

Hydrogen Storage in Underground Lined Rock Shafts

Dr Anastasios Stavrou
Rock Mechanics Leader

HYDROGEN STORAGE IN CAVERNS 2022

14th March 2022



Arup at a glance

ARUP



\$3.2bn* turnover

75 yrs of profitable trading debt free

15,000+ people

89 offices

33 countries

*as at Mar 2021 *19/2020 financial year*

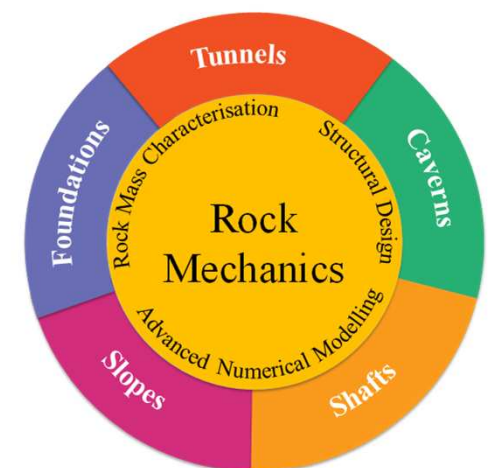
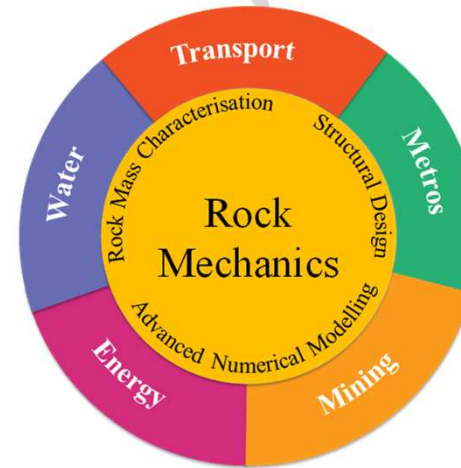
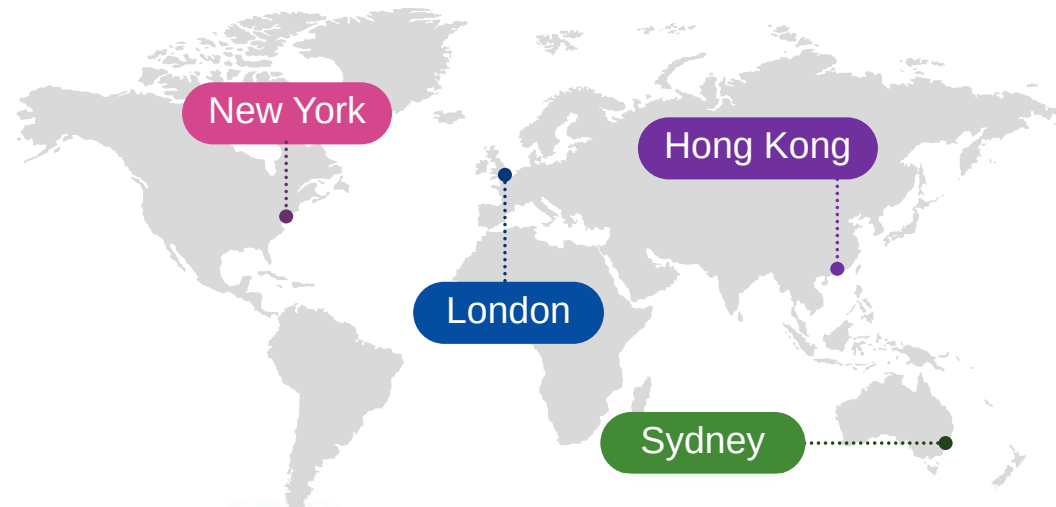
Global Engineering Rock Mechanics Team

“Arup is uniquely positioned to deliver GeoEnergy Storage projects with all the necessary experts available under one roof”



Dr Anastasios Stavrou
Rock Mechanics Leader

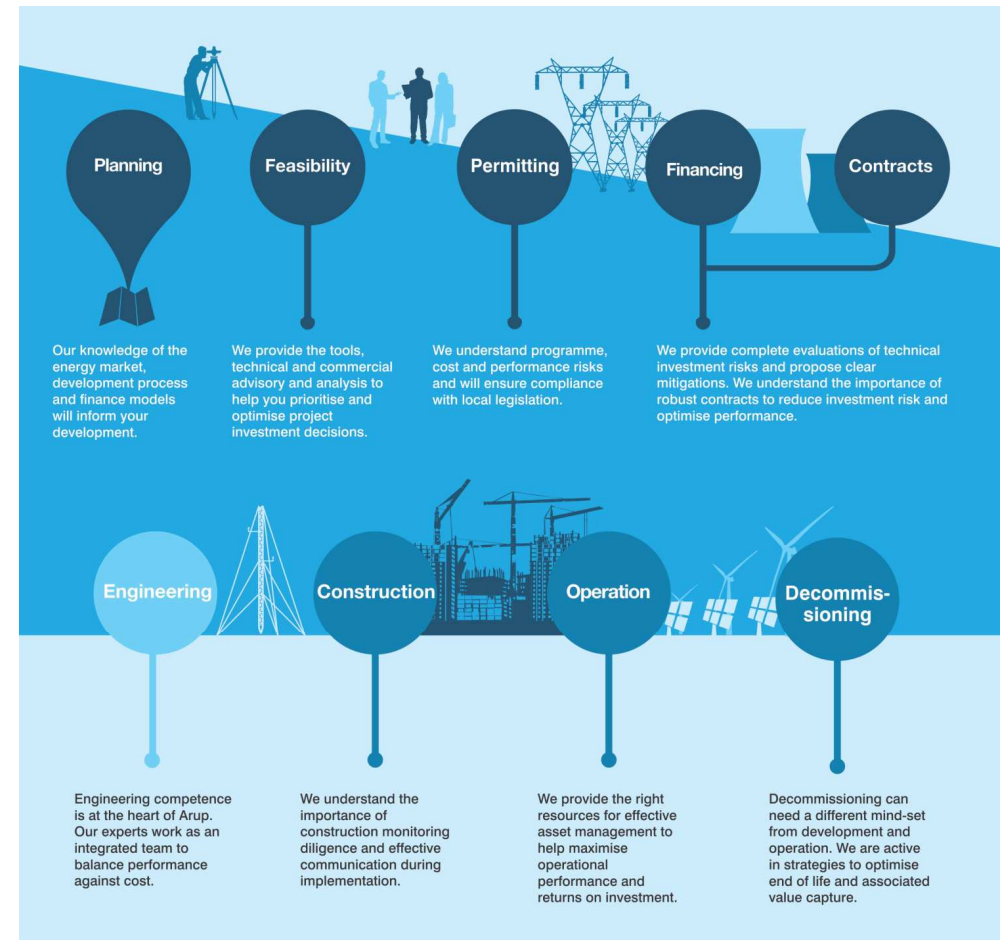
Engineering Rock Mechanics Centres of Excellence



Why Arup?

Capability & Experience

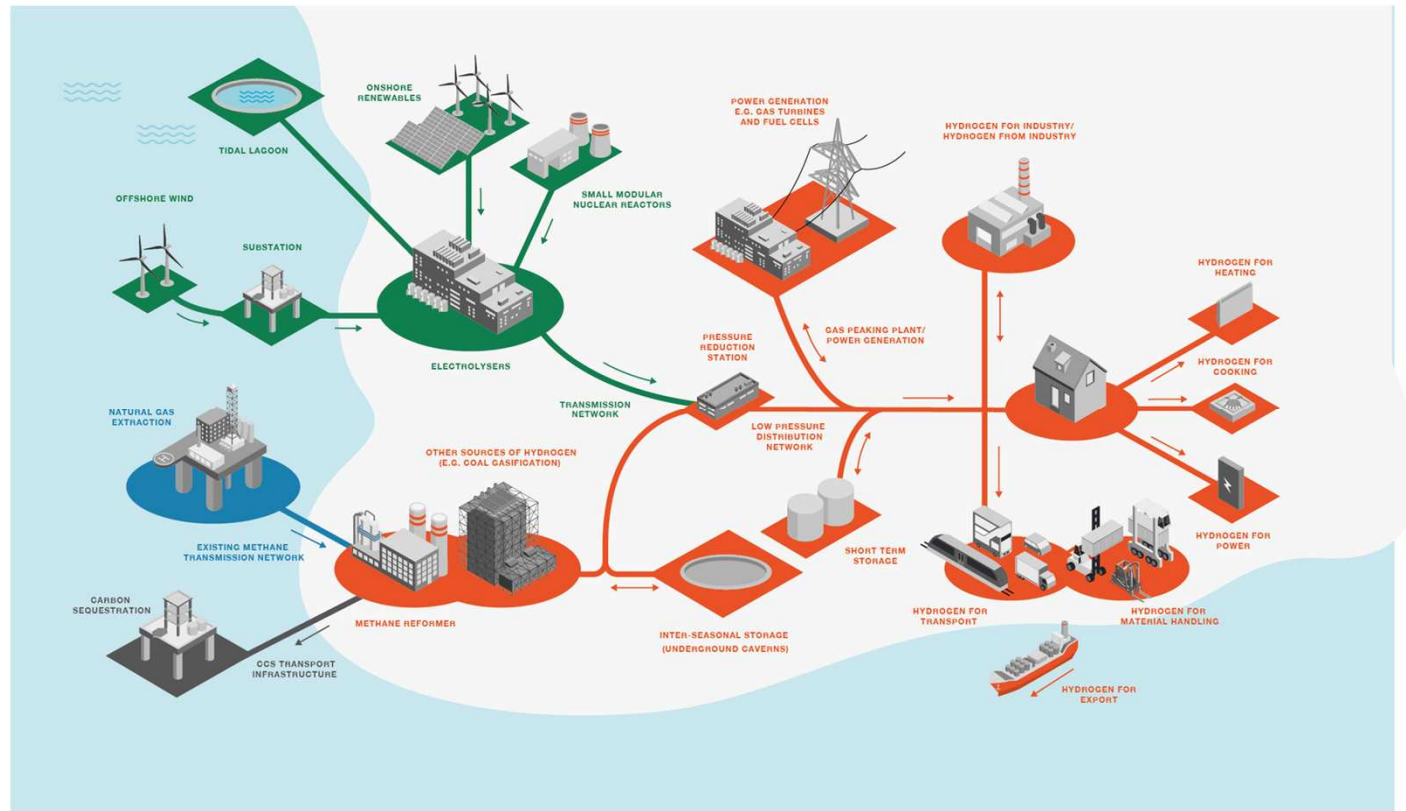
The multidisciplinary nature of Arup covers the full spectrum of **GeoEnergy Storage** projects, from formulating government policy, transaction advisory, feasibility studies through to detailed design and project management of construction contracts, operation, decommissioning and repurposing.



Why Arup?

Capability & Experience

Arup is at the forefront of hydrogen projects across every aspect of the hydrogen chain as an end to end delivery partner.



Why Hydrogen?

Our thought leadership

Arup is a thought leader in exploring and articulating hydrogen's role in the energy system as it transitions to zero carbon emissions by 2050.

We have published a number of studies exploring hydrogen's role in the future energy economy

ARUP

Energy systems: A view from 2035
What will a future energy market look like?



www.arup.com/energy

The Future of Energy

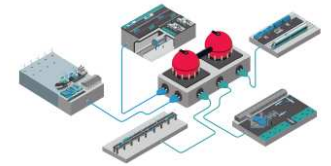


Catalysing hydrogen investment
What the market needs to deliver the progress in hydrogen infrastructure

Catalysing Hydrogen Investment

ARUP

Hydrogen Transport -
Fuelling The Future
The Future of Energy



Hydrogen Transport

ARUP

Establishing a Hydrogen Economy
The Future of Energy 2035



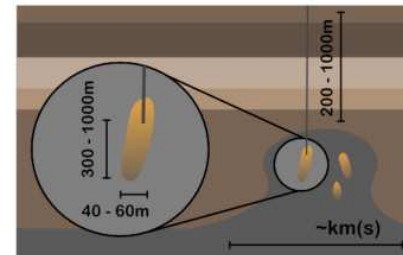
www.arup.com/energy

Establishing a Hydrogen Economy

Hydrogen Storage

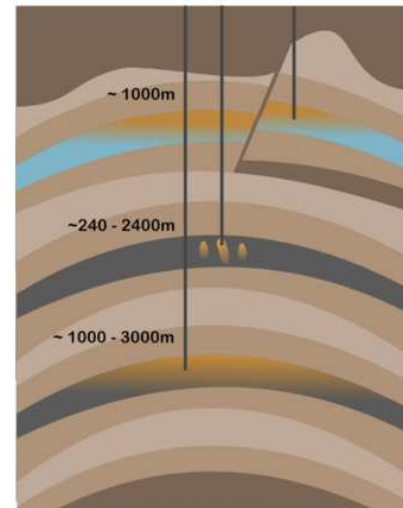
Establishing a Hydrogen Economy

- Hydrogen is expected to play a significant role in decarbonising the UK's energy system.
- Hydrogen in the UK doesn't come without challenges.
- The network of the future will require unprecedented volumes of **underground hydrogen storage** capacity to allow for a stable flow of hydrogen into the grid.



salt caverns

typically onshore



saline aquifers

typically shallower onshore and deeper offshore
(non-drinking water)

layered salt

both onshore and offshore

depleted oil and gas reservoirs

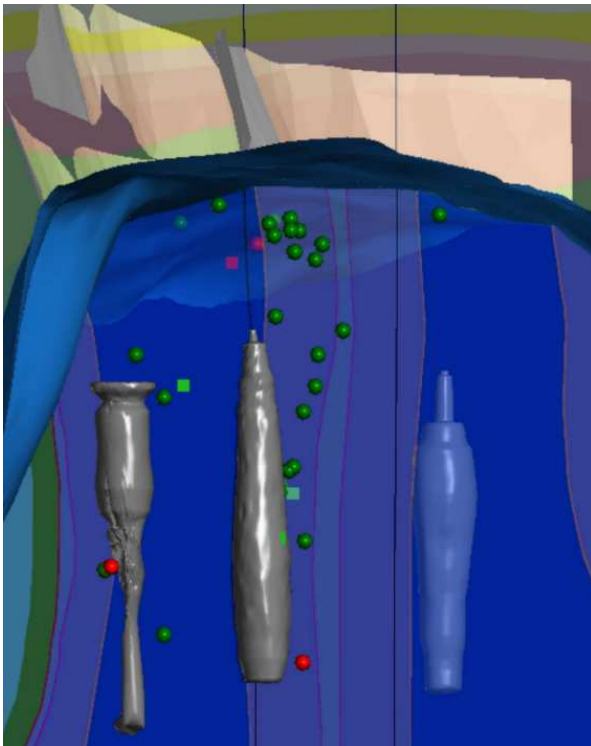
typically offshore

Where can hydrogen be stored?

Geoscience and the hydrogen economy
(The Geological Society of London, 2021)

Salt Caverns

Hydrogen Storage



Salt cavern integrity assessment.
(Bosq et al., 2020)

Existing Underground Hydrogen Storage projects:

- UK - Teeside
- US Texas - Clemens Dome, Moss Bluff, Spindletop

Pilot & Demonstration Projects:

- EWE - HyCAVmobil (Rudersdorf, Germany)
- Gasunie - HyStock (Netherlands, Zuidwending)
- Storengy - HyPster (France, Etrez)

Key Benefits:

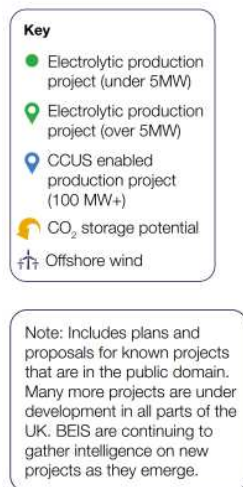
- Very high safety (salt caverns are naturally very gas tight)
- Lower capital costs at large scales
- Flexibility of storage at high volumes and pressures for inter-seasonal storage

Constraints:

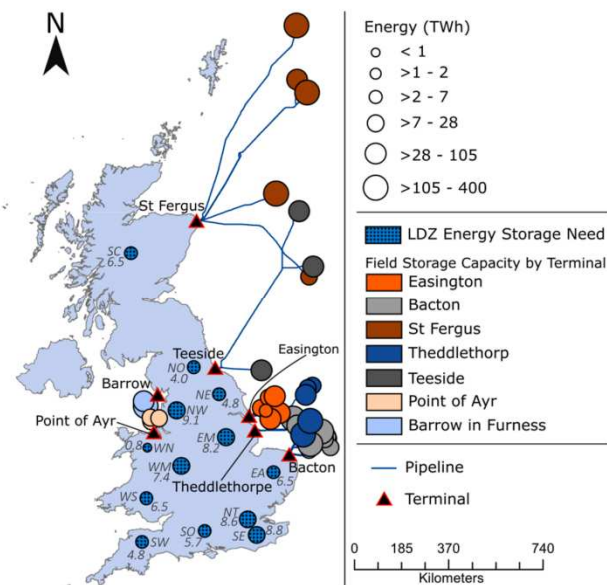
- Specific specific geological conditions
- Salt deposits of suitable thickness, extent, quality (halite purity) and depth

Hydrogen Storage

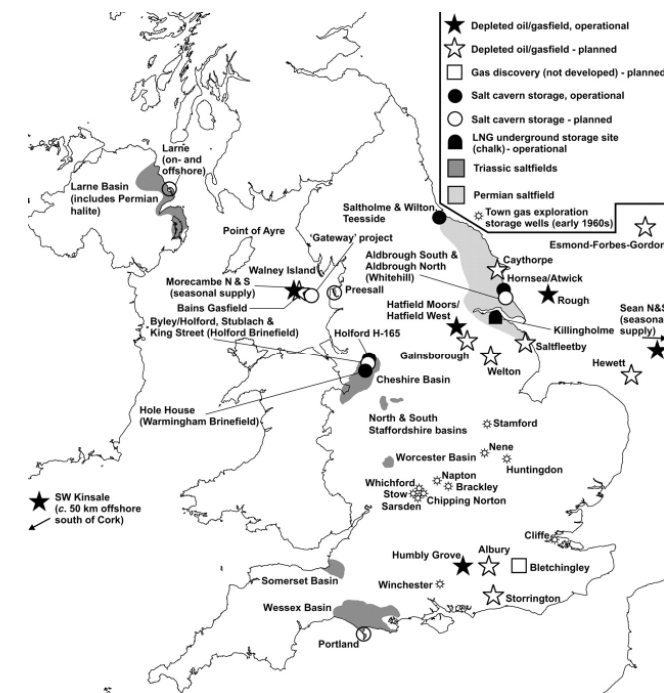
Establishing a Hydrogen Economy



Proposed UK electrolytic and CCUS-enabled hydrogen production projects.
UK Hydrogen Strategy (BEIS, 2021)



Location of UK Local Distribution Zones storage needs compared to depleted oil and gas reservoir storage capacity.
(Mouli-Castillo et al., 2021)



Distribution of the main halite basins onshore in Britain and the location of underground gas storage sites.
(Evans and Holloway, 2009)

Hydrogen Storage

Establishing a Hydrogen Economy

- A range of options are available for the storage of hydrogen underground.
- The future hydrogen economy is likely to need a **combination** of underground storage solutions.
- The **Lined Rock Cavern** (LRC) concept is less dependent on the host rock providing a **greater spatial versatility**.
- The **Lined Rock Shaft** (LRS) concept takes its basis in the technology that was developed for the LRC.

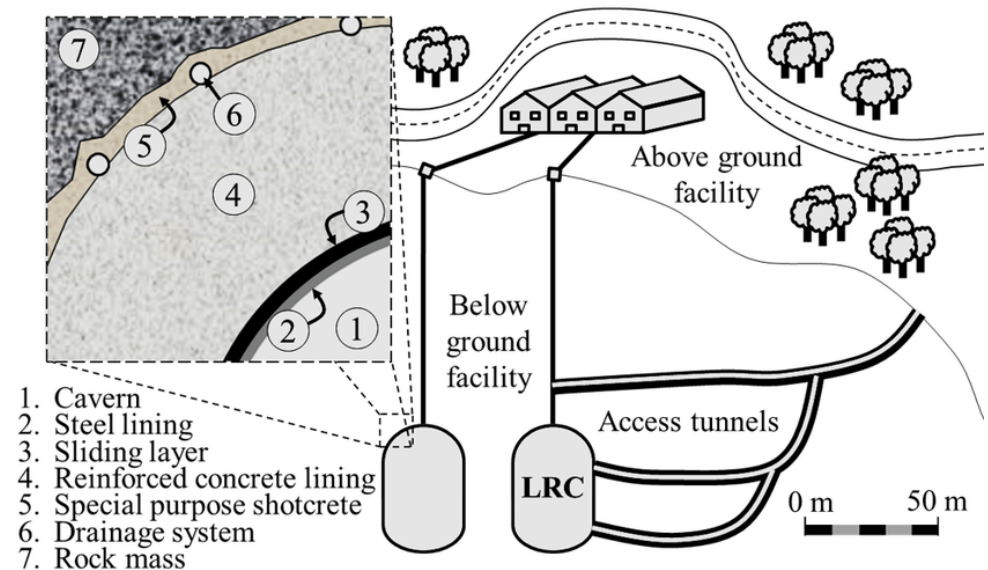
	Depleted Reservoir	Aquifer	Salt Cavern	Lined Rock Cavern (or Shaft)	Abandoned Mine
 Favourable					
 Medium					
 Poor					
Tightness	Medium	Medium	Favourable	Favourable	Poor
Flexibility	Medium	Medium	Favourable	Medium	Poor
Working / cushion gas ratio	Medium	Medium	Favourable	Favourable	Favourable
In-situ reactions	Poor	Medium	Favourable	Favourable	Medium
CAPEX	Favourable	Medium	Medium	Poor	Medium
Standard practise	Poor	Poor	Favourable	Poor	Poor

Comparison of geological storage options.
(modified after Crotogino et al., 2018)

Lined Rock Cavern

Concept Overview

- The LRC concept provides an option of greater flexibility in several aspects.
- The main principle is to store gas in high pressure at shallow depths.
- The rock mass absorbs the pressure load, and the lining ensures gas tightness.
- The system consists of three components:
 - sealing layer (to ensure tightness)
 - pressure-distributing part (to transmit loads)
 - rock mass (to carry the pressure)



The principal components of the LRC concept.
(Johansson et al., 2018)

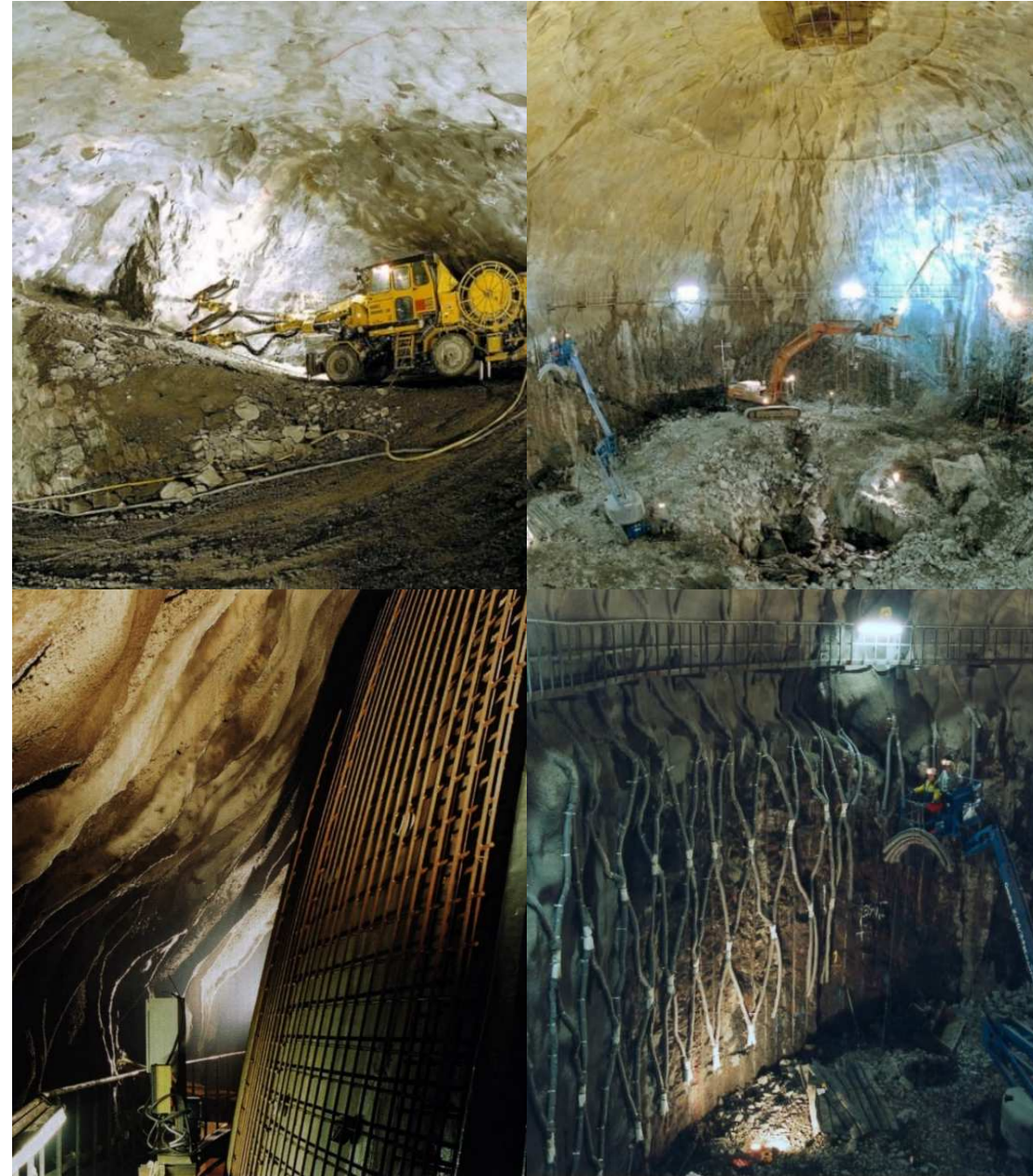
Lined Rock Cavern

Existing Facility

Skallen Gas Storage Facility, Sweden:

- First LRC for natural gas storage
- Excavation with drilling and blasting
- Bottom-up construction of liner
- 51 m high and 35 m diameter cavern
- 115 m rock cover
- Geometric volume of 40,000m³
- Pressure range 20-200 bar
- Total gas volume of ~10 MNm³
- 90% working gas capacity

Construction of the Skallen facility
(Johansson et al., 2018)



Lined Rock Cavern

Under Construction

HYBRIT hydrogen storage facility in Luleå, Sweden:

- Proven technology from the Skallen facility
- First LRC for underground hydrogen storage
- Joint venture initiative planned for a fossil fuel-free steelmaking process (hydrogen storage)
- 100 m³ storage cavern, 30m rock cover
- Pressures up to 250 bar
- Construction started in 2021, due to begin operation in 2022, tests will continue until 2024



Construction of the rock cavern storage facility for fossil-free hydrogen in Luleå has reached the halfway point (HYBRIT, 2022: www.hybritdevelopment.se/en/)

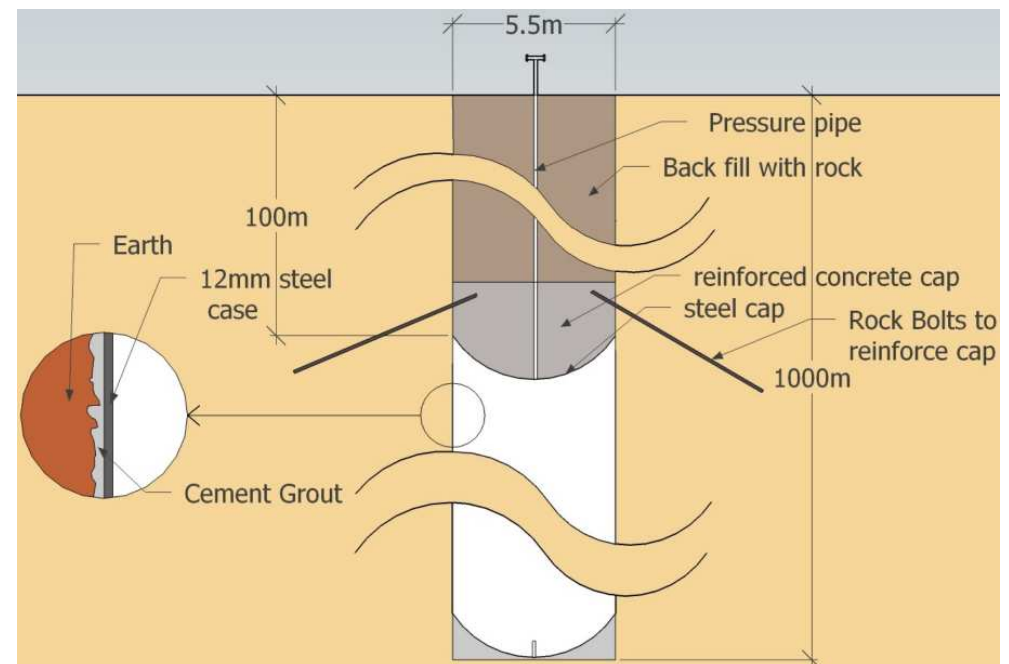
Lined Rock Shaft

Concept Overview

Arup and Gravitricity are currently studying the feasibility of storing hydrogen in purpose-built underground shafts.

This would involve sinking a lined rock shaft with a capping system, to create a demonstration pressurised hydrogen storage vessel.

Storing hydrogen using the Lined Rock Shaft (LRS) does not require specific geological conditions.



Concept sketch for creation of gas containment in drilled shaft.
(Lavine et al., 2016)

Lined Rock Shaft

Concept Overview

Readiness

The individual components of the Lined Rock Shaft concept are all relatively mature technologies on their own.

Cheap

Surrounding ground carries the load from the gas pressure, reducing the material cost of the lining.

Repeatable

The design can be transferred in different locations with minimal adjustments dependent on ground conditions and site requirements

Safe

All phases of construction can be safely undertaken from the surface. Reduced risk of leak or explosion.

Large Scale

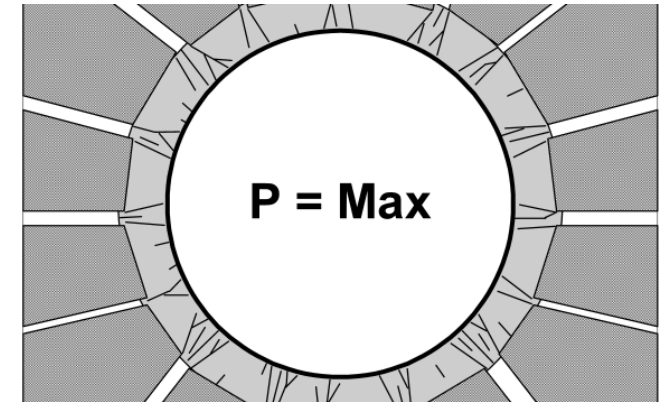
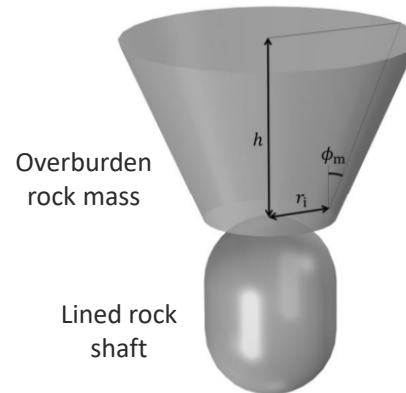
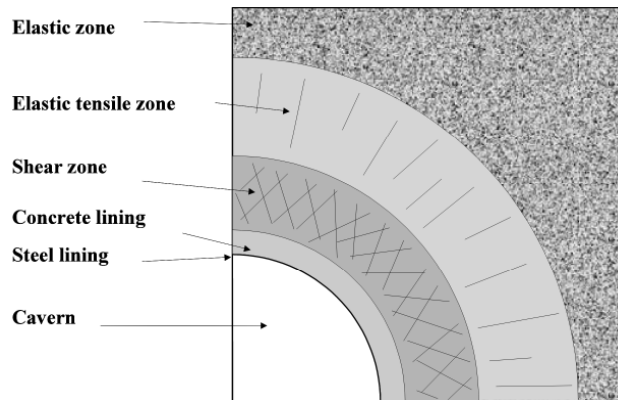
Larger diameter and deeper shafts offer larger storage capacity. A shaft “farm” can be built in the same location for larger storage requirements.

Footprint

The surface footprint is very small and the visual intrusion is virtually zero.

Design Considerations

Hydrogen Storage in Lined Rock Shafts



Rock Mass Failure

The load from the pressurised vessel is passed through the lining system to the rock mass. Shear plasticity or brittle fracturing may develop depending on the internal pressure, rock mass strength and the in-situ stress conditions.
(Johansson, 2003)

Uplift Failure of the Overlying Rock

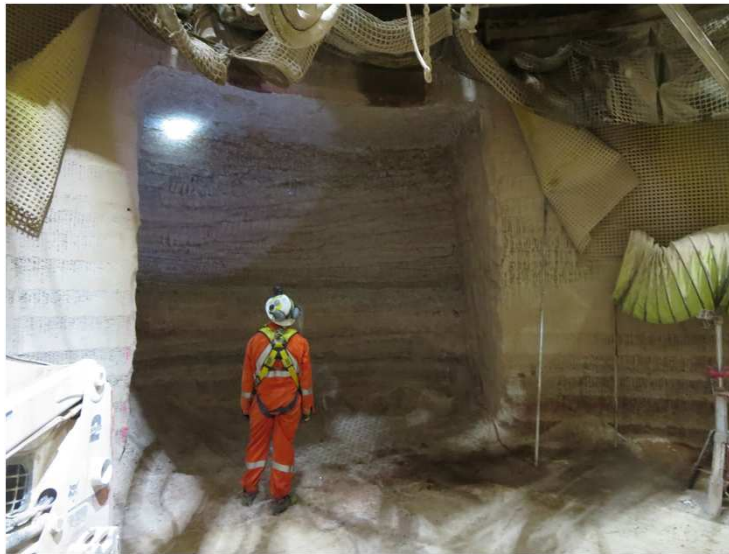
The cap system design will have to provide uplift resistance against the internal vessel pressure. Placing the cap underground allows for the overburden to provide this resistance and the plug to engage with the rock mass.
(Damasceno et al., 2020)

Failure of the Lining System

Rupture of the steel lining may develop by large rock mass deformation (expansion) as it is loaded by the gas pressure. Steel hydrogen embrittlement and fatigue due to cyclic loading are important design aspect.
(Johansson et al., 2018)

Lined Rock Shaft

Arup Deep Shaft Experience



BHP Jansen Project | Canada

Arup was appointed for the rock excavation and design of the permanent shaft linings to a depth of 1,000m.



Anglo American Woodsmith Project | UK

Arup is currently undertaking the detailed Engineering Design of the permanent linings for the 1600m deep mineshafts.

Hydrogen Storage in Lined Rock Shafts

Summary

- Arup and Gravitricity are currently studying the feasibility of storing hydrogen in purpose-built underground shafts.
- Site selection is not restricted by specific geological conditions.
- The solution proposed integrates individual components with high level of readiness into a unique solution that has not been trialled before.
- Safe and repeatable storage technology for other locations.
- Larger diameter and deeper shafts offer larger storage capacity. A shaft “farm” can be built in the same location for larger storage requirements.
- Shaft dimensions is primarily driven by shaft sinking technology, lining design, ground behaviour and maximum operating pressure.
- Rock mass characterisation is important for rock-support interactions.

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Hydrogen Storage in Caverns 2022

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