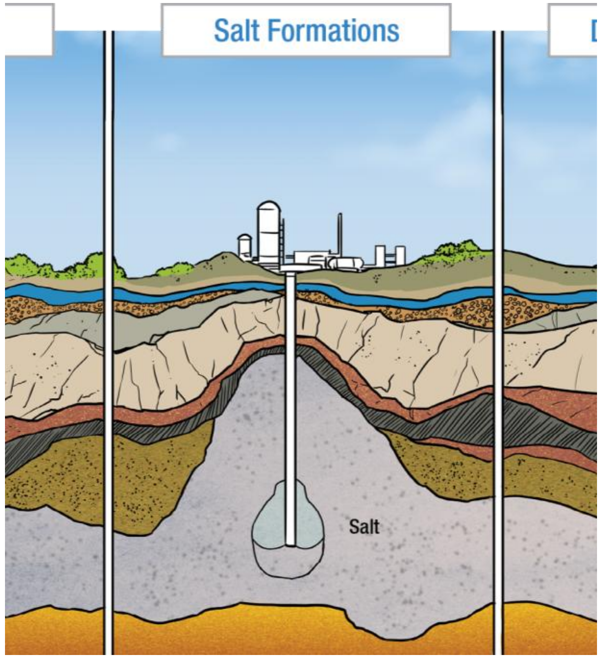
- The highest reservoir $H_2$ capacity and demand response was achieved by the 7 well pattern with distance of 1000m between each well

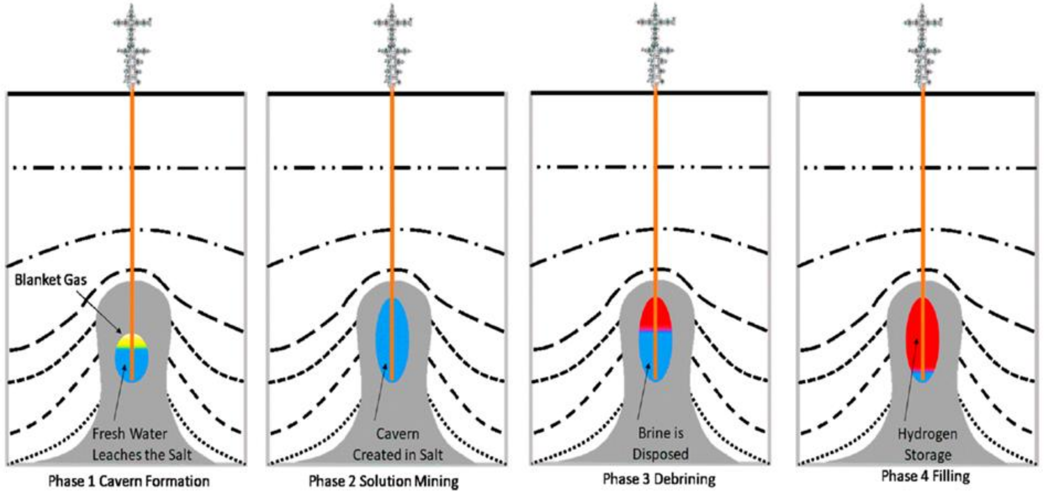
| Cycle | Injection volume (billion $sm^3$) | Production volume (billionn $sm^3$) | RF (%) | Response to demand (%) |
|---|---|---|---|---|
| 1 | 1.06 | 0.513 | 48 | 32 |
| 2 | 1.50 | 0.879 | 58 | 55 |
| 3 | 1.81 | 1.16 | 63 | 72 |
| 4 | 2.09 | 1.41 | 67 | 88 |



# UHS in Salt Cavern

- Salt caverns are alternatives to porous storages.
- They are created as artificial cavities in underground salt formations using solution mining process, whereby water is injected at high pressures to dissolve the salt rock.
- Potential formations include salt domes, salt pillows, and bedded salts.
- The volumes of a single salt cavern can vary from 150,000 to 1,000,000 $m^3$.
- The storage and recovery of hydrogen involves its compression and decompression, between the minimum and maximum working pressure, depending on the depth of the cavern's location.



# Evaluate long-term geomechanical stability of hydrogen storage in salt caverns.

**Specific Objectives:**

1. Assess stress, strain, and volume convergence over time.
2. Investigate the effects of cyclic loading from gas injection/withdrawal.
3. Identify key operational parameters affecting stability.

**Location**: East Yorkshire, UK

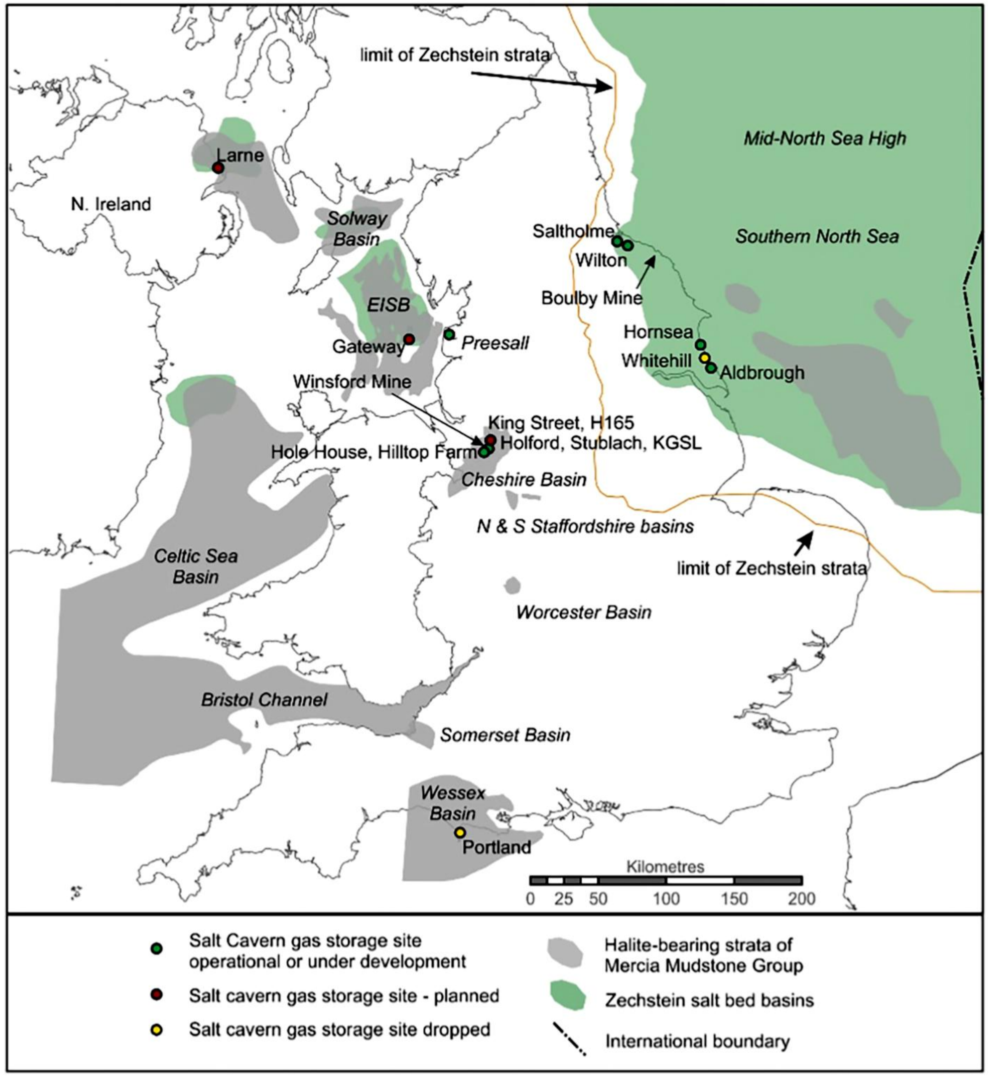
**Geological Formation**: Zechstein Group Halite

**Key Layers**: Z1–Z5 stratigraphy

**Salt formation**: Fordon Evaporites (Z2)

**Storage site**: Atwick

**Existing Storage**: Originally used for natural gas storage



# Workflow

**Numerical modelling approach:**

- 3D finite element modelling using FLAC software.

**Modelling parameters:**

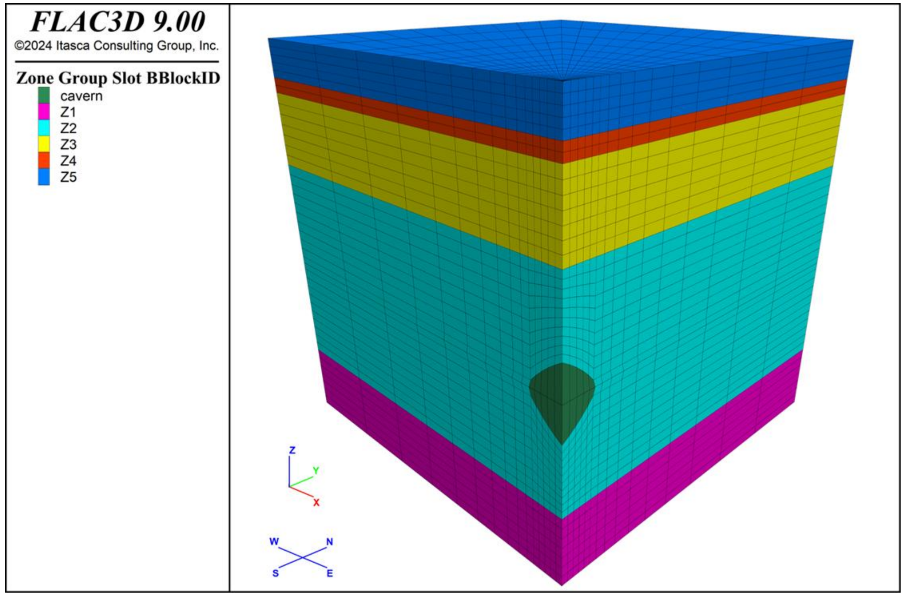
- Drucker-Prager model for non-salt layers and Viscoelastic WIPP model for salt rock

**Simulation Scenarios:**

- Initial stress equilibrium
- Cavern excavation
- 16 cycles of natural gas storage, followed by 30 cycles of hydrogen storage
- Each cycle was divided into four stages, gas injection, shut-in, withdrawal, and a final shut-in period, each lasting three months
- The minimum and maximum operating pressures were set to 120 and 270 bar, respectively (150 bar swing)

**Sensitivity analyses for:**

- Cycle duration variations (phase durations: 1.5, 3, 6 months)
- Pressure fluctuation impacts (the pressure swing reduced by 30% and 50%)




Key Geomechanical Parameters investigated:

- Stress & Strain Analysis
- Creep-Induced Deformation
- Volume Convergence Estimations

# Geological data

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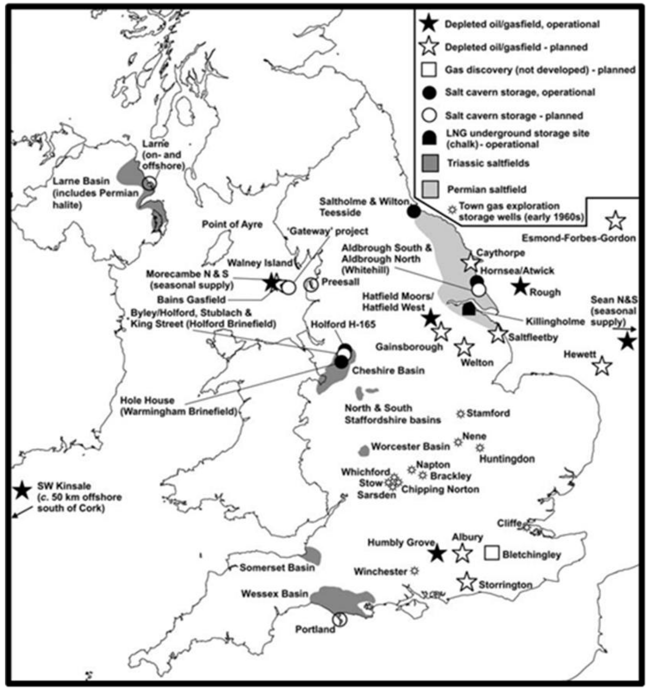
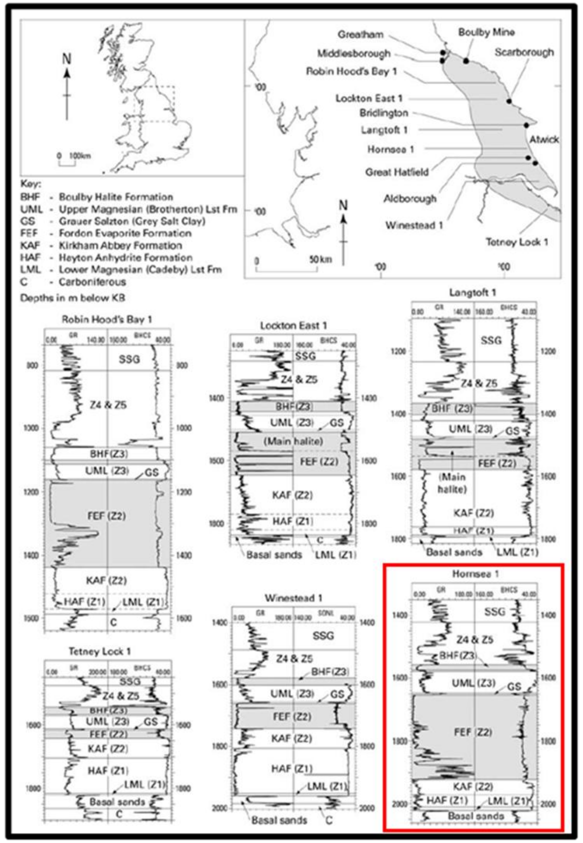
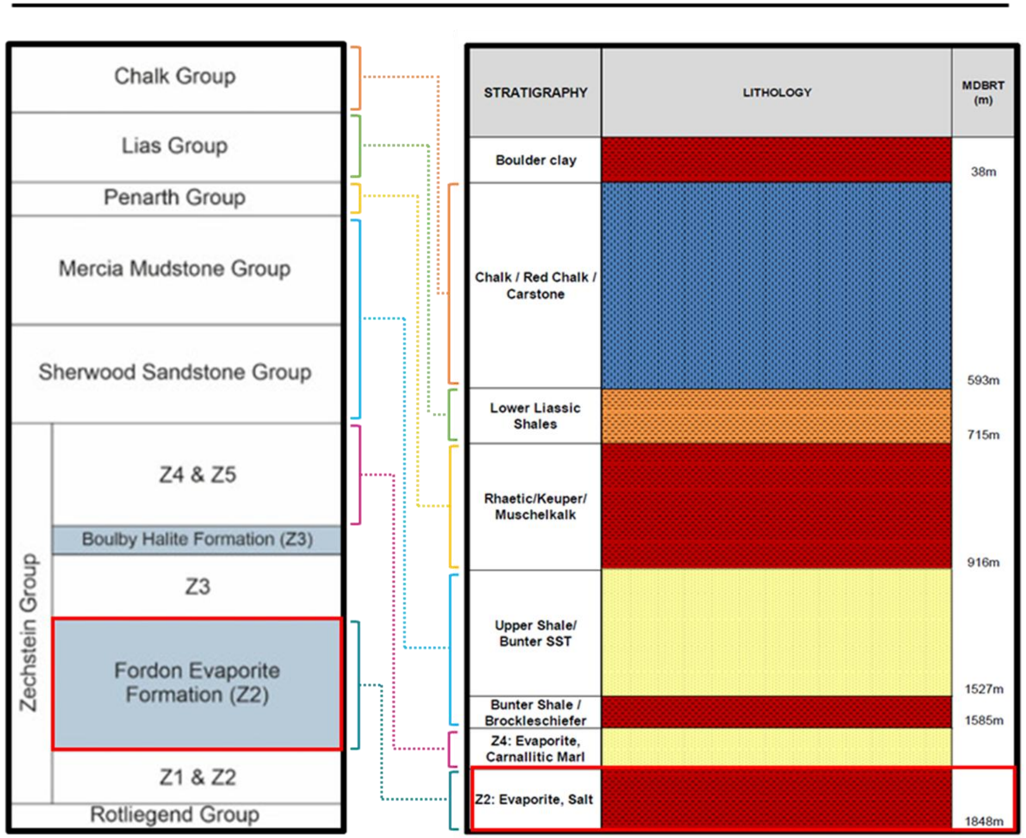



(Evans, D. J., and S. Holloway, 2009)




(Evans, D. J., and S. Holloway, 2009)

## Atwick Site




(Williams, John D. O. et al., 2022)

(Environmental Impact Assessment Scoping Report, 2023)

Workflow

# Rock mechanical properties

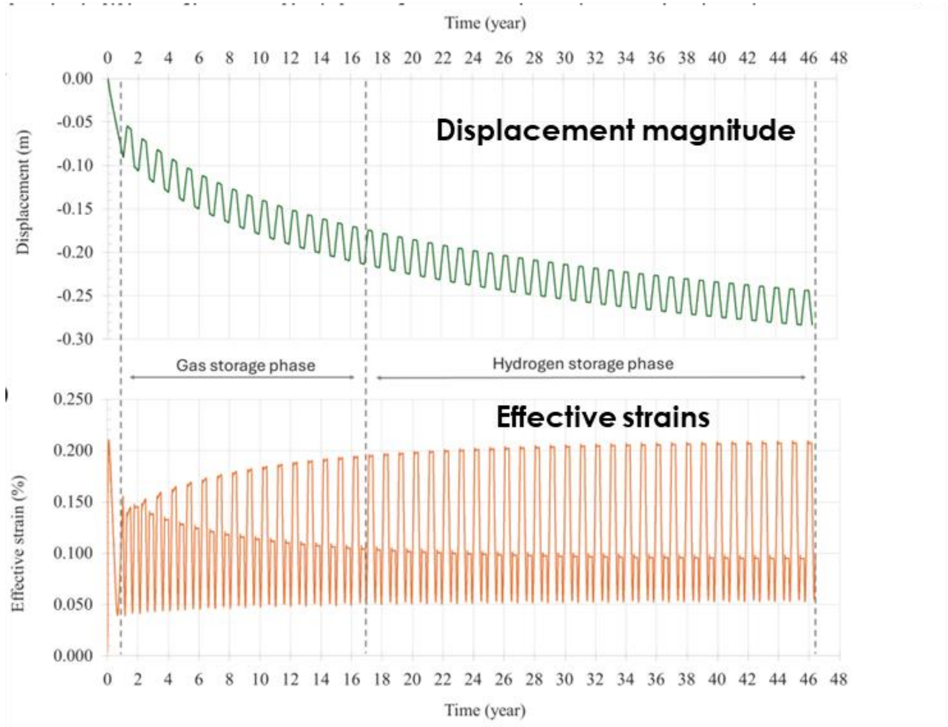
- Mechanical properties for the various geological layers were derived from laboratory tests

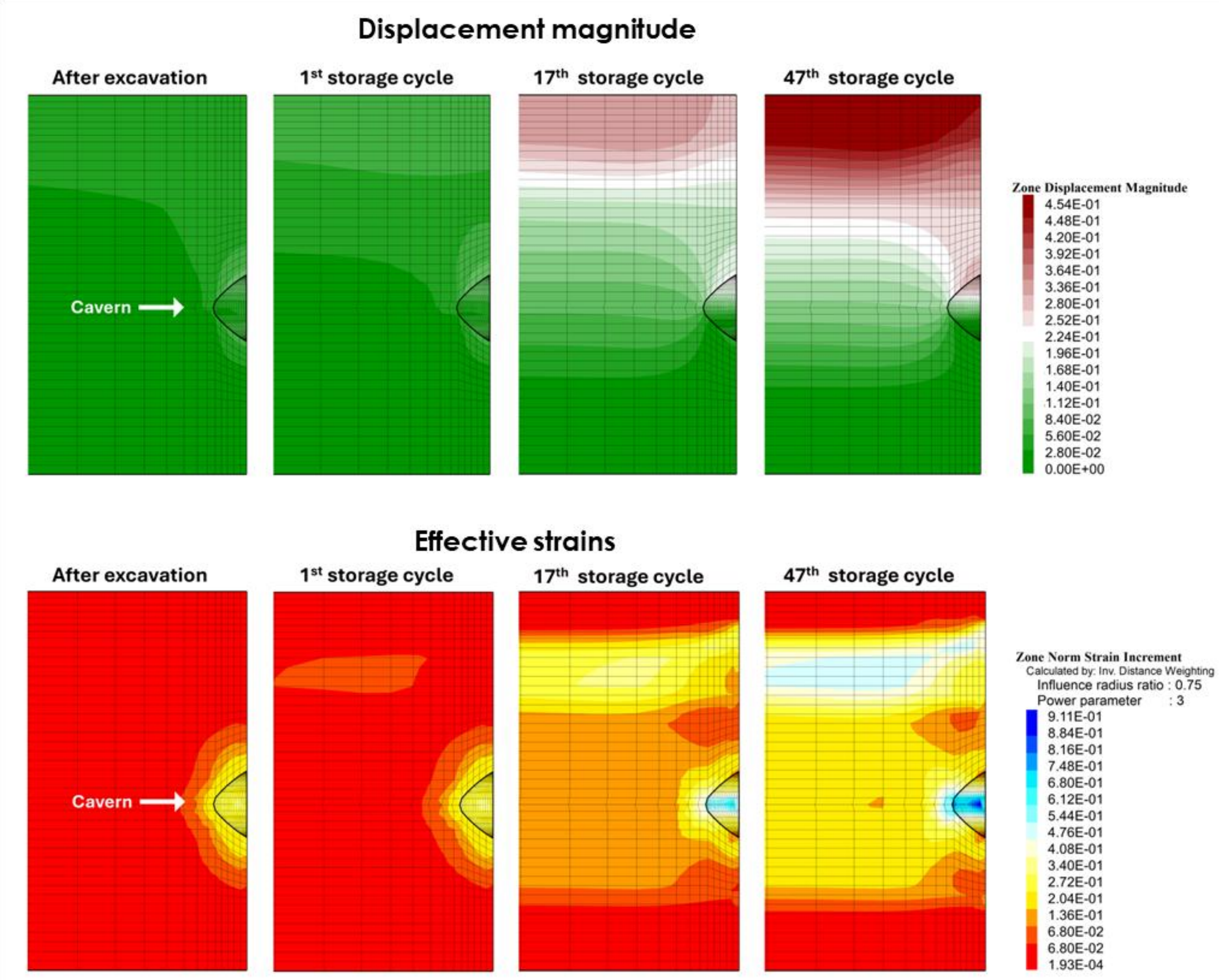
| Strata | Density [kg/m3] | Poisson's Ratio | Young's Modulus [MPa] | Tensile Strength [MPa] |
|---|---|---|---|---|
| **Z1** | 2940 | 0.299999 | 60000 | 8.44 |
| **Z2** | 2150 | 0.250004 | 25000 | 1.6 |
| **Z3** | 2150 | 0.16887 | 20340 | 1.43 |
| **Z4** | 2300 | 0.199959 | 7010 | 1.89 |
| **Z5** | 2550 | 0.090268 | 14180 | 2.75 |

# Results - Stress & Displacement Analysis

**Key findings:**

- Gradual subsidence observed due to salt creep.
- The maximum displacement is **concentrated at the roof and sidewalls**, where stress redistribution occurs.
- Maximum strain remained well below failure limits (~0.21% vs. 3% threshold).
- No abrupt



# Impact of Cycle Duration

**Shorter vs. Longer Cycles:**

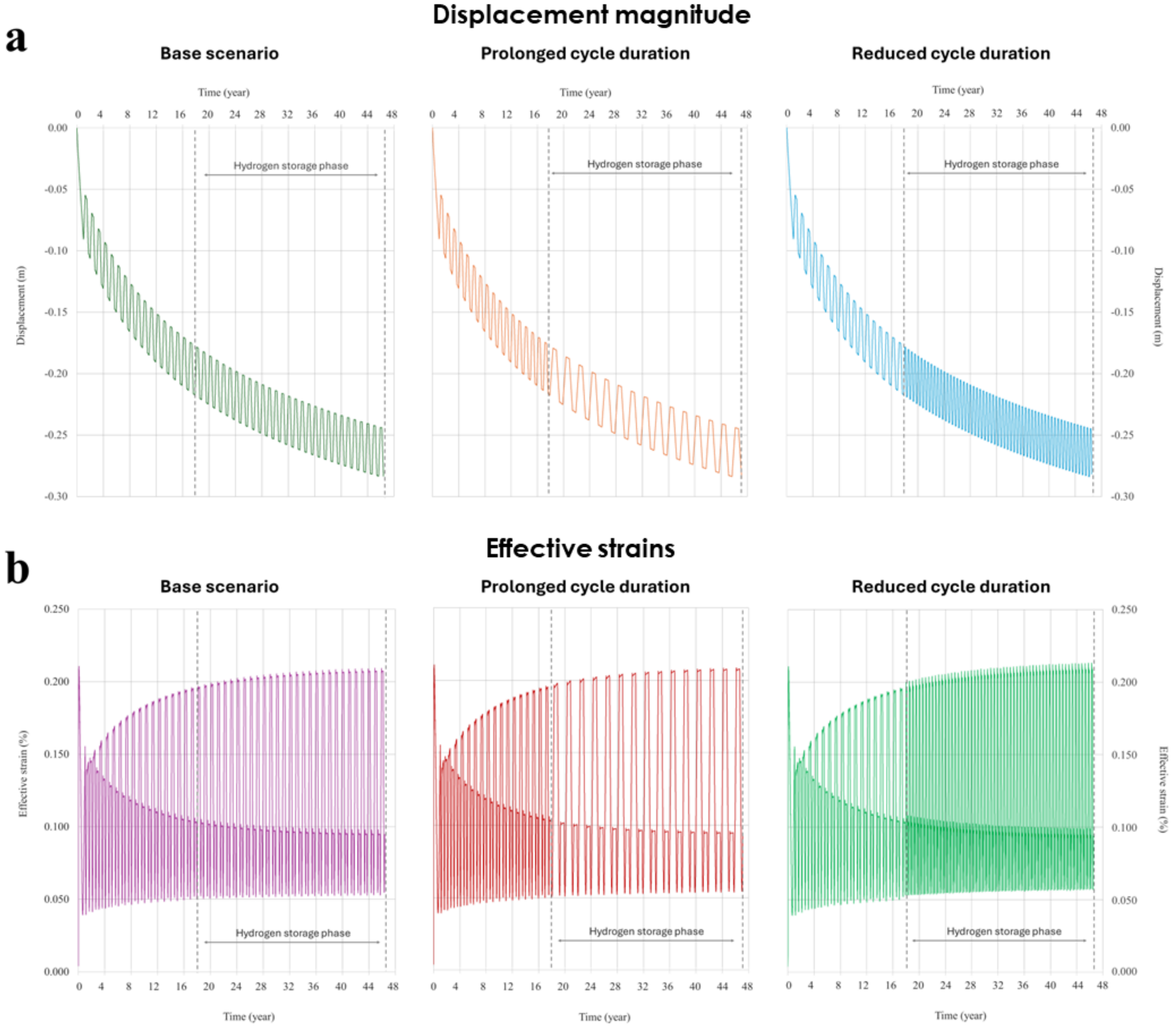
- Shorter cycles cause more frequent but smaller stress variations, leading to slower creep deformation.
- Longer cycles lead to larger cumulative stress redistributions, accelerating cavern convergence.

**Displacement Behaviour:**

- In both cases, displacement increases steadily, but longer cycles result in ~17% more displacement after 47 years.

**Effective Strain Trends:**

- The maximum strain (~0.21%) remains well below the failure threshold (3%).Strain accumulates more rapidly with longer cycles, especially near the cavern roof.

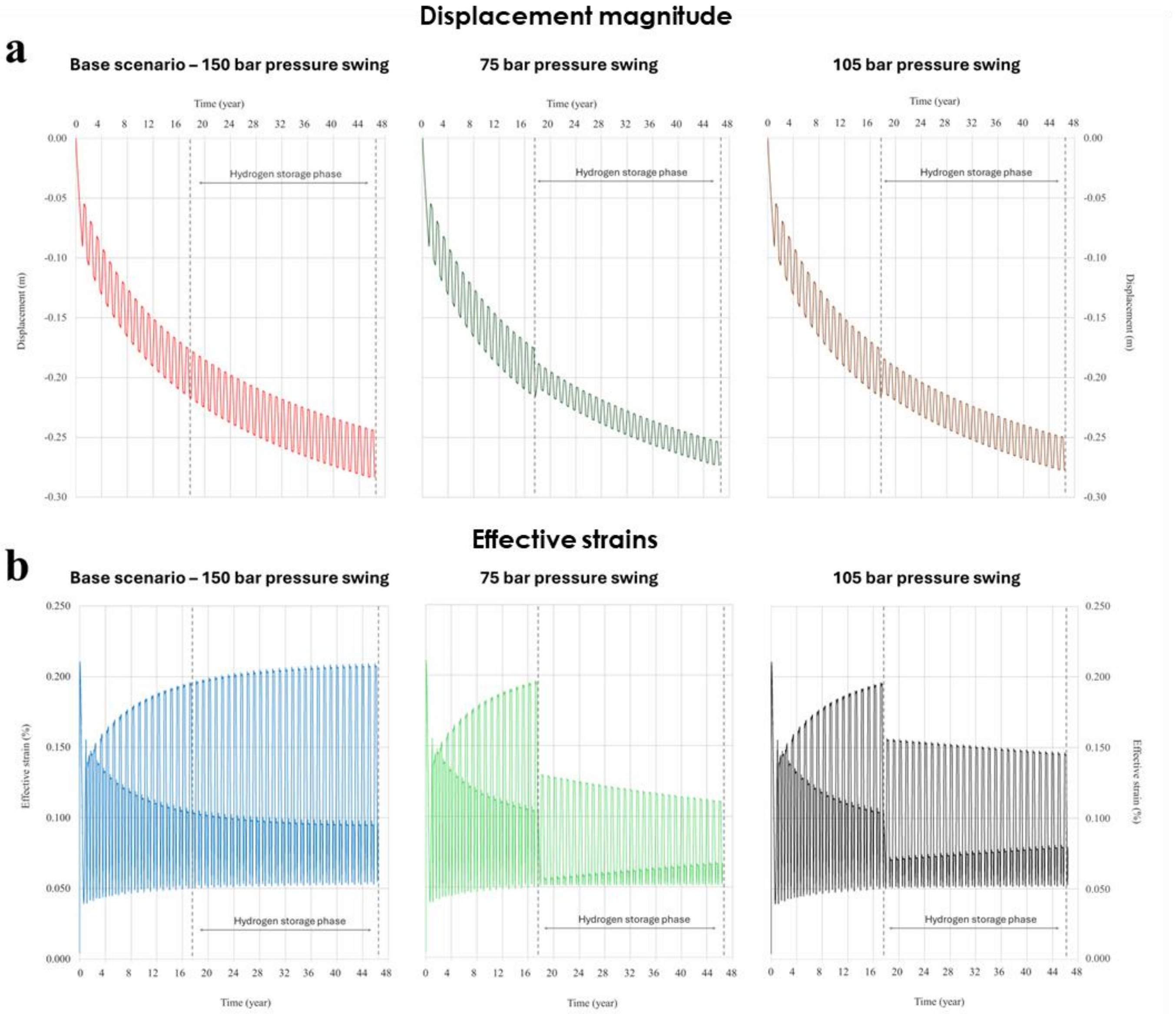


# Impact of Pressure Fluctuations

**Wider Pressure Swings:**
- Increased pressure range leads to higher stress variations, which accelerates salt creep and deformation.
- Leads to higher strain accumulation near the cavern roof and walls.

**Narrower Pressure Swings:**
- Reduces stress fluctuations, slowing down creep behaviour.
- Minimises strain buildup, keeping displacement lower.

**Strain & Displacement Behaviour:**
- With wider swings, displacement accumulates 30% faster compared to a narrow pressure range.
- Strain hotspots shift deeper into the cavern walls as pressure swings increase.



# Long-Term Volume Convergence Trends

## Key Findings:

**Base Case (Normal Hydrogen Storage Conditions):**

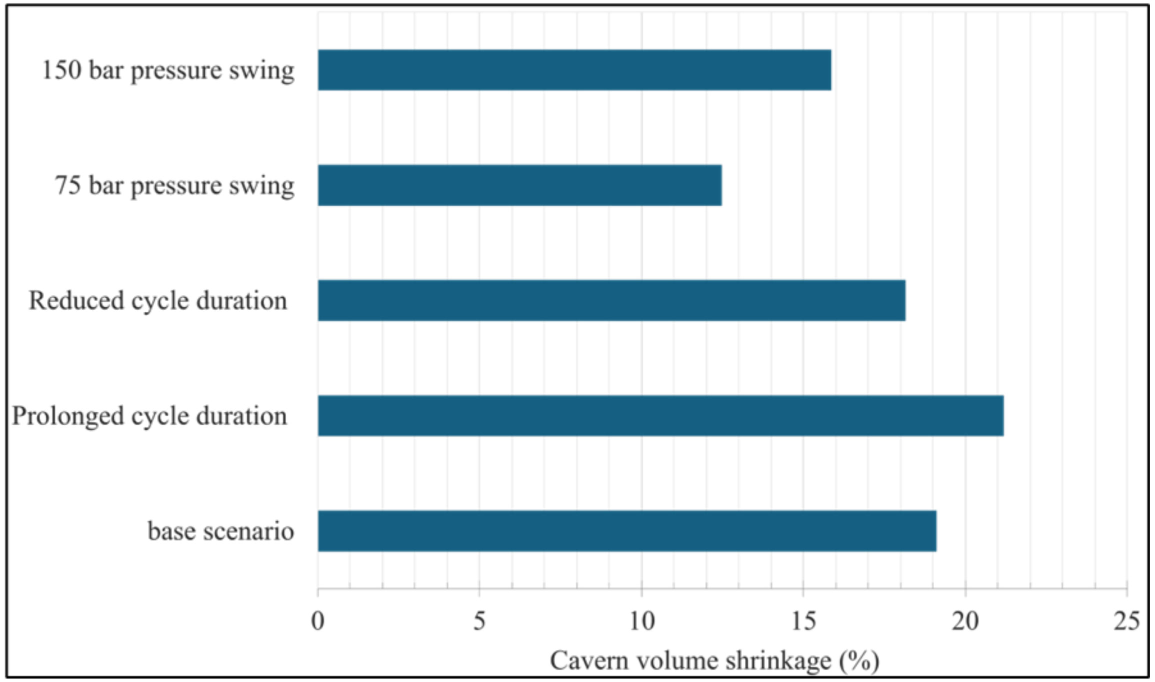
- The cavern shrinks by **19.11% after 47 years**.

**Effects of Shorter Cycles:**

- Less strain accumulation, resulting in **slightly lower shrinkage (~18.15%)**.

**Effects of Narrower Pressure Swings:**

- Cavern shrinkage is **dramatically reduced to 12.48%**, improving storage longevity.



# Key Takeaways from this Webinar

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- When evaluating the technical challenges associated with underground hydrogen storage (UHS), the ranking of storage methods is as follows:
  - USH in Saline Aquifer > USH in Depleted Gas Reservoir> Salt Caverns
- Key factors influencing microbial reactions during the UHS process include temperature and salinity.
- The quality of the reservoir, particularly the net-to-gross (NTG) ratio, significantly impacts the volumetric storage and delivery of gas.
- The geomechanical stability of salt caverns can be enhanced through the implementation of suitable operational strategies, such as cyclic injection and withdrawal, as well as pressure swings and their duration.
- Hydrogen diffusion is primarily influenced by the presence of salt impurities.

# Large Scale UHS is NOT safe and scalable

## But YOU and I can make it safe and scalable


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