# B-linepack+ Alpha

**End of Phase**

09.Febuary.26

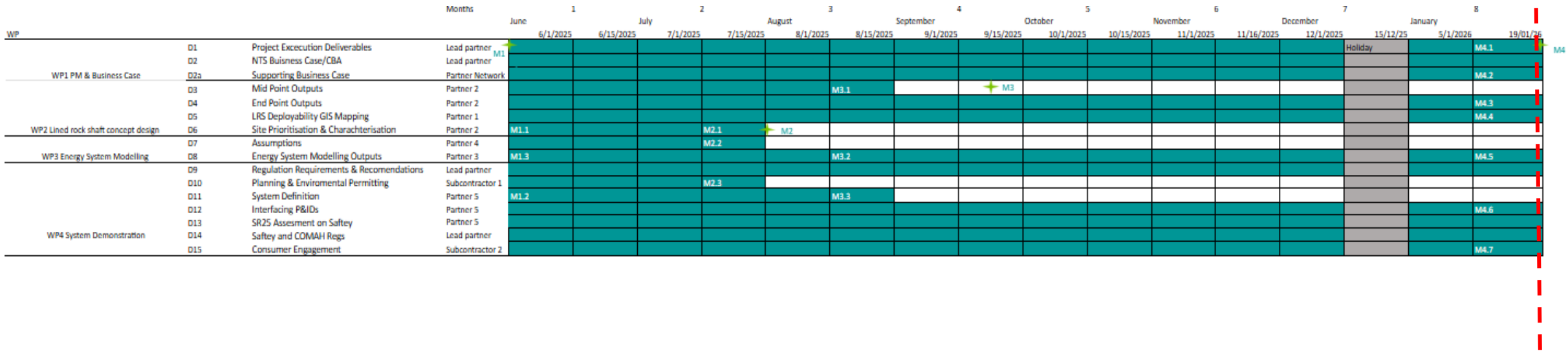
# Agenda

Intro and Welcome
PM – Updated Gannt, milestones and risk register
WP1 PM & CBA
WP2 LRS Concept Design
WP3 Energy System Modelling
WP4 System Demonstration
Project Specific Conditions
Comms/Engagement Plan
Whats next and Beta Application
AOB

national gas transmission

# Project Plan Status

We are here



# Project Finances Table

| Taken from Project Direction (or latest amended Project Direction) | | | | |
|---|---|---|---|---|
| Project partner name | Total project costs (£)* | Project Compulsory Contribution (£)** | Total SIF Funding requested (£)*** | Actual spend (£)**** |
| National Gas Transmission | 121,358 | 50,000 | 71,358 | 112,237 |
| Energy Reform | 99,505 | 9,949 | 89,556 | 89,556 |
| Guidehouse | 11,120 | 1,120 | 10,000 | 10,000 |
| Longitude Consulting Engineers | 164,825 | 17,575 | 147,250 | 147,250 |
| Gravitricity | 110,050 | 10,050 | 100,000 | 100,000 |
| SGN | 5,296 | 568 | 4,728 | 4,728 |
| Premtech | 75,032 | 7,543 | 67,489 | 67,489 |
| University of Edinburgh | 9,100 | 1,100 | 8,000 | 8,000 |
| Totals | 596,286 | 97,905 | 498,381 | 539,260 |

# Key Risks/Issues Resolved

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| R11 | A critical team member from a supplier moves off the project | High | High | a) Skills and competencies to be understood across the team<br>b) Critical skills duplicated where possible<br>c) Where not possible detailed documentation to be kept in order for project to continue<br>d) Handover pack produced. | All | Lead partner | Closed | Swapped out partners via PDCR with Longitude hiring former Gravitricity staff to continue work on project and still deliver on time. |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| R17 | Land availability and risk around need to purchase new land for demonstrator | High | High | Early engagement with NGT estates manager to confirm land ownership and boundary's took place in Discovery. Further engagement to be done on notification of award to determine exact land available at shortlisted sites. | WP2 | Lead partner | Closed | Have continued engagement with L&Cs team especially as selecting Billingham Enron site for demonstrator. We will need to renegotiate the lease with the land owner and purchase new land in neighbouring fields to enable the demonstration project. Need confirmation at mid point review or asap after that ofgem would be willing to fund costs associated with land purchase/lease or not.<br>If not, we would need to reconsider the demonstrator site selection again. Flagged by L&Cs team that it would be complex and take time to negotiate multiple land leases with multiple owners for project in area at Billingham Enron site but possible.<br><br>Mitigated by selecting ETZ in Aberdeen for demonstrator. |

# WP1 PM & Business Case

D1 Project Execution Deliverables

D2 CBA and Business Case

D2a Supporting Business Case

national gas transmission

# D1 – Project Execution Deliverables

**Tasks Completed:**

- Weekly PM meetings setup
- PU team been engaged with project and on stakeholder engagement for both projects as well as H2 Teeside blending project.
- Contract signed, resigned and PO's issued
- Workshop had on environmental permitting and planning with WSP and Longitude
- Workshop on energy system modelling
- Meeting minutes, Quarterly reports to MO etc

**To do:**

- Show and tell to organise
- Beta Application

# 2 & 2a - CBA and Business Case

- Sessions held to discuss energy system modelling alignment, technologies to use as counterfactuals and assumptions.
- Capex and Opex estimates for LRS revised with longitude engineers for standard and modified systems
- Engaged with suppliers and work with SIF R1 Compression team to determine robust labour rates for FEED, decommission costs, commissioning and construction costs for Beta phase and will be updated prior to Beta application with final figures.
- To note, LOHC CAPEX figure needs sense checked with Hyscale team (ERM) who did CBA for that project to align and confirm is correct assumption prior to Beta application

# CBA Option 1 – LRS

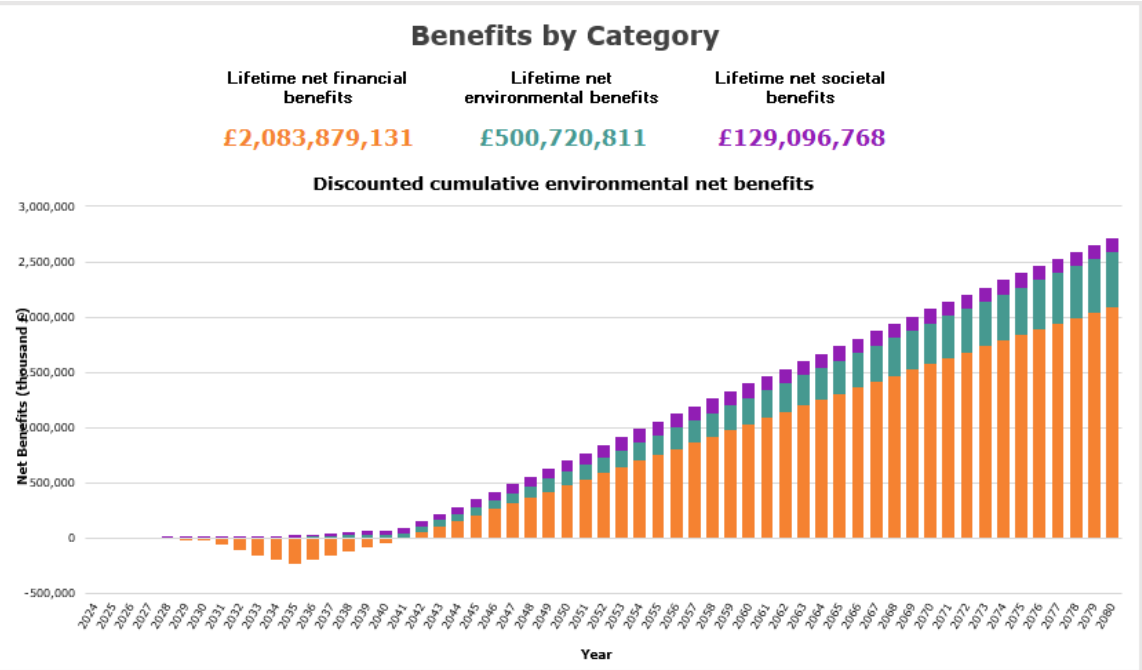
- Payback Period **15 years** due to 5 year demo period for technology and upfront cost/time to deploy 16 commercial units
- CAPEX to deploy 16 commercial units = **£411M**
- OPEX = **£384k** per shaft per annum
- NPV = **£2.71B**
- Penalty fee 'avoided cost' applies to all CBA options = **£7.02B cumulative out to 2080.**
- Whole system cost savings = **£26.53M per annum**

| CBA Option | CBA Option 1 |
|---|---|

**Key Financial Metrics**

| Term | NPV |
|---|---|
| 10 | -£143,533,322 |
| 20 | £217,038,907 |
| 30 | £913,520,625 |
| 45 | £1,938,141,140 |
| Whole Life | £2,713,696,710 |

| Payback period | 15 Years |
|---|---|
| *Project breaks even in 2040* | |



# CBA Option 2 – Salt Cavern

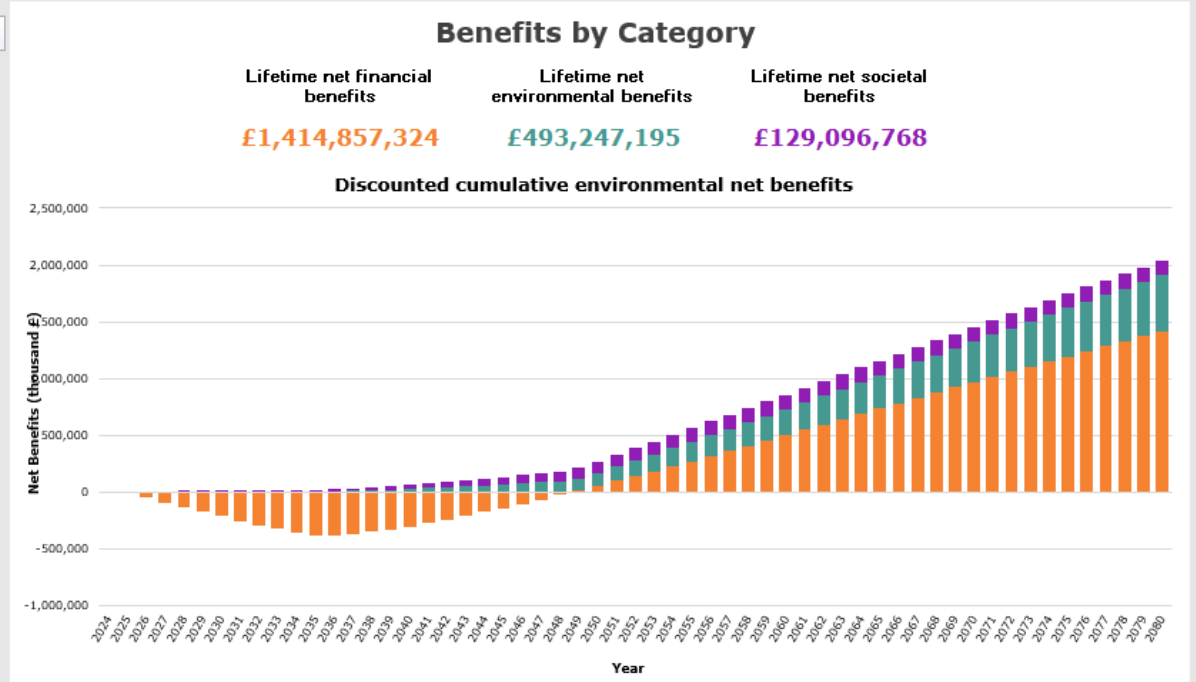
- Payback Period **20 years** due to 10 year to develop 1 larger salt cavern and upfront cost to do so.
- CAPEX to deploy 1 larger salt cavern = **£491M**
- OPEX = **4% of CAPEX** per annum
- NPV = **£2.04B**
- Penalty fee 'avoided cost' applies to all CBA options = **£7.02B cumulative out to 2080.**
- Whole system cost savings = **£1.9M per annum**

| CBA Option | CBA Option 2 |
|---|---|

**Key Financial Metrics**

| Term | NPV |
|---|---|
| 10 | -£317,311,909 |
| 20 | -£105,535,256 |
| 30 | £446,965,796 |
| 45 | £1,335,067,122 |
| Whole Life | £2,037,201,287 |

| Payback period | 20 Years |
|---|---|
| *Project breaks even in 2046* | |



# CBA Option 3 – LOHCs

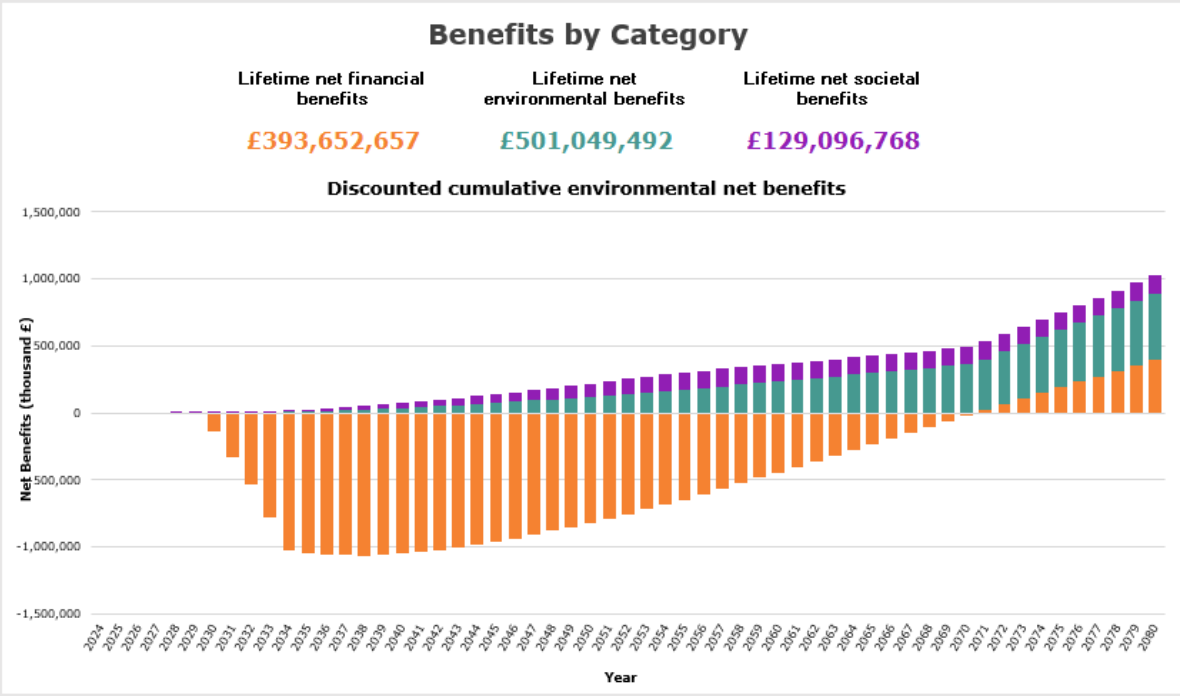
- Payback Period **44 years** due to high deployability CAPEX
- CAPEX to deploy 16 commercial units = **£1.3B**
- OPEX = **4% of CAPEX** per annum
- NPV = **£1.02B**
- Penalty fee 'avoided cost' applies to all CBA options = **£7.02B cumulative out to 2080.**
- Whole system cost savings = **£9.53M per annum**

| CBA Option | CBA Option 3 |
|---|---|

**Key Financial Metrics**

| Term | NPV |
|---|---|
| 10 | -£766,303,527 |
| 20 | -£889,736,526 |
| 30 | -£447,166,806 |
| 45 | £364,751,941 |
| Whole Life | £1,023,798,917 |

| Payback period | <1 Years |
|---|---|
| Project breaks even in 2028 | |



# WP2 Lined Rock Shaft Concept Design

D3 Mid-Point Outputs – Longitude
D4 End point Outputs – Longitude
D5 LRS Deployability GIS Mapping - UoE
D6 Site Prioritisation and Characterisation – Gravitricity/NGT

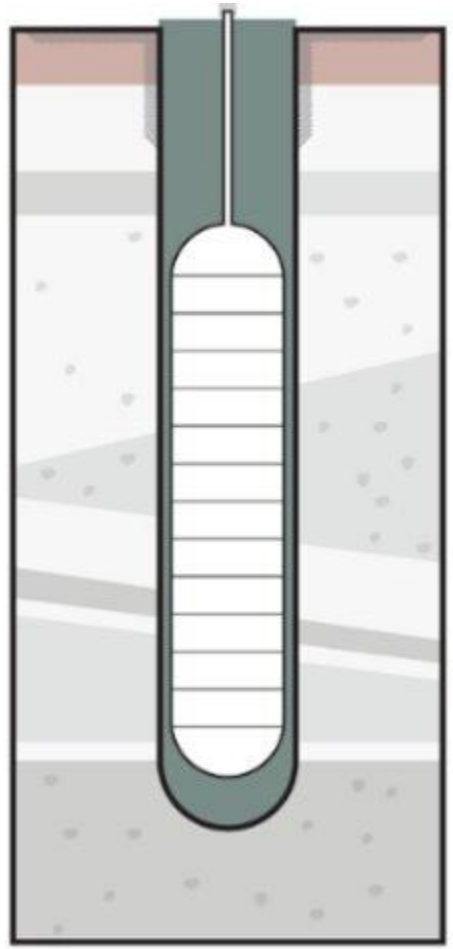
national gas transmission

# Deliverables

## Hydrogen storage in underground lined rock shafts

### Mid-Point

| Deliverable | Title | Comments |
|---|---|---|
| D3.1 | High-level system design | Sub-surface Basis of design and requirements register complete for system (LGG-L057401-R01, LGG-L057401-R04) |
| D3.2 | Advanced concept design for all subsystems | This deliverable comprises the following suits of design notes which in turn provide evidence for D3.3, D3.4, D3.5 and D3.8:<br><br>**Sub-Surface Process Design Note** complete (LGG-L057401-R08)<br>**EC&I design note** complete (LGG-L057401-R02, LGG-L057401-R10)<br>**Geomech and Structures Design note** complete (LGG-L057401-R09)<br>**Civils design note** complete (1102-002-01) |
| D3.3 | Materials defined | See D3.2 |
| D3.4 | Component specifications outlined | See D3.2 |
| D3.5 | CAD P&IDs showing site layout and equipment | See D3.2 |
| D3.6 | GA Drawing | **General Arrangement Drawing** complete (LGG-L057401-D01) |
| D3.7 | System requirements | See D3.1 |
| D3.8 | GI Requirements | See D3.2 |



### End-Point

| Deliverable | Title | Comments |
|---|---|---|
| D4 | End-Point Outputs | **Construction Plan** complete (LGG-L057401-R06, LGG-L057401-R07)<br>**Test Plan** complete (LGG-L057401-R03)<br>**FMEA** complete (LGG-L057401-R05) |

# Sub-Surface Containment

Hydrogen storage in underground lined rock shafts

## Overview

- Longitude responsible for the design of the sub-surface containment for the B-Linepack+ project
- H2 storage deployed in purpose-sunk shaft
- Multi-layer liner used for gas-tightness and to transfer some of the load from the internal gas pressure to the surrounding rock mass
- Overall system size reduced from Discovery phase
- System and sub-system requirements generated
- Sub-system design progress and de-risking
- Cost modelling for demonstrator and full-scale systems updated
- Beta phase schedule optimised
- Sub-surface design, fabrication and construction failure modes and mitigation plans identified

| Property | Value | Notes |
|---|---|---|
| Storage capacity | 0.53 tonnes | Total hydrogen gas storage capacity assuming average storage temperature of 20 degrees Celsius. |
| Cushion gas | 0.09 tonnes | The amount of gas which is permanently stored in the sub-surface containment. It prevents unwanted loading on the liner and shaft walls when the working gas has been removed. |
| Working gas | 0.44 tonnes | Available gas for injection and withdrawal. |
| Maximum Operating Pressure | 200 Barg | Maximum operating storage pressure. During commissioning this pressure will be incrementally increased from atmospheric pressure and liner/geological strains assessed before pressure is increased. |
| Inner storage diameter | 1.26 m | Internal diameter of the gas-tight liner |
| Inner storage length | 29 m | Internal length of the gas-tight liner |
| Internal storage volume | 35 $m^3$ | Internal volume of the gas-tight liner |
| Overburden depth | 12 m | Depth of backfill in competent rock to provide resistance to vessel uplift pressure. |
| Shaft diameter | 2.484 m | Excavated diameter of shaft prior to liner installation |
| Shaft depth | 47 m | Excavated depth of shaft prior to liner installation assuming 5m of superficial deposits. |

# Sub-surface storage requirements

LONGITUDE
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Detailed requirements register compiled with compliance plan for each requirement

| REQ NO | Requirement | External Reference | Compliance Stage | Compliance Plan | Safety Critical (Y/N) |
|---|---|---|---|---|---|
| **High level** | *The technical demonstrator system...* | | | | |
| 01-001 | ...shall safely store hydrogen | N/A | Detailed Design Review | Evidence that all materials, equipment and components are suitable for all operating cases using high-pressure gaseous hydrogen | Y |
| 01-002 | ...shall validate the performance of an LRS | N/A | Concept Design Review | Test plan that shall sufficiently demonstrate all performance aspects of an LRS | N |
| 01-003 | ...should demonstrate the commercial value of an LRS | N/A | Concept Design Review | Test plan that shall sufficiently demonstrate all commercial aspects of an LRS | N |
| 01-004 | ...shall demonstrate the safety of an LRS | N/A | Detailed Design Review | Analysis shows the safety of the system. A test plan that shall sufficiently demonstrate all safety aspects and the safe operation of an LRS | Y |
| 01-005 | ...should demonstrate the construction and installation of an LRS | N/A | Detailed Design Review | Installation procedure demonstrates as near as feasible the methods used for a full-scale system | N |
| 01-006 | ...shall provide learnings and de-risking for future LRS systems | N/A | Detailed Design Review | Evidence of design development to support future systems. Test plan that shall provide suitable learning to de-risk future systems. | N |
| **Technical** | *The technical demonstrator system...* | | | | |
| 01-007 | ...shall be suitable for the geological conditions of the deployment location | N/A | Detailed Design Review | Analysis using data from site ground investigation, including geomechanical modelling | Y |
| 01-008 | ...shall use the rock mass surrounding the LRS to help support the internal gas pressure | N/A | Detailed Design Review | Analysis using data from site ground investigation, including geomechanical modelling | N |
| 01-009 | ...shall be suitable for high pressure gaseous hydrogen storage for the life of the system | N/A | Detailed Design Review | Evidence that all materials, equipment and components are suitable for all operating cases using high pressure gaseous hydrogen for the life of the system | Y |
| 01-010 | ...should store sufficient hydrogen to demonstrate the thermodynamic behaviours of a full-scale LRS system | N/A | Concept Design Review | Thermodynamic model to demonstrate behaviour | N |
| 01-011 | ...should cycle for a minimum of 5000 times to demonstrate the life of a full-scale LRS system | N/A | Concept Design Review | Test plan that completes 5000 cycles within system life | N |
| 01-012 | ...should cycle for the minimum number of cycles required such that a steady-state rock mass response is achieved | N/A | Operation & Testing | Test data showing steady state behaviour | N |
| 01-013 | ...shall have a life sufficient to perform all required commissioning and testing | N/A | Concept Design Review | Evidence that all materials, equipment and components are suitable for the life of the system considering service conditions | N |
| 01-014 | ...shall be suitable for storing hydrogen at purity levels up to and including hydrogen 5.0 - 99.999% | N/A | Detailed Design Review | Evidence that all materials, equipment and components are suitable for the expected hydrogen purity | Y |
| 01-015 | ...shall not result in a significant loss of hydrogen purity from injection to withdrawal | N/A | Concept Design Review | Evidence that there are no sources of impurity that could contaminate the hydrogen | N |
| 01-016 | ...should be capable of injecting from min to max operating pressure in 24 hours to demonstrate the behaviour of a full-scale LRS system | N/A | Concept Design Review | Well, sub-surface and top-side process design demonstrating capability. Thermodynamic model to demonstrate behaviour. | N |
| 01-017 | ...shall be capable of withdrawing from max to min operating pressure in 12 hours to demonstrate the behaviour of a full-scale LRS system | N/A | Concept Design Review | Well, sub-surface and top-side process design demonstrating capability. Thermodynamic model to demonstrate behaviour. | N |

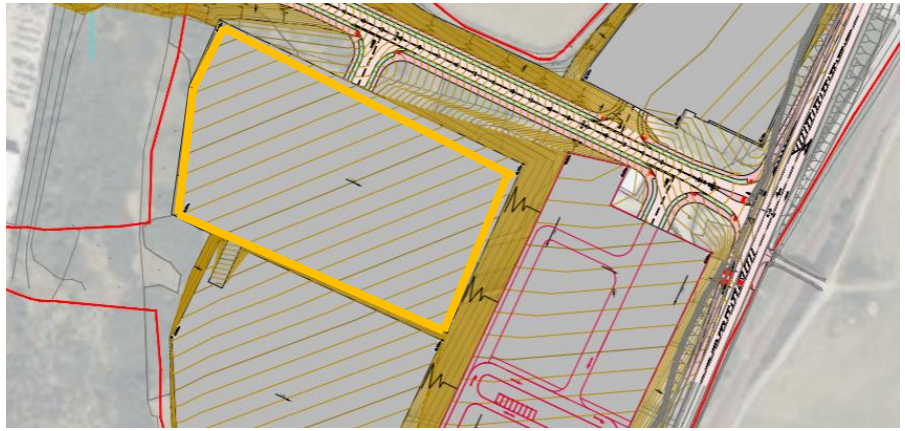
# Sub-surface storage DFMEA

Design FMEA generated following various workshops to identify failure models for each sub-system

| Risk ID | | | | Risk | | | | Control | | | | | Correction Action | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Category | Function | Requirement | Failure mode | Effects | Severity | Causes | Prevention control | Occurrence | Detection control | Detection | RPN | Action | De-risk control (For filtering purposes only) |
| 1 | Design | Civils | Hydrogen containment | Overburden failure. | Containment failure. Uplift of overburden. | 10 | Incorrectly specified friction behaviour between overburden and shaft. Overburden uplift prevention insufficient. | Calculation prepared based on Lined Rock Cavern literature. Geomechanical modelling to characterise uplift behaviour. Engagement with shaft sinkers and civils contractors. Additional features proposed to increase uplift resistance e.g., rock anchors, keyed sections, and shear pins. | 7 | When: Once representative system built. How: Sensing equipment Extent: Pass/fail analysis. | 8 | 560 | Overburden design study. | Monitoring, Modelling |
| 2 | Design | Civils | Shaft sinking | Shaft wall collapse. | Unrecoverable damage to lining system. Loss of shaft. | 8 | Overburden shaft section collapse due to insufficient support during construction to facilitate sufficient friction between overburden plug and rock mass. Incorrect Design. | Shotcrete, mesh, pre-grouting, all suggested as potential methods to support overburden shaft section to act as temporary lining whilst remainder of system installed to facilitate achieving friction requirement. | 7 | When: Detected without physical testing. How: Ground engineering calculations. Extent: Pass fail analysis | 2 | 112 | Overburden design study. | Modelling |
| 3 | Methodology | Civils | Liner installation | Unable to construct overburden | Loss of shaft. | 8 | Unable to achieve overburden / shaft friction coefficient. Incorrect overburden design. | Concrete plug design used in Lined Rock Caverns deployment for tunnels surrounding chamber. Overburden designed to reduce reliance on frictional coefficients. Engagement with shaft sinkers and civils contractors. Additional features proposed to increase uplift resistance: anchors, keyed sections, shear pins. Roughening of shaft wall would be feasible using existing excavating equipment. | 8 | When: Once representative system built. How: Assess roughness of shaft lining. Extent: Pass/fail analysis. Unclear. | 8 | 512 | Overburden design study. | Modelling |
| 4 | Design | Civils | Hydrogen containment | Uplift of overburden due to poor engagement with rock mass | Lining failure. Loss of containment. | 8 | Cooling and shrinking of concrete overburden plug following install results in voids between concrete and rock mass. | Use non-shrink concrete. Engaged with concrete specialists to understand concrete behaviour and start to specify suitable products. | 7 | When: Detect without physical testing How: Manufacturer material data sheet developed thro' prior physical testing. Extent: Pass/fail analysis. | 2 | 112 | Overburden design study. Engage with material experts. | N/A |
| 5 | Design | Civils | Liner installation | Overburden / shaft friction coefficient unachievable. | Unable to construct. Loss of shaft. | 8 | Unexpected geological conditions. | Overburden design to reduce reliance on frictional coefficient. Detailed GI designed to sufficiently characterise ground conditions at site. | 5 | When: During site investigation. How: Review geological conditions. Extent: Pass fail analysis. | 5 | 200 | Overburden design study. | Site GI |
| 6 | Methodology | Civils | Shaft sinking | Damage to surrounding geological integrity. | Reduce maximum operating pressure. | 6 | Drilling causes damage to surrounding rock mass. Incorrect procedure for geological conditions. | Augur drilling has relatively low impact on rock mass. Disturbance factor can be applied to account for damage in rock mass properties for modelling. Pre-grouting may be used to stabilise rock mass prior to drilling. Region of displaced rock due to excavation relaxation can be determined from geomechanical modelling. Detailed GI expected to accurately characterise ground conditions, therefore the drilling procedure should be appropriate. | 5 | When: Once representative system built How: Monitor lining. Unclear Extent: Pass fail analysis unclear. | 9 | 270 | Engagement with shaft sinkers. Engagement with ground stabilisation contractors. | Monitoring |

# Key steps

Sub-system design development and de-risking



| Test stage | Duration (days) | Cumulative duration (days) | Pressure cycles (non-hydrogen) | Pressure cycles (hydrogen) | Pressure cycles total |
|---|---|---|---|---|---|
| Commissioning (non-containment) | 34 | 34 | 0 | 0 | 0 |
| Commissioning (containment) | 67 | 101 | 18 | 7 | 25 |
| Operational testing | 114 | 215 | 0 | 75 | 100 |
| Accelerated life testing | 418 | 633 | 4,900 | 0 | 5,000 |
| Decommissioning testing | 2 | 635 | 0 | 0 | 5,000 |

## Site Selection (1101-004-02)

- Weighted scoring matrix used to determine most appropriate site for technology and commercial demonstration
- Highest scoring site Billingham ICI with Energy Transition Zone, Aberdeen (ETZ) second.
- Billingham requires additional land agreement which adds unfavourable risk to the project
- ETZ selected due to indication of good geology, availability of land and support for the project

## Test Plan (LGG-L057401-R03)

- Staged test plan to bring sub-systems online safely
- Designed to verify safety, performance and commercial viability
- Life-testing performed using water rather than hydrogen
- Test programme expected to last 1.5 years
- Safety systems periodically tested throughout

# Key steps cont.

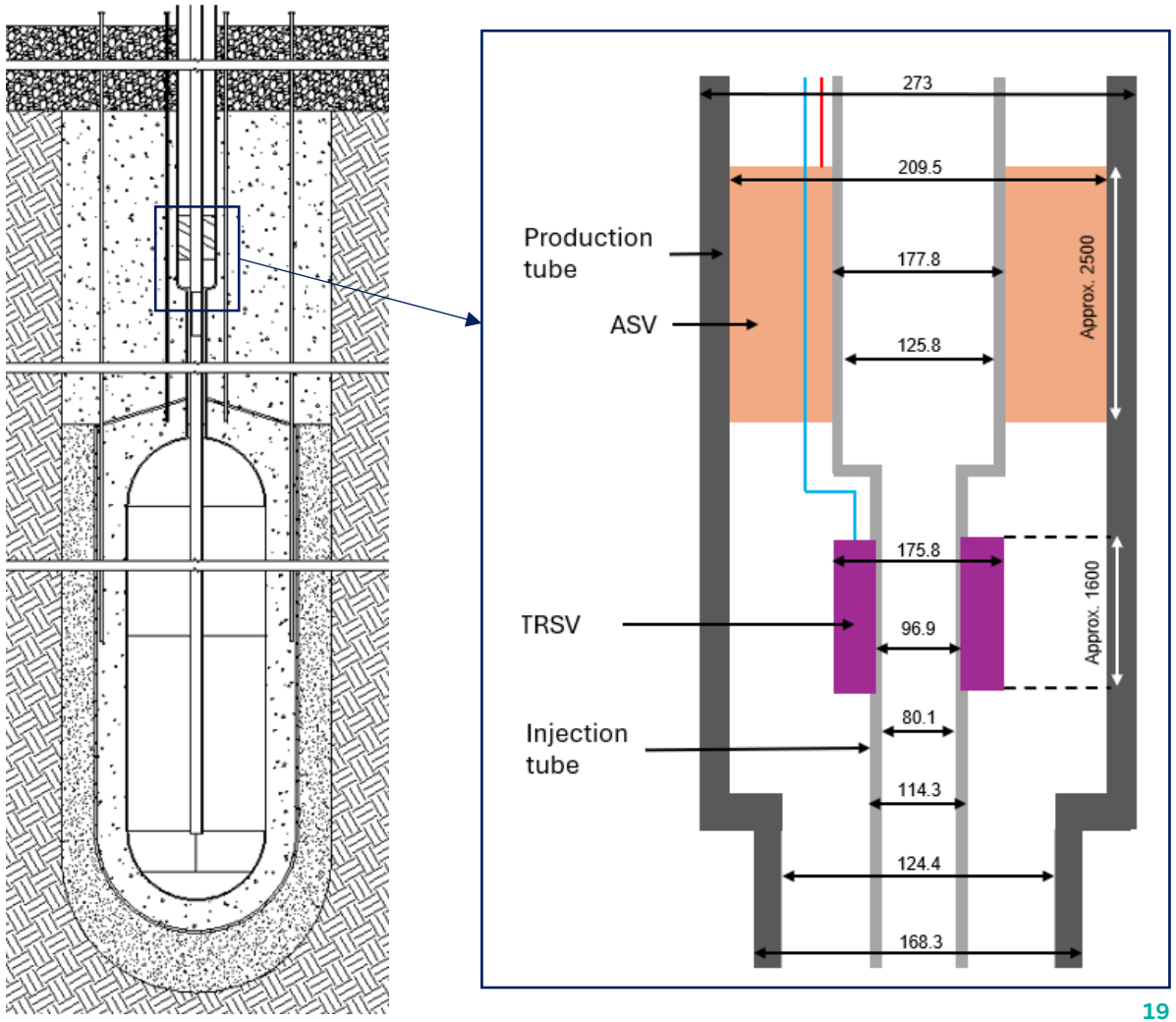
Sub-system design development and de-risking

### Geomech & Structures (LGG-L057401-R09)

- Engagement with fabricators and material experts to detail liner requirements
- Gas tight liner 316L austenitic steel
- Tungsten Inert Gas (TIG) and Plasma welding
- Structural Liner s355 carbon steel
- Concrete and grout will provide load transfer
- Materials test programme defined. Resistance to hydrogen embrittlement of high importance

### Sub-Surface Process (LGG-L057401-R08)

- Casing string design to be pipe-in-pipe solution
- Safety valve provided for both inlet and outlet
- Containment monitoring for temp and pressure on outer surface of injection tube
- Injection 12hrs, withdrawal 6hrs
- Temp regulation by re-circulation heating
- Leak management concept generated
- Dosing pipes included to test leak management system periodically

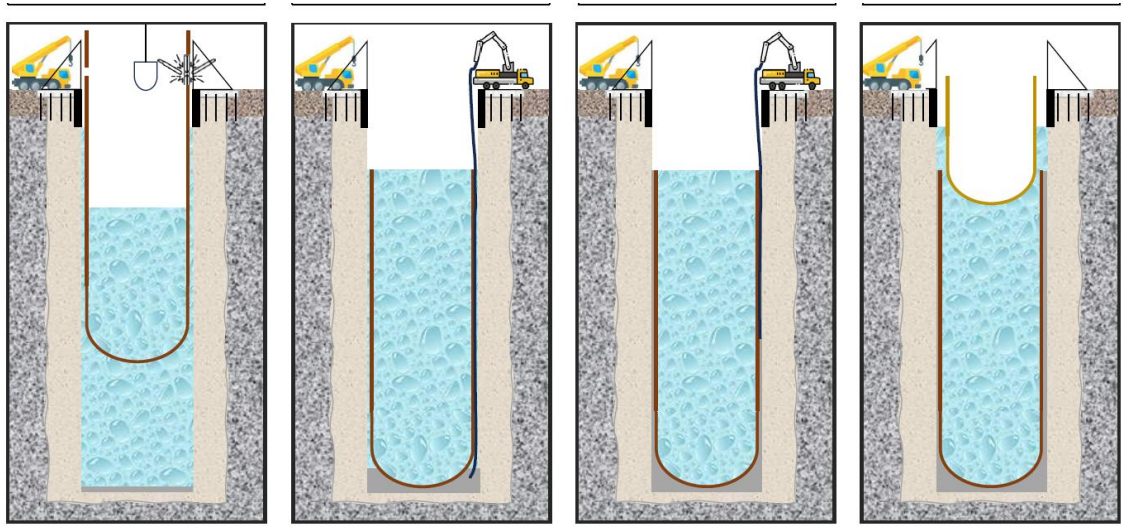


# Key steps cont.

Sub-system design development and de-risking

**Construction** (LGG-LO57401-R07)

- Major contractors identified and discussions held regarding methodology, cost and schedule
- Major stages:
  - Site preparation and security
  - Shaft sinking (including initial pre-sink through unconsolidated material)
  - Liner and casing string installation
  - Overburden installation
  - Surface process and electrical equipment set-up
- Construction methodology refined and cost confidence increased
- Critical path identified throughout remaining project phases
- Shaft excavated with rotary piling rig fitted with large auger drill bit
- 2.5m diameter and 47m depth (reduced from Discovery phase)
- Ground investigation to be conducted early next phase to increase cost confidence and provide specific site data for liner design.

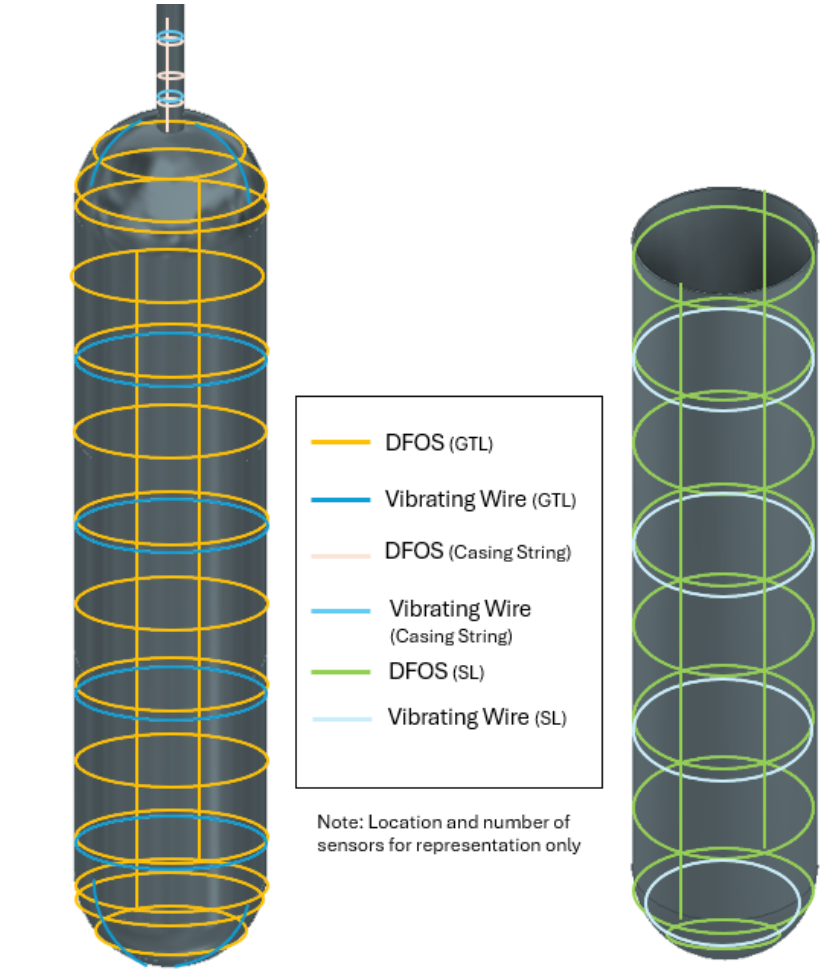


# Key steps cont.

Sub-system design development and de-risking

### Electrical Controls and Instrumentation

- High level controls architecture defined for control hardware and communication signals
- Operating modes identified
- Cause and Effect analysis highlighted operational requirements and shutdown scenarios
- Safety management system to integrate with wider safety system of the site
- Grid requirements expected to be a maximum of 0.5MW
- Bespoke Electrical Power Unit and Control Cabin to be installed at site
- Instrumentation identified for temperature, pressure and strain of the liner system
- Redundancy included for critical data collection
- Instrumentation identified for monitoring of rock mass and overburden movement
- Data used to maintain safe operations and validate system modelling and behaviour



# Risk and Next Steps

Major risks and next design and development phases

**Design**

De-risk material and liner behaviour before going underground

Material and multilayer test programme

**Cost**

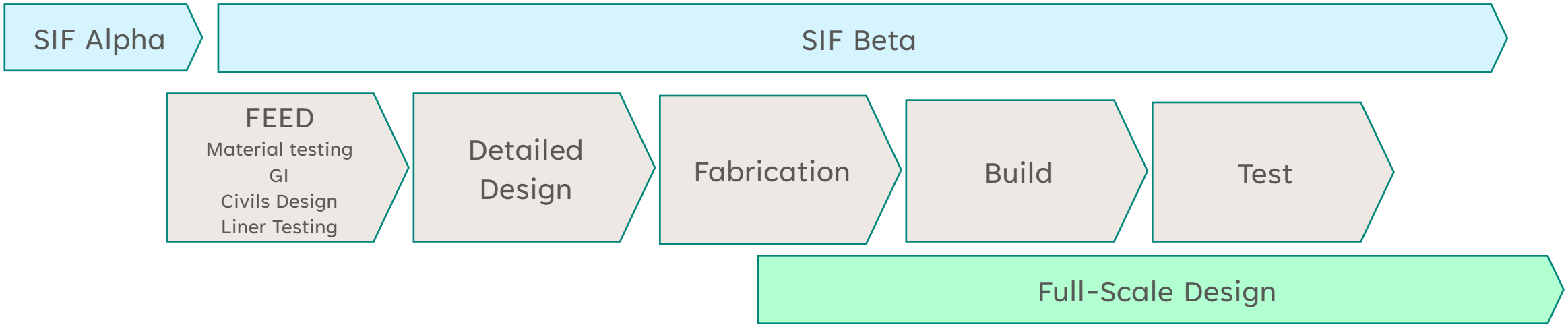
Site specific ground conditions cause increase in shaft sinking/ civils costs

BGS data analysed and GI to be conducted at the start of Beta

**Schedule**

First-of-a-kind design and build uncertainties

Contingency planning and major design and build steps investigated with subject experts



# D5 – LRS Deployability GIS Mapping

## Lined Rock Shaft Deployability Methodology Workflow

**1. Define land use**
Using the EU CORINE Land use 2018 dataset.

↓

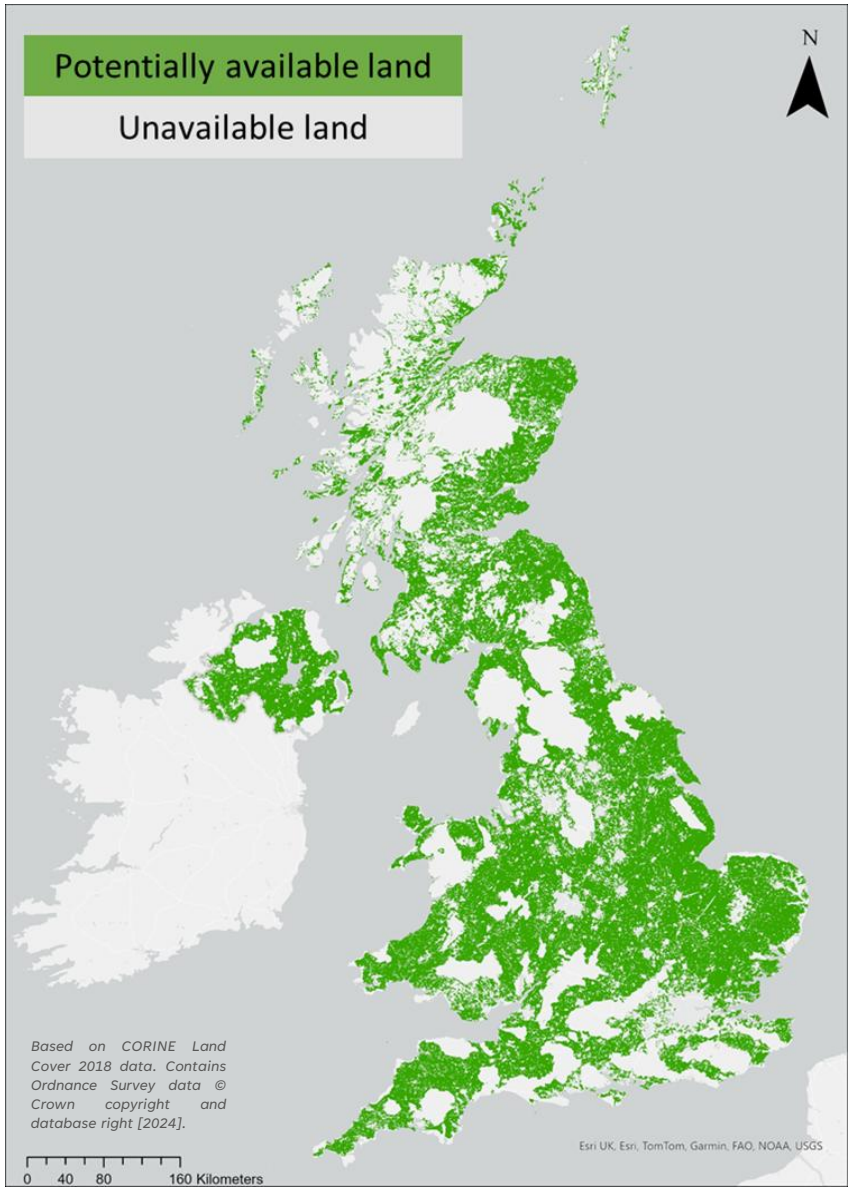
**2. Identify protected areas**
Such as SSSIs, National Parks, AONB, SACs etc.

↓

**3. Create exclusion map**
Leaving only regions potentially suitable for infrastructure deployment.

↓

**4. Assess remaining land on...**
Minimum uniaxial compressive strength and lithological assumptions.

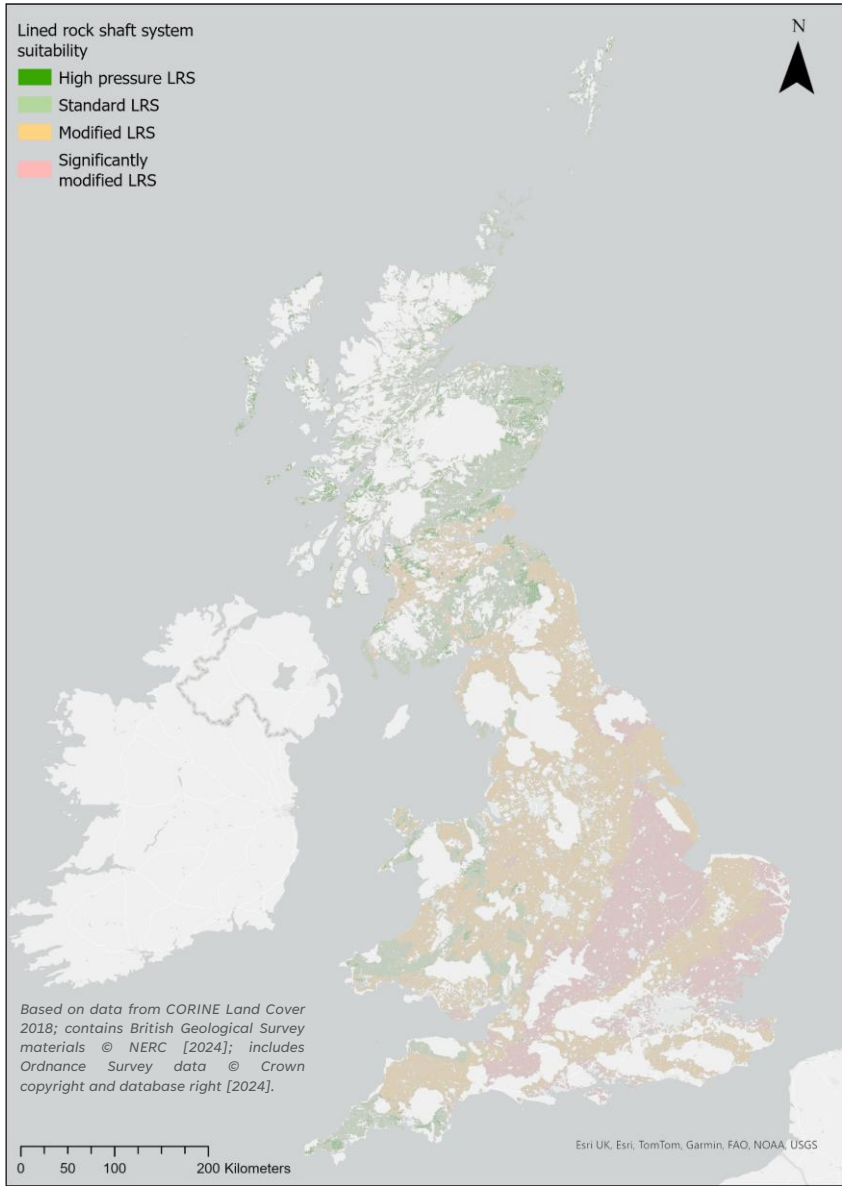



*Land potentially available for development.*

# D5 – LRS Deployability GIS Mapping

Land remaining after exclusions was divided into 0.5 km² grid squares and assessed for suitability for lined rock shafts based on the criteria outlined below.

| Shaft System design | Requirements |
|---|---|
| Higher pressure system | **Strength criteria:** UCS >25 MPa (Medium strong). |
| | **Lithologies:** Intrusive igneous rocks, mafic extrusive rocks, and high-grade metamorphic rocks. |
| Standard system | **Strength criteria:** UCS > 25 MPa (Medium strong). |
| | **Lithologies:** Any rock type. |
| Modified system | **Strength criteria:** UCS > 1 MPa (Very weak). |
| | **Lithologies:** Any rock type. |
| Significantly modified system | **Strength criteria:** UCS < 1 MPa. |
| | **Lithologies:** Any rock type. |




*GB wide assessment of LRS deployment suitability*

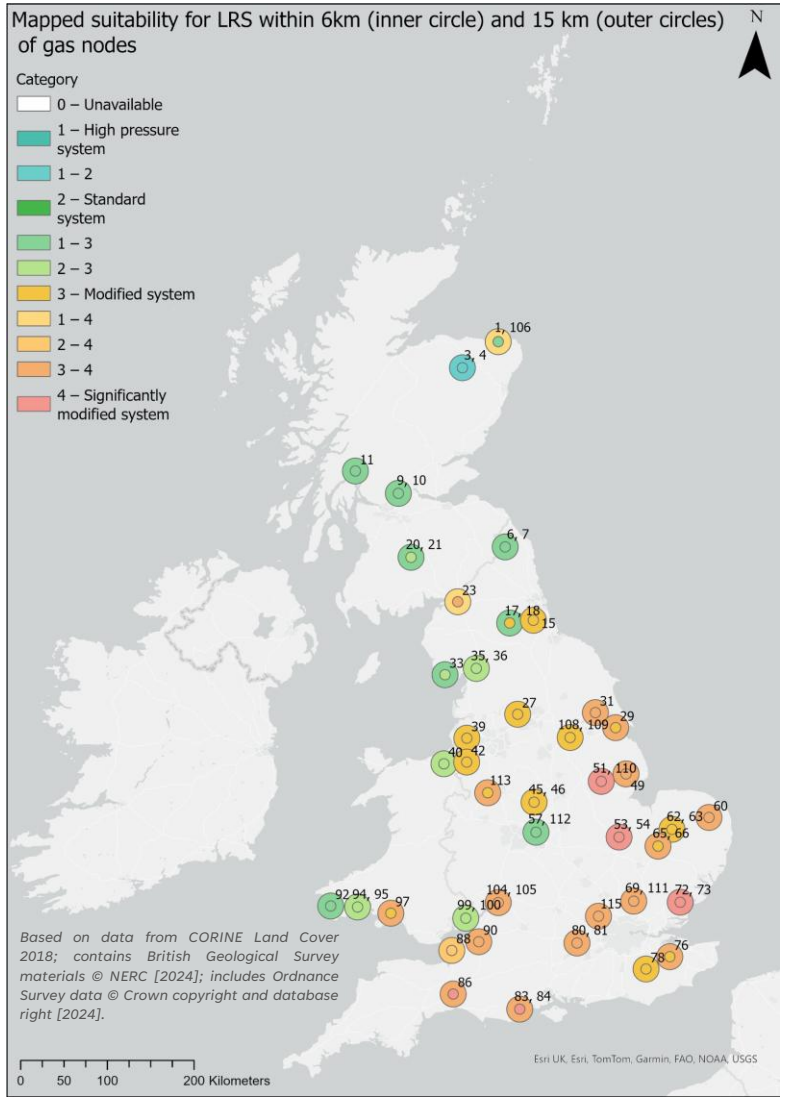
# D5 – LRS Deployability GIS Mapping

## Lined Rock Shaft Nodal Deployability

*Several key infrastructure nodes, such as gas nodes, electrical bus nodes, gas terminals, and compressors, were mapped across the study area. Inclusion zones with radii of 6 km and 15 km were established around these points. Within these zones, the geology was assessed to determine the suitability of available land for hosting lined rock shafts. Suitability categories were assigned accordingly and are represented using a color-coded scale on the accompanying map.*

| | A | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|
| 1 | Node type | Name 1 (Node number) | Name 2 (Second node number) | X | Y | 6km - Suitable for LRS? | 6km - LRS system range | 6km - LRS system range (#) |
| 2 | Gas nodes | 3 | 4 | 342859 | 831799 | Yes | High pressure - Standard | 1 - 2 |
| 3 | Gas nodes | 1 | 106 | 384106 | 861875 | Yes | High pressure - Modified | 1 - 3 |
| 4 | Gas nodes | 9 | 10 | 268960 | 686864 | Yes | High pressure - Modified | 1 - 3 |
| 5 | Gas nodes | 11 | 0 | 219407 | 712643 | Yes | High pressure - Modified | 1 - 3 |
| 6 | Gas nodes | 6 | 7 | 392170 | 625021 | No - lacks full grid square | High pressure - Modified | 1 - 3 |
| 7 | Gas nodes | 20 | 21 | 283582 | 613051 | Yes | Standard - Modified | 2 - 3 |
| 8 | Gas nodes | 23 | 0 | 337449 | 561750 | Yes | Modified - Significantly modified | 3 - 4 |
| 9 | Gas nodes | 17 | 18 | 397300 | 537239 | Yes | Modified | 3 |
| 10 | Gas nodes | 15 | 0 | 424661 | 540374 | Yes | Modified | 3 |
| 11 | Gas nodes | 35 | 36 | 358824 | 484798 | Yes | Standard - Modified | 2 - 3 |
| 12 | Gas nodes | 33 | 0 | 322789 | 477546 | Yes | Standard - Modified | 2 - 3 |
| 13 | Gas nodes | 39 | 0 | 347935 | 404285 | Yes | Modified | 3 |
| 14 | Gas nodes | 27 | 0 | 406554 | 431893 | Yes | Modified | 3 |
| 15 | Gas nodes | 31 | 0 | 496185 | 433784 | Yes | Modified - Significantly modified | 3 - 4 |
| 16 | Gas nodes | 108 | 109 | 467065 | 405041 | Yes | Modified | 3 |
| 17 | Gas nodes | 29 | 0 | 519548 | 416408 | Yes | Modified | 3 |
| 18 | Gas nodes | 40 | 0 | 321511 | 374724 | Yes | Standard - Modified | 2 - 3 |
| 19 | Gas nodes | 42 | 0 | 347746 | 376704 | Yes | Modified | 3 |
| 20 | Gas nodes | 113 | 0 | 372002 | 341311 | Yes | Modified | 3 |
| 21 | Gas nodes | 45 | 46 | 425463 | 330421 | Yes | Modified | 3 |
| 22 | Gas nodes | 57 | 112 | 427691 | 295770 | Yes | High pressure - Modified | 1 - 3 |
| 23 | Gas nodes | 51 | 110 | 502940 | 354439 | Yes | Significantly modified | 4 |
| 24 | Gas nodes | 49 | 0 | 531509 | 363069 | Yes | Modified - Signifcantly modified | 3 - 4 |
| 25 | Gas nodes | 53 | 54 | 523474 | 290158 | Yes | Significantly modified | 4 |
| 26 | Gas nodes | 65 | 66 | 568411 | 279742 | Yes | Modified | 3 |
| 27 | Gas nodes | 62 | 63 | 584481 | 299085 | Yes | Modified | 3 |
| 28 | Gas nodes | 60 | 0 | 627183 | 312801 | Yes | Modified - Significantly modified | 3 - 4 |
| 29 | Gas nodes | 72 | 73 | 593995 | 214977 | Yes | Significantly modified | 4 |

*Workbook summarising each gas nodes suitability for LRS and its system design capability.*




Gas nodes suitability to host LRS

# D6 Site Prioritisation and Characterisation

## Knapton

**Pros**
- Centrica owned site with land availability and previous planning engagement

**Cons**
- Geotechnically not suitable to host demonstonstorar at scale to do suitable full scale system testing

## Billingham (Enron)

**Pros**
- Links into ECH well to demonstrate linepack value for hydrogen transmission of LRS

**Cons**
- Requires renegotiation of land lease from owner and purchase of new land for demo

## ETZ Aberdeen

**Pros**
- ETZ owned with good land availability and planning and enviro mental permitting preferred option

**Cons**
- Not able to understand network Integration as part of demo only cycling of the LRS in a offline system

# WP3 Energy System Modelling

D7 – Assumptions – ER/Guidehouse

D8 – B-linepack+ Energy System Modelling - ER

national gas transmission

# D7 – Assumptions

For M2.2, Guidehouse provided ER with the following:

- Proportional hourly hydrogen demand profiles for buildings, industrials, transport, and storage injection across six representative days for 2030 and 2040.
- Also provided profiles for blue H2 production, green H2 production, storage withdrawal and imports across six representative days for 2030 and 2040.
- Green and blue hydrogen production values in GWh by UK region for each representative day.

# Introduction

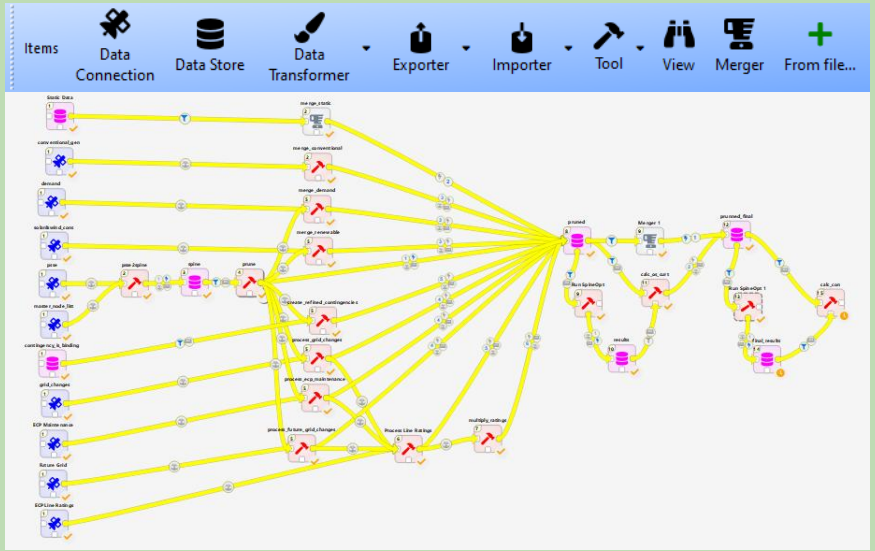
- Hydrogen-based energy systems provide less intrinsic flexibility than natural gas systems
- Reduced pipeline linepack coincides with higher renewable-driven variability
- Electricity and hydrogen networks become increasingly interdependent
- Maintaining efficient operation requires new sources of short-term flexibility

- Developed a co-optimised model of Great Britain electricity and hydrogen systems (2040)
- Represents pressure-driven gas flows and pipeline linepack explicitly
- Assesses the system value of distributed short-duration hydrogen storage
- Compares LRS with alternative storage technologies
  - Liquid Organic Hydrogen Carrier (LOHC)
  - Additional large-scale cavern storage

# Spine Open-Source Framework

## Spine Toolbox

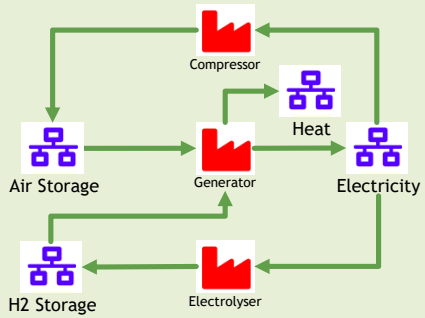
Comprehensive multi-tool and workflow management



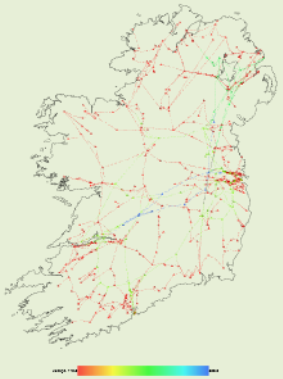

- Create and manage coherent, repeatable, complex workflows
- Manage, convert and manipulate data
- Store and access data in a centralised, problem independent format with rich API
- Link models

## SpineOpt

Richly featured and uniquely flexible energy system model akin to Plexos




SpineOpt CAES Model



SpineOpt Irish Grid Model

- Designed from the ground up to model the energy transition
- Flexible structure allows technologies to be represented at an arbitrary level of detail
- Multi-system, multi-sector, multi-model
- Uniquely flexible approach to time and uncertainty giving finer control of model dimensions
- Methodologies to capture more scope and more detail
- Co-optimise investments, markets, operations and grid

# GB system study

- Scenario data gathered to build a co-optimised H2 and electricity energy system model, including transmission.
- Simplified gas network validated by National Gas.
- Simplified electricity network validated by NESO.
- Hydrogen demand, production and imports provided by Guidehouse for 6 representative days disaggregated by NUTS 1 region
- High level assumptions (demands, portfolios, IC capacities) taken from ENTSO TYNDP National Trends scenario.
- Disaggregation informed by Guidehouse data / FES.

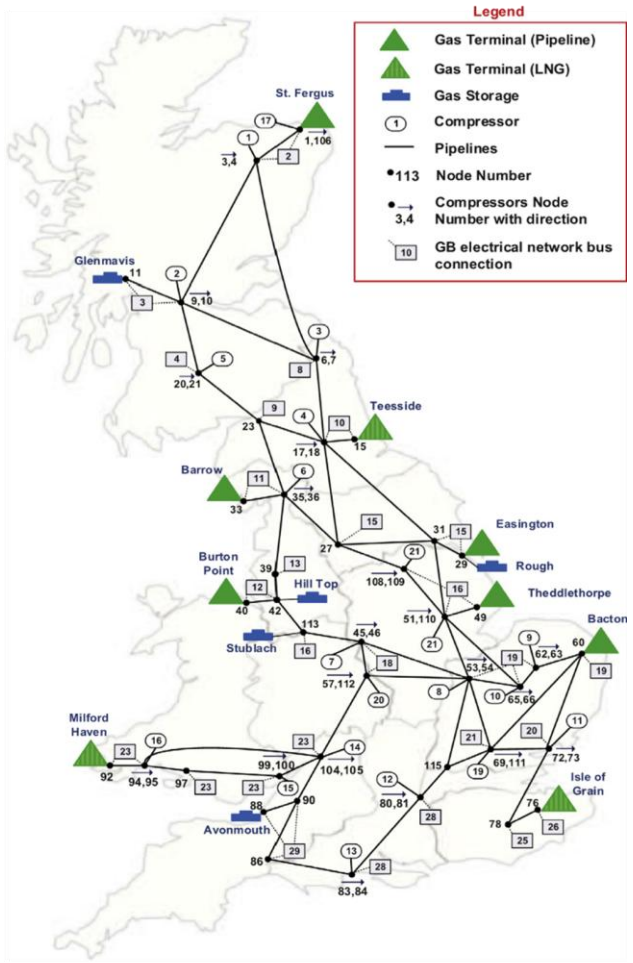
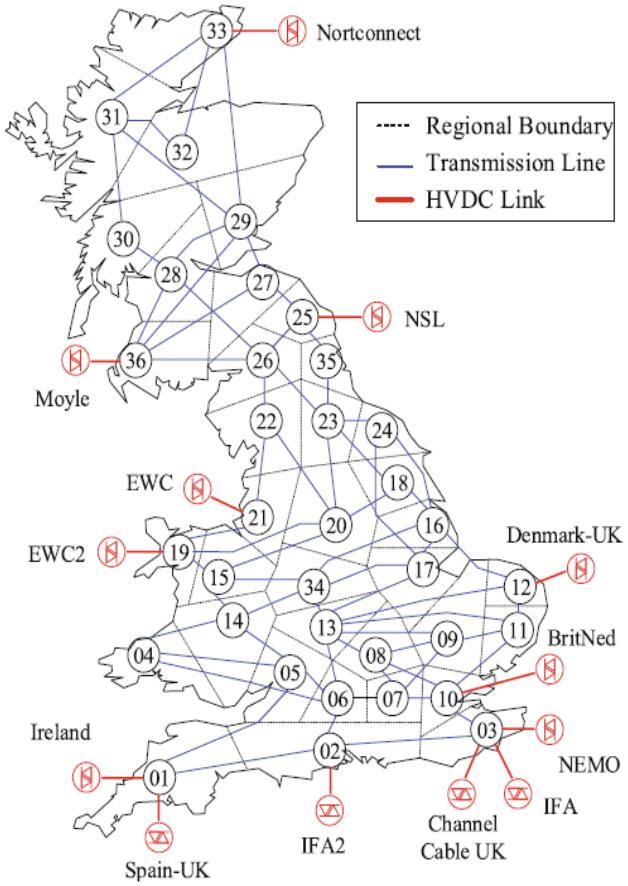



Fig. 6. GB simplified NTS gas network.



# National Trends Scenario

- TYNDP National Trends Scenario selected, providing comprehensive and detailed portfolios for electricity and hydrogen, along with demand and renewables time series for 2040
- Built from TSO inputs that reflect each country's NECPs, long-term strategies and hydrogen strategies, rather than a top-down optimisation of "least-cost Europe".
- NT assumes strong energy-efficiency and continuing electrification of transport and heating (EVs, heat pumps, hybrid heat pumps).
- Large increases in wind and solar; offshore wind in particular ramps up between 2030 and 2040
- Hydrogen plays a moderate, rather than extreme role, with a focus on industry and heavy transport

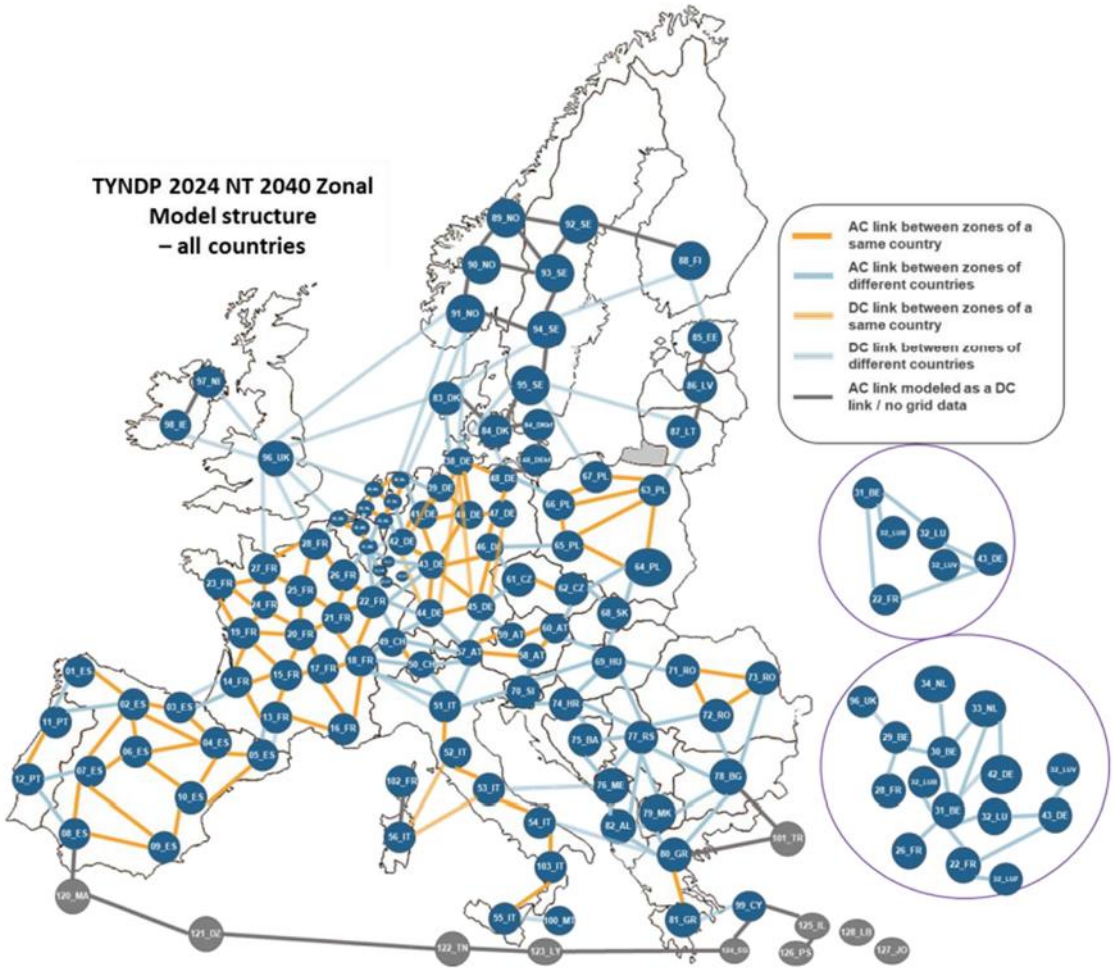



*Figure 7 - TYNDP 2024 NT 2040 Zonal model structure*

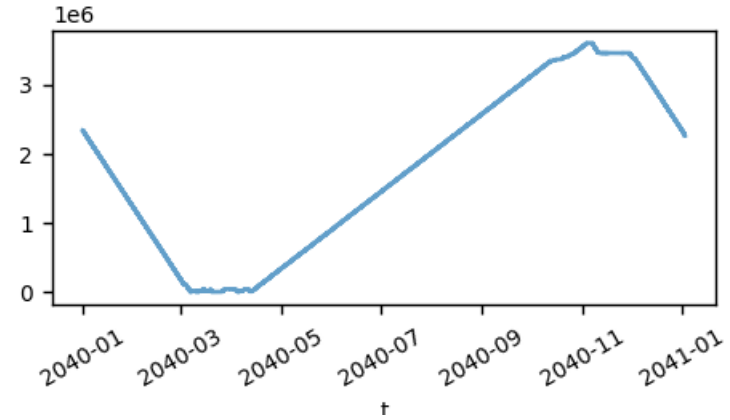
# GB Capacity Portfolio (2040)

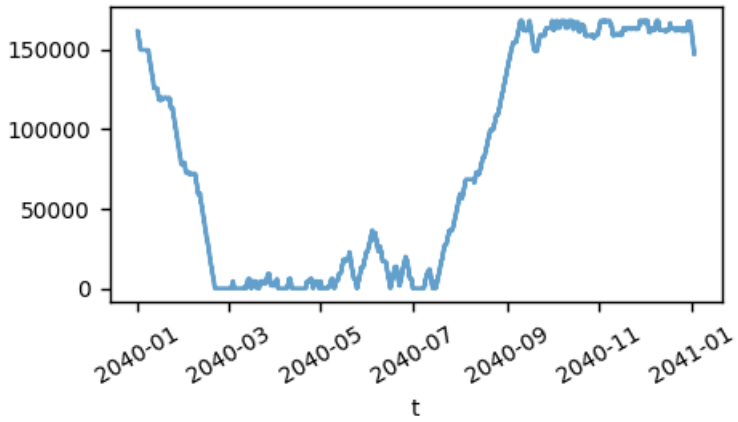
- GB electricity and hydrogen capacities in 2040 are dominated by large-scale renewable deployment. Total wind capacity reaches 137 GW, with offshore wind forming the largest share. Solar PV reaches over 59 GW, combining rooftop and utility-scale installations.
- Thermal capacity is significantly reduced, with 13 GW nuclear and 11 GW gas providing firm and dispatchable capacity.
- Hydrogen electrolysers reach 25 GW, while battery storage consists of 23 GW of power and 37 GWh of energy capacity.
- Hydro capacity in GB remains broadly stable rather than expanding.
- Implicit DSR, alongside energy limited, price activated explicit DSR (22.9 GW)

| Technology | Capacity |
|---|---|
| Offshore wind | **95 GW** |
| Onshore wind | **42 GW** |
| Solar PV (total) | **59 GW** |
| Nuclear | **13 GW** |
| Gas | **11.0 GW** |
| Batteries | **23.3 GW** |
| Hydro | **5.1 GW** |
| Electrolysers | **25.2 GW** |

# Disaggregation & Model Updates

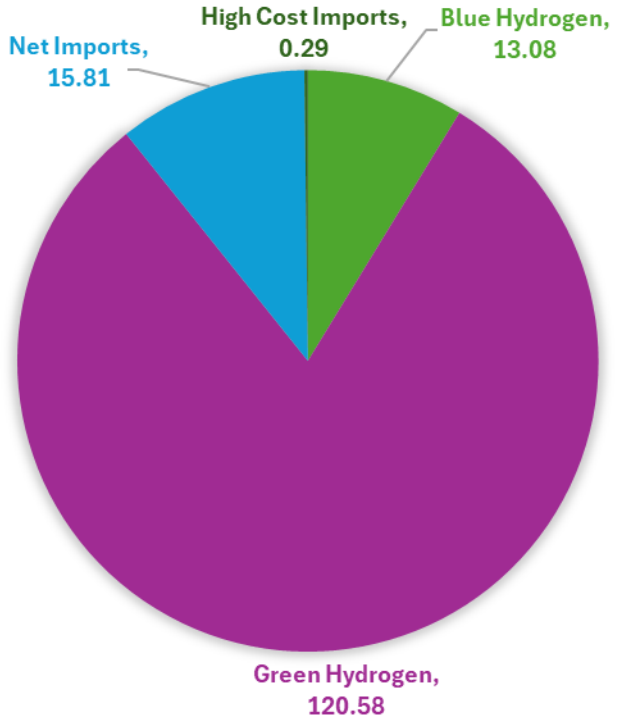
- National Trends portfolio disaggregated across Gas and Electricity nodes using FES & Guidehouse data
- Imports / exports facilitated with all interconnectors modelled and NT 2040 prices at country nodes.
- NT has hydrogen import at 1 terminal only
- Additional higher cost back-up supply made available at 4 additional terminals
- 2 stage model
  - Optimise long-term storage at daily resolution
  - Rolling model at 3h resolution
- LT storage targets set at the end of each day
- Penalty applied if target not met
- LT storage can still play limited role providing intraday flexibility



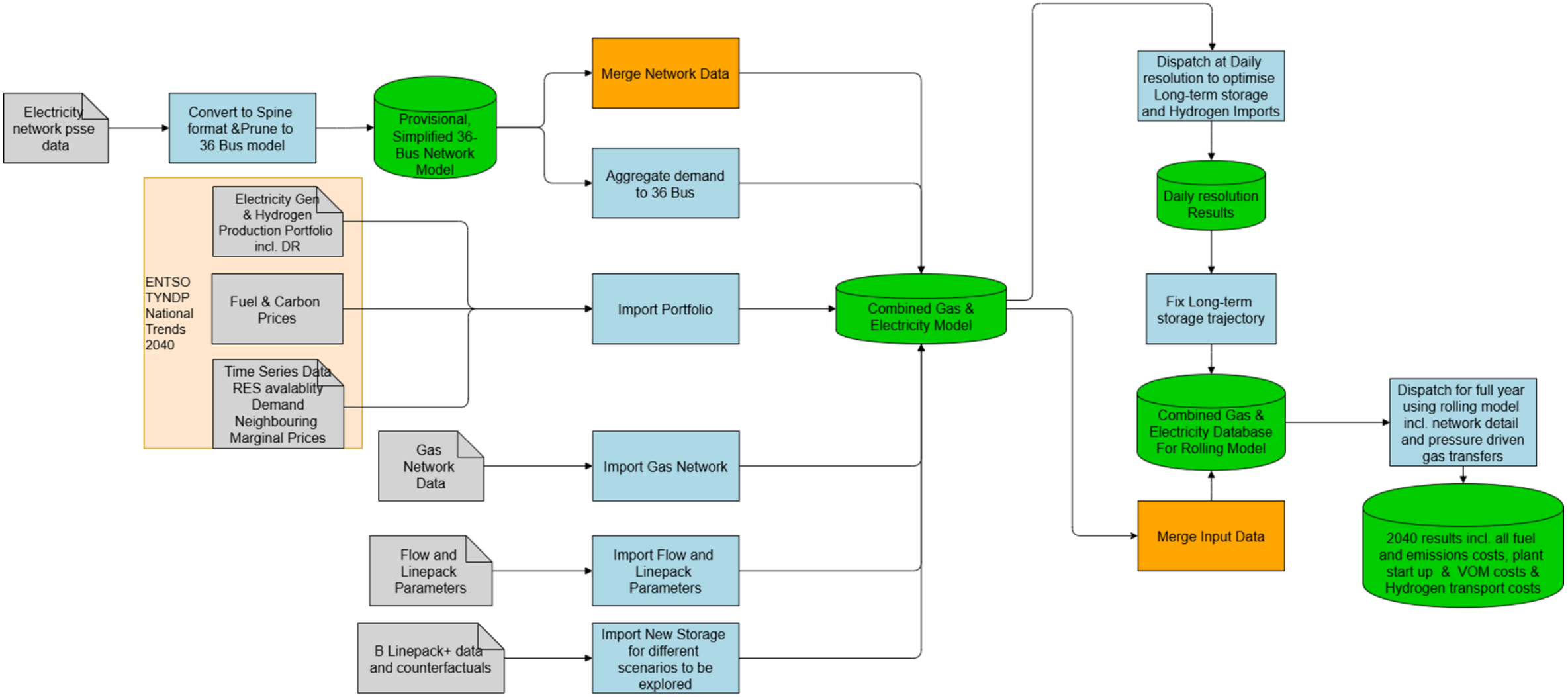



# Hydrogen Summary

- Hydrogen demand is met by a combination of green hydrogen, blue hydrogen and imports
- 25.2 GW of electrolysers provide valuable system flexibility and are dispatched when electricity prices are low
- 1.5 GW of steam methane reformers (combined with CCS) are also included and dispatched when required to meet hydrogen demand
- 4 GW of import / export capacity assumed between GB and Belgium
- Average Price at the Belgium node: €82.74 / MWh (£72.81 / MWh)
- Back-up supply at 4 additional terminals at higher price point £176
- 8.25 TWh of large-scale hydrogen storage (existing gas storage)
- Annual demand in 2040 is 148 TWh



# Workflow


Electricity network psse data
Convert to Spine format &Prune to 36 Bus model
Provisional, Simplified 36-Bus Network Model
Merge Network Data
Aggregate demand to 36 Bus
ENTSO TYNDP National Trends 2040
Electricity Gen & Hydrogen Production Portfolio incl. DR
Fuel & Carbon Prices
Time Series Data RES avalablity Demand Neighbouring Marginal Prices
Import Portfolio
Gas Network Data
Import Gas Network
Flow and Linepack Parameters
Import Flow and Linepack Parameters
B Linepack+ data and counterfactuals
Import New Storage for different scenarios to be explored
Combined Gas & Electricity Model
Dispatch at Daily resolution to optimise Long-term storage and Hydrogen Imports
Daily resolution Results
Fix Long-term storage trajectory
Combined Gas & Electricity Database For Rolling Model
Merge Input Data
Dispatch for full year using rolling model incl. network detail and pressure driven gas transfers
2040 results incl. all fuel and emissions costs, plant start up & VOM costs & Hydrogen transport costs

# Dispatch Model & Scenarios

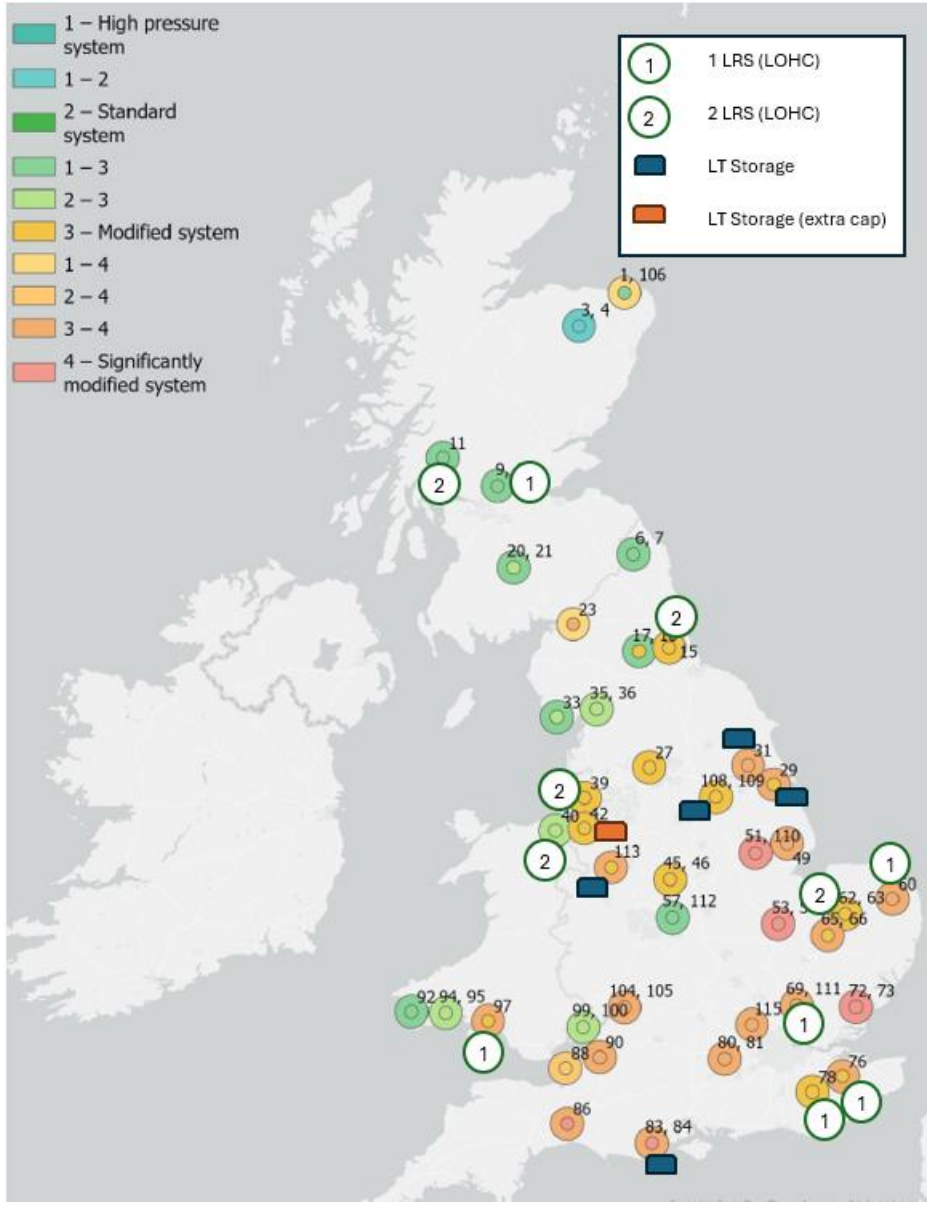
- Dispatch model minimises operating costs for co-optimised hydrogen and electricity system
- Rolling model solves for 366 days with 72 hour window
- Costs include fuel costs, carbon costs, start-up costs, VOM costs, with TYNDP assumptions
  - Natural Gas: 18.06 £/MWh
  - Nuclear: 5.39 £/MWh
  - Carbon Price: 129.36 £/ton
- A throughput cost was added to each of the linepack stores, calibrated to Guidehouse's 2040 hydrogen compressor cost estimates, with a small uplift (15%) to account for additional pipeline transport and operational costs consistent with published hydrogen pipeline transport tariffs reported by the European Hydrogen Backbone.
- The model sees a cost for additional linepack use, avoiding over-use and valuing other forms of flexibility

- 4 core scenarios are examined
  - Base scanrio (no additional hydrogen storage)
  - LRS scenario (16 shafts)
  - LOHC (matched in size and location)
  - Large-Scale Storage (matched energy capacity at single site)

| Scenario | Hydrogen Storage Capacity (GWh) (excluding system linepack) |
|---|---|
| Base | 8,250.0 |
| LRS | 8,280.5 |
| LOHC | 8,280.5 |
| Large-Scale Storage | 8,280.5 |

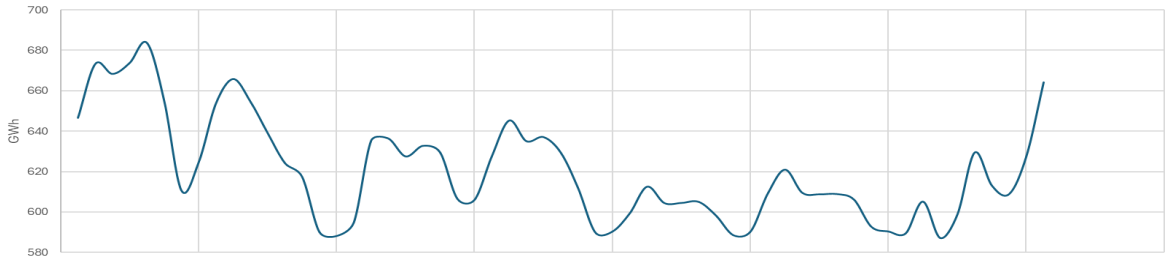
# LRS and Counterfactual Storage Siting

- Nodes ranked based on throughput with 1 LRS at each node
- Significantly modified systems avoided (Deliverable 5 “UK wide mapping of lined rock shaft deployability and system integration”)
- Modified systems kept to maximum of 1 system at each node
- Total of 16 systems distributed across 11 nodes
- Total capacity (working gas) 30.5 GWh
- Long-term storage capacity ~ 8.25 TWh
- System linepack ~ 830 GWh
- 16 LRS systems represents an increase of 3.7% of short term storage
- 16 LRS systems represents an increase of 0.34% of total system storage

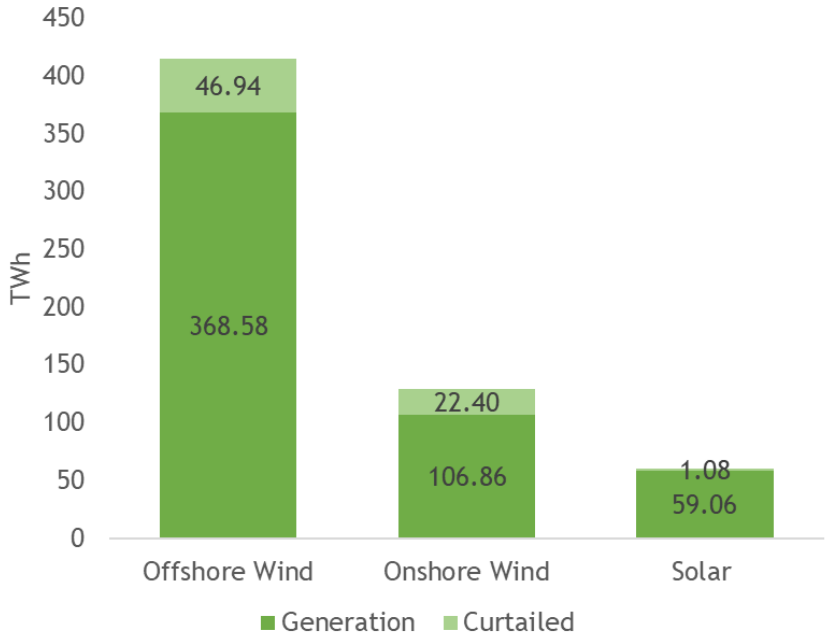


# Base Scenario Results

- The majority of hydrogen demand is met by production from the electrolysers - 120.6 TWh
- Significant net imports make up the next largest category at 15.8 TWh
- The relatively modest SMR fleet (with CCS) produces 13.1 TWh with the balance met with high cost imports totalling 0.29 TWh
- Up to 828 GWh of hydrogen is stored in the gas pipelines (signicantly reduced capacity compared to NG system)
- An average daily swing of 42.4 GWh is seen, with a maximum swing of 208 GWh

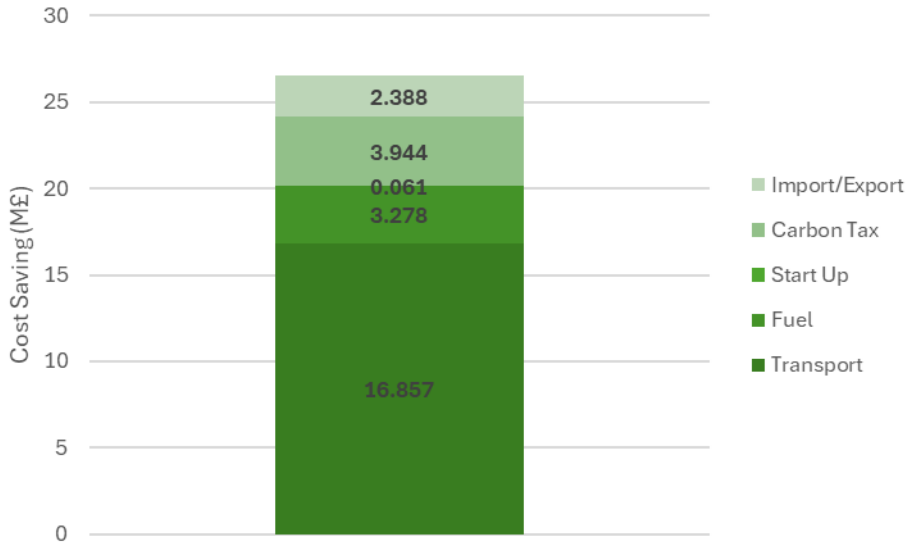



- 534.5 TWh of renewable energy generated
- 70.4 TWh of renewable energy curtailed
- This represents 11.6% of the available renewable energy
- Offshore wind dominates, with 369 TWh generated, followed by onshore wind at 107 TWh and solar at 59 TWh



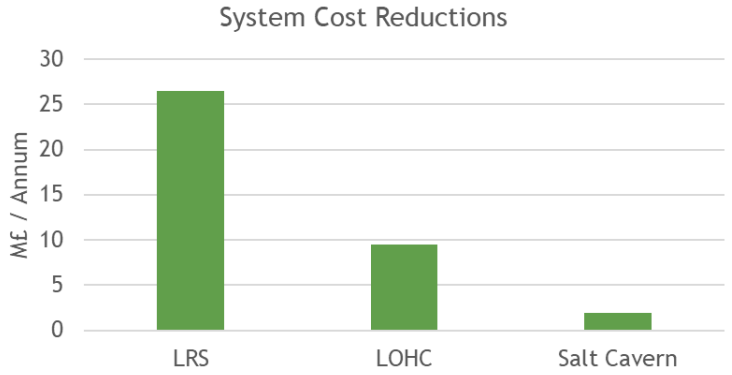
# LRS Results

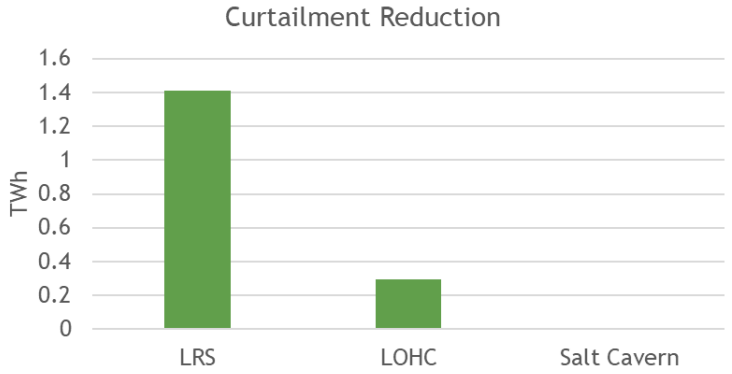
- Significant cost savings are seen over the year - M£26.53 over 1 year of operation
- Cost savings result from
  - More efficient imports / exports with a small reduction of 93.5GWh of net imports from Belgium
  - Reduced fuel and carbon costs. An additional 1.4TWh of renewable energy is generated
  - Reduced compressor costs, with reduced reliance on system linepack
- While the LRS is dispatched to minimise total system costs (electricity & hydrogen), with cost savings spread across the system, maximum system linepack is reduced from 828 GWh to 818 GWh
- Average daily swing reduces from 42.9 to 41.2 GWh with the maximum daily swing down to 196 GWh from 208.9 GWh.

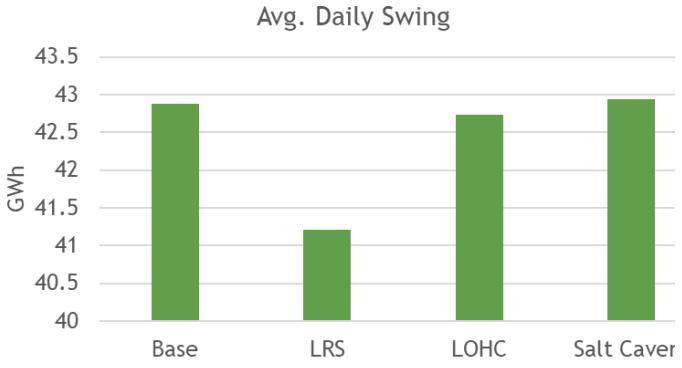


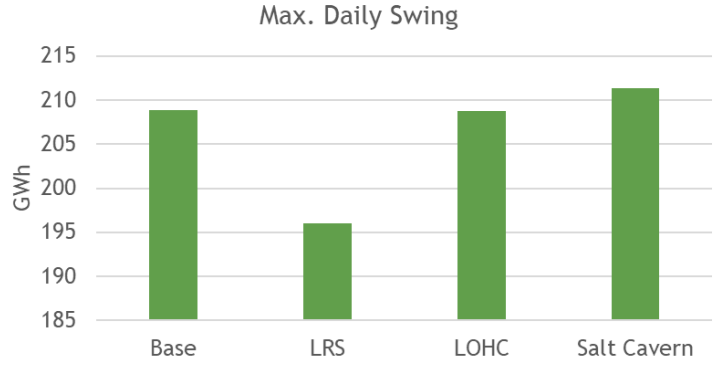
# Counterfactual Storage Results

- Liquid Organic Hydrogen Carriers deployed at the same sites, with the same capacities generated lower cost savings of M£9.53 across the year, as the system has a significantly lower round trip efficiency
- The additional long-term storage capacity saw modest cost savings of M£1.94, primarily driven by more efficient imports / exports of Hydrogen, with minimal impact of fuel costs and transport costs
- The LRS was also the most effective at reducing system level curtailment of wind and solar generation
- The LOHC has a modest impact on system linepack (Average swing 42.7, Max. swing 208.8)
- The additional salt-cavern capacity sees slightly higher values of linepack swing (Average swing 42.9, Max. swing 211.4)



# Discussion & Conclusions

- Distributed hydrogen storage provides high system value in a future co-optimised electricity and hydrogen system
- LRS is more effective at managing short-term system flexibility than the counterfactual storage options examined
- Even at modest scale, LRS materially reduces reliance on transmission linepack
- The benefits extend beyond cost savings to include
  - reduced renewable curtailment
  - improved operational behaviour of the hydrogen network
- Hydrogen networks experience a loss of intrinsic flexibility relative to natural gas due to reduced linepack
- Geographically distributed storage is particularly effective at replacing this lost flexibility
- Location, injection/withdrawal rates, and efficiency are as important as total storage capacity
- LRS uniquely delivers
  - system cost reductions
  - curtailment reduction
  - lower average and peak linepack utilisation

# WP4 System Demonstration

D9 Regulation Recommendations - NGT
D10 Planning and Enviromental Permitting – WSP
D11 System Definition – Premtech
D12 Interfacing P&IDs - Premtech
D13 SR25 Assessment on Safety - Premtech
D14 Safety and COMAH Regulations - NGT
D15 Consumer Engagement - ESC

national gas transmission

# D9 Regulatory Recommendations

| Market Stage | Nascent (2028 to mid 2030s) | (Growing Mid 2030s to 2040) | Established (2040 onwards) |
|---|---|---|---|
| Description | H2 pipelines connect industrial clusters that have their own H2 production source. Market liquidity and maturity is very low. | Network backbone takes shape as clusters connect, aided by growth in electrolyser and power station demand. Market liquidity increases | Supply and demand are firmly established. H2 trading market and balancing point established. High market liquidity and maturity. |
| Linepack role | Producers will size H2 production to meet hub demand. Pipeline linepack may therefore merely act as a store for back up H2 if producers experience operational issues. | The market commercial construct and role of linepack shifts closer to its traditional role in the current NG set up, allowing commercial flexibility products to be introduced | Flexibility becomes a scarce commodity, with linepack having to accommodate intraday and multi-day mismatches between supply and demand |
| Regulatory Recommendation | Due to decrease in linepacking capability with hydrogen fuel and nascent state of network, ofgem to consider exception for networks to own and operate bolster "Linepack+" only storage for a pre stipulated time frame to provide energy to offtakers. Ensure networks provide transition plans that consider future new build H2 pipeline sizing to include linepacking capacity for connecting future clusters. Not to be deemed as oversizing. | Networks will no longer be able to own & operate storage assets. Give incentives on fast cycle storage commercial products for storage developers to purchase "Linepack+" storage. OR deem "Linepack+" as operational storage if business case on system flexibility and resilience is deemed economically favourable when compared to developing other whole system enabling infrastructure. | Allow linepack flexibility services utilising LDES via balancing zones, frequent balancing periods and auction system. "Linepack+" storage built in nascent market generating revenue over a threshold for certain commercial products is to pay back ofgem incentive given in growing market conditions to developers. |
| Key Risk | Pipeline sizing and development of storage assets simultaneously leads to assets under utilised in this period with uncertain supply/demand profiles. | Risks stranded asset class if Linepack+ storage cannot be sold by networks to commercial developers/operators | Complexity of balancing zones and auction system may be difficult to implement and not incentivise frequent trading. |

# D9 – Next Steps

- We were unable to set-up an **engagement meeting** with ofgem to go over current network license where it stipulates networks cannot **own and operate storage assets**. Intention is we wish for LRS to be treated similar to how ownership of **gas holders at GDN level** was permitted and treated previously.
- Therefore, prior to Beta we must present **resilience challenges** and highlight the need for **operational hydrogen storage** deployment across certain sections of Project Union.
- For example, NTS Materials Pipeline Assessment | ENA Innovation Portal, concluded that for 100% hydrogen transmission **only 50% of the NTS** could operate at a pressure of **at least 70 bar** due to **fatigue and fracture toughness** assessments.
- This further coupled with the **lower volumetric energy density** of hydrogen as a fuel means National Gas's **linepacking capability** will be significantly impacted in some routes of Union.
- Current **natural gas MAOP is 85ba**r generally across the NTS allowing for significant linepack capability for energy resilience.

| Key | MAOP Band |
|---|---|
| | 50-60bar |
| | 60-70bar |
| | >70bar |
| | Unchanged |

# D10 Planning and Environmental

WSP have completed the following aspects of the Planning and Environmental Scope:

- Environmental and Planning Site Options Appraisal report - WSP have prepared this report and identified one preferred demonstrator site and five commercial sites through an options appraisal process whereby a Red Amber Green (RAG) rating was assigned to each option using professional judgement. WSP updated this report this following NGTs review and will be discussed the outcomes of the appraisal with NGT during a workshop on Monday 15th September 25.

- Consenting Strategy – WSP prepared a Consenting Strategy for Billingham site instead of ETZ due to uncertainty on site selection at the time the project was undergoing a partner change. This work will need to be redone in early Beta phase.

- Engagement (Local Planning Authority / Environment Agency) – WSP did not complete this element of the scope due to uncertainty at the time regarding site selection and which authority to engage with e.g. EA or SEPA. This part of the scope will be undertaken as part of the Beta phase of the project.

# Demo Sites Planning and Environmental Permitting (RAG status)

**Table 4-3 – Summary of RAG Ratings (Demonstrator Sites)**

| Planning Parameters | Site Option 1 | Site Option 12 | Site Option 14 |
|---|---|---|---|
| Planning Policy Provision | | | |
| Site Allocation | | | |
| Article 4 Directions | | | |
| Planning History Searches | | | |
| Hazardous Substances Consent | | | |
| Score | 1 High<br>4 Low | 5 Low | 5 Low |
| Conclusion | High | Low | Low |

**Table 5-4: Summary of RAG Ratings (Demonstrator Sites)**

| Environmental Topic | Site Option 1 | Site Option 12 | Site Option 14 |
|---|---|---|---|
| Air Quality | | | |
| Cultural Heritage and Archaeology | | | |
| Ecology | | | |
| Landscape and Visual | | | |
| Geology and Soils | | | |
| Noise | | | |
| People and Communities | | | |
| Water, Drainage and Flood Risk | | | |
| Score | 2 High<br>4 Moderate | 1 High<br>5 Moderate | 0 High<br>1 moderate |

STRATEGIC INNOVATION FUND (SIF) ALPHA B- LINEPACK HYDROGEN STORAGE INNOVATION PROJECT
Project No.: UK0042588.3685 | Our Ref No.: UK0042588.3685
National Gas Transmission

| Environmental Topic | Site Option 1 | Site Option 12 | Site Option 14 |
|---|---|---|---|
| | 2 Low | 2 Low | 7 low |
| Conclusion | High | High | Low |

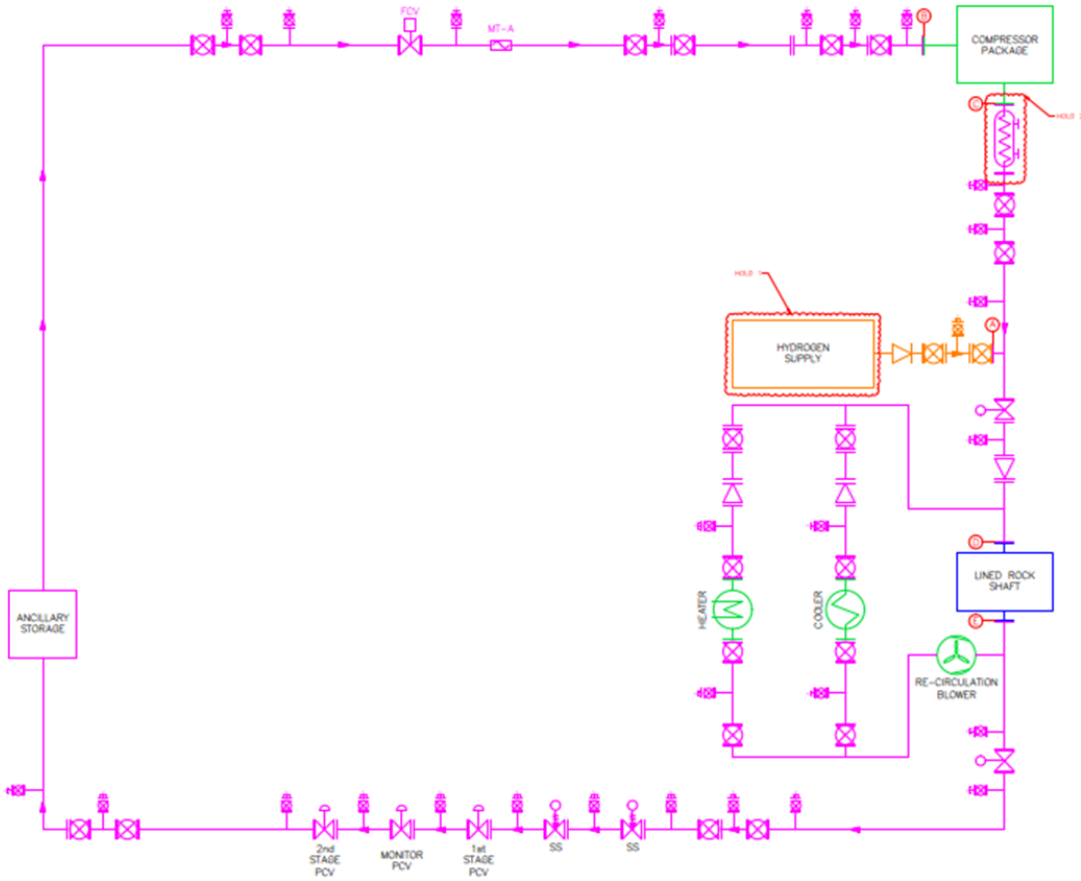
# D11 System Definition

| Parameter | Unit | Value | Comment |
|---|---|---|---|
| Line Rock Shaft Pressure | Barg | 200 | As provided by Longitude |
| Maximum Operating Pressure (MOP) | | 200 | As provided by Longitude |
| Lined Rock Shaft Safe Operating Limit | | 212 | SOL = MOP*1.06 as per T/PM/PS/3 |
| Maximum Entry into compressor | | 50 | Based on Project Union BoDD |
| Minimum Entry into compressor | | 30 | Based on Project Union BoDD |
| Flow rate | Scmh | 408 | Based on 0.44te of hydrogen ans a 12-hour cycle time |
| Mass flow Rate | Kg/hr | 36.7 | Based on 0.44te of hydrogen ans a 12-hour cycle time |
| Maximum Allowable Velocity | m/s | 40 | Filtered hydrogen is required |
| Material Design Temperature | °C | -20to +60 | |
| Expected normal operating temperature | °C | 10 to 30 | |
| Lined Rock Shaft Operational Temperature | °C | 10 to 70 | |
| Lined Rock Shaft Absolute Temperature | °C | 0 to 80 | |

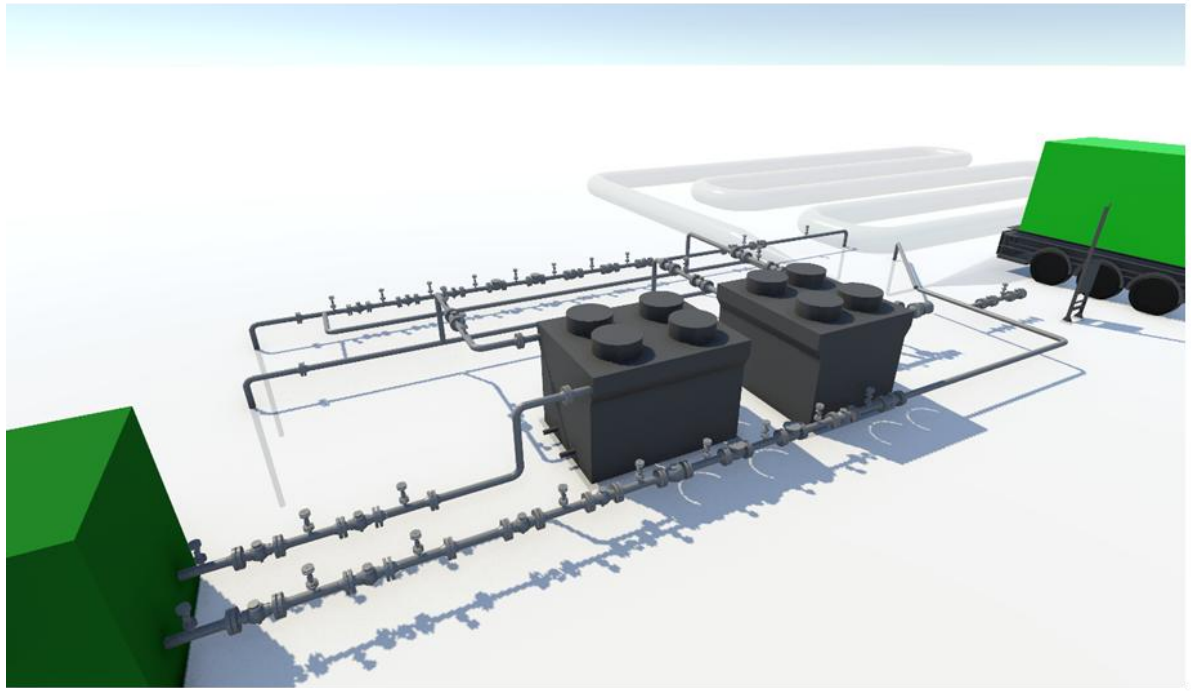
- The design parameters are based on provided information and are dependent on factors such as the geology
- The size of the LRS was reduced during the Alpha Phase (see Longitude slide for deliverable D4) but the more conservative values have been used to ensure suitability
- 100NB pipework is proposed to be used for the demonstrator facility

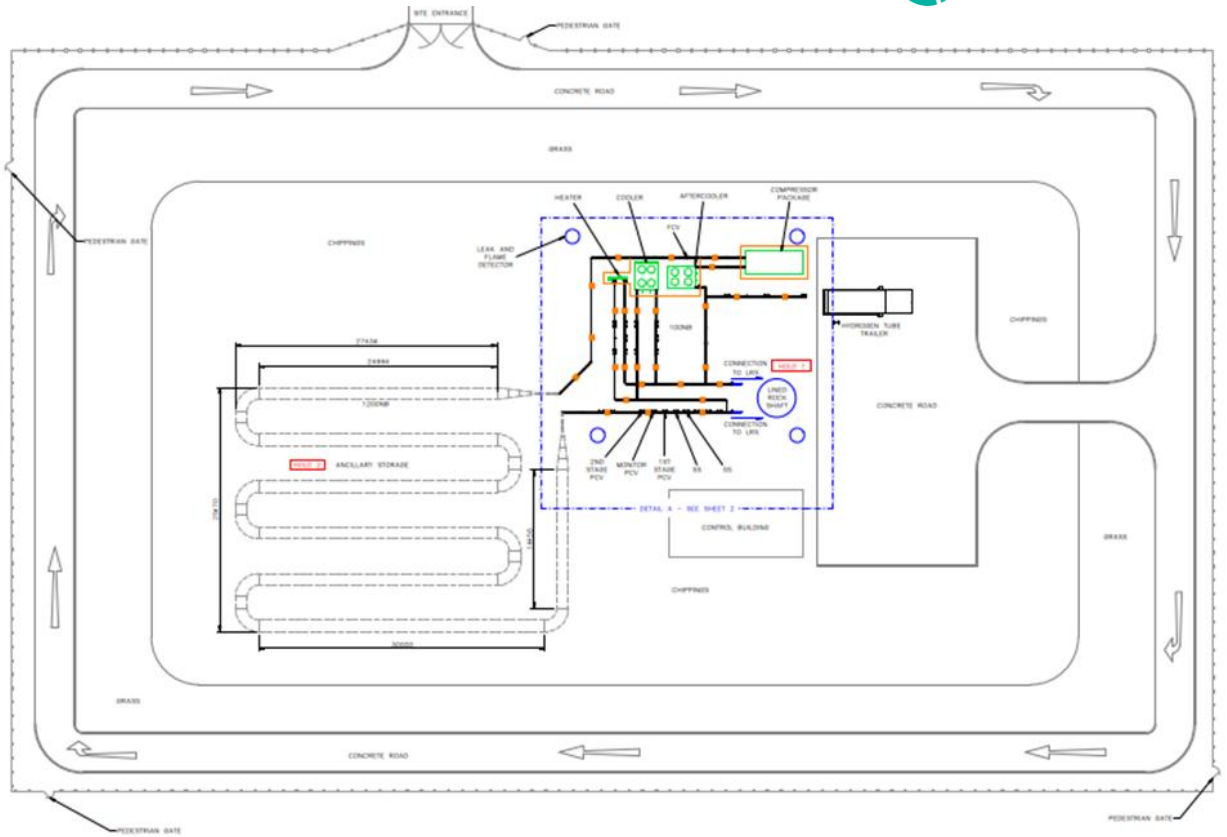
# D12 Interfacing P&IDS (Proposed Arrangement)

- Premtech were responsible for the design of the top-side process equipment
- Hydrogen supply is assumed from a tube trailer at 200barg
- Recirculation heating and cooling system included to maintain within LRS operational temperature limits
- Flow control valve stream shall control the flow through the demonstrator to simulate pipeline withdrawal and injection rates
- Compression and pressure reduction included to simulate increasing and decreasing pressure to pipeline and LRS operating pressures
- Ancillary Storage (oversized pipework) included within the design



# D12 Interfacing P&IDS



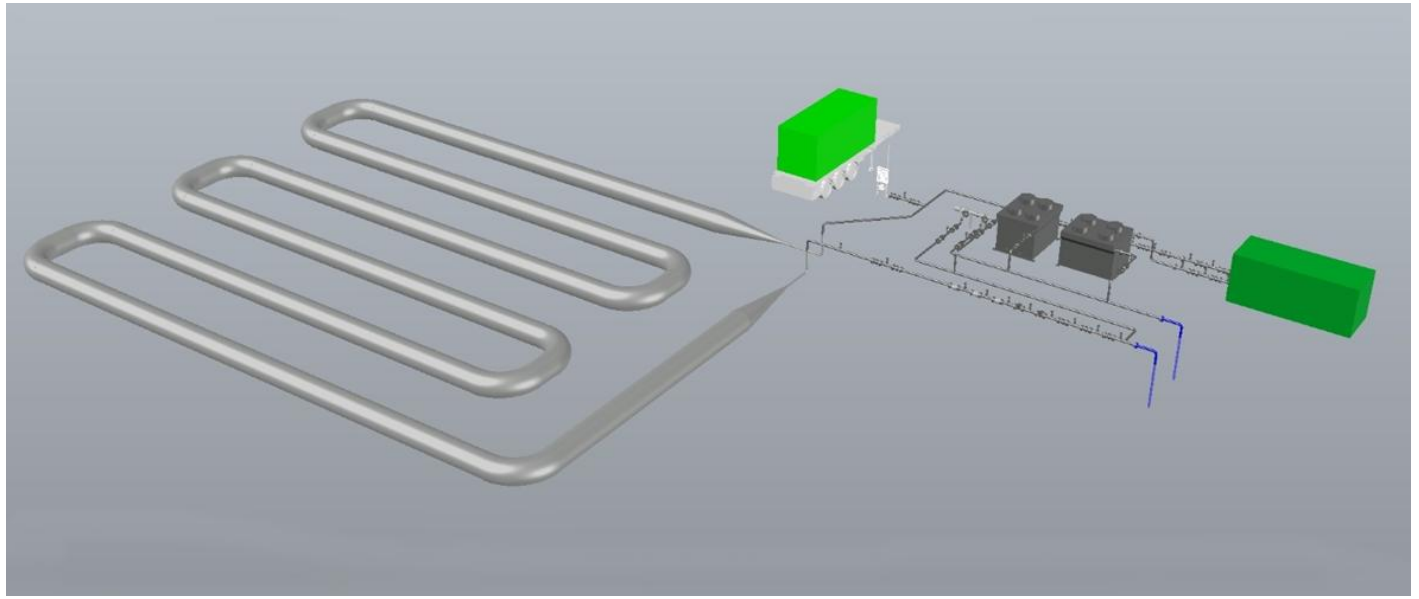



- The Location is within the Aberdeen ETZ and will be within a new fenced site with a site road allowing access to all assets.

- Arrangement includes an independent aftercooler located downstream of the compressor but this may be included within the compressor package

# D12 Interfacing P&IDS (Ancillary Storage)

- There are 2 options for the Ancillary Storage:
  - 200 barg tube trailer
  - 50 barg large bore pipework
- Design includes 50 barg large bore pipework as a conservative arrangement
- The storage includes >100m of 1200NB pipework



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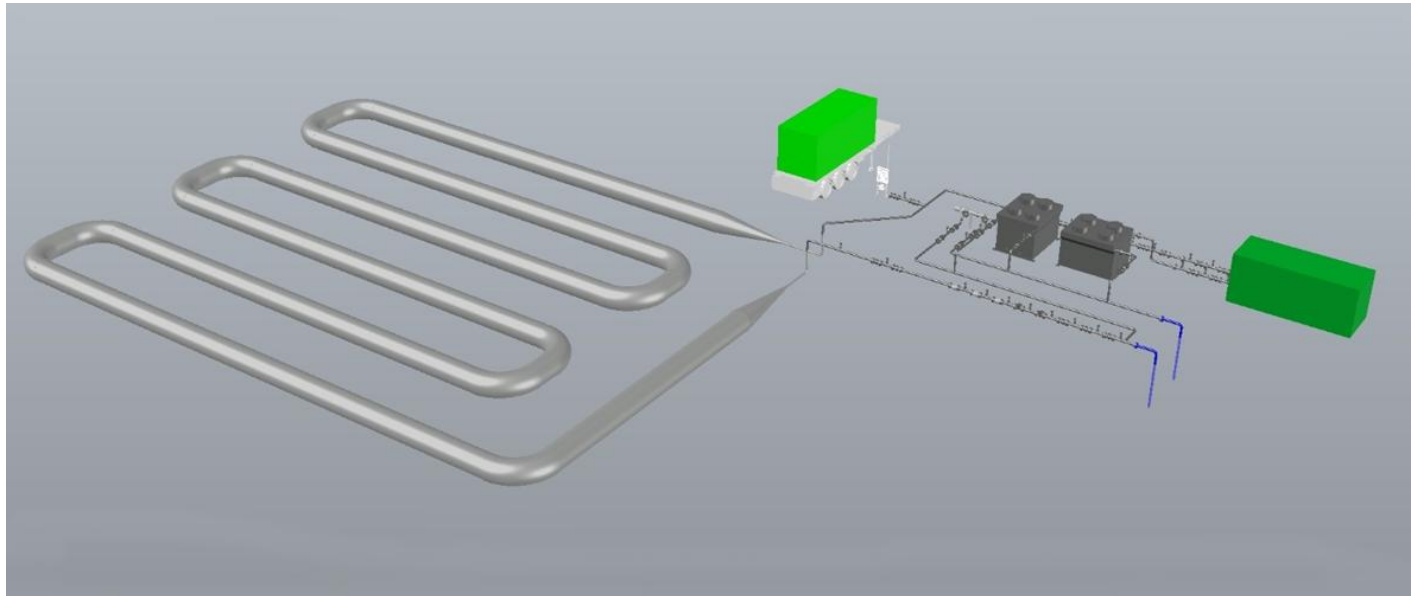


# D12 Interfacing P&IDS (Vendor Discussions)

- Compressor and Heater Suppliers have been engaged based upon initial parameters (greater flow rates that the revised parameters)

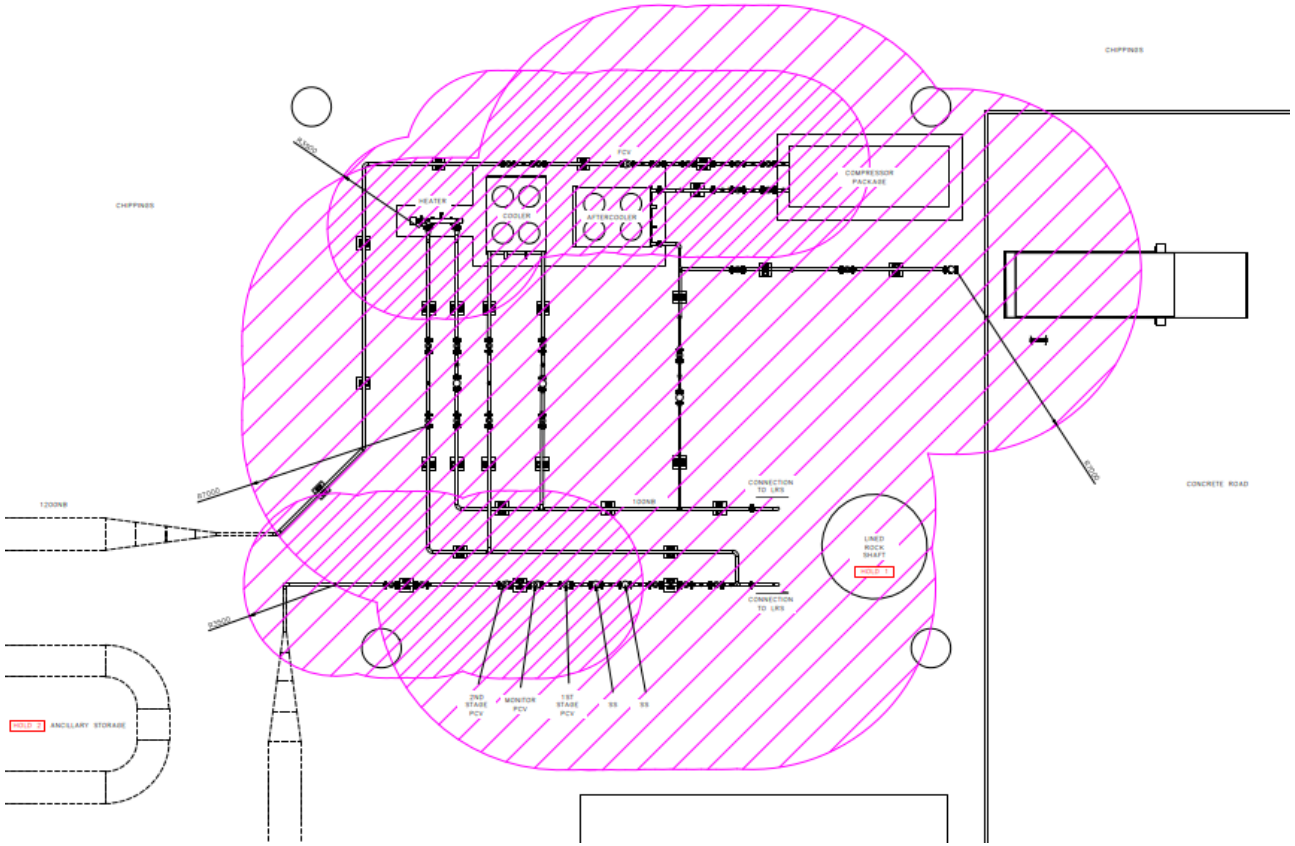
- ATLAS COPCO have provided details for a compressor package, including schematics and a proposal cost (circa £1.3m)
  - The compressor would have to be purchased rather than leased.
  - ATLAS compressor package includes an aftercooler

- EXHEAT have provided details of a heater for the recirculation temperature control (circa £30k)

- Exact details of the packages, including costs shall need to be confirmed during the Beta Phase

# D13 Safety Assessment

- An initial IGEM/SR/25 Edition 2 Supplement 1 hazardous area assessment has been completed.
- Zones are shown for 200 barg and 50 barg hydrogen
- A final assessment will be needed during Beta once the equipment package designs are confirmed and any automatic venting requirements confirmed



# D14 COMAH Implications for Lined Rock Shafts

## Process

**1. Establishment Classification**
- Determine if the site is Lower Tier or Upper Tier based on hydrogen quantity.
- Verify hydrogen classification under COMAH regulations.

**2. Notification to the Competent Authority**
- Prepare and submit COMAH notification.
- Include site details, nature and quantity of hydrogen, and activities.

**3. Major Accident Prevention Policy (MAPP)**
- **Develop MAPP for both Lower and Upper Tier sites.**
- **Describe safety management system and accident prevention measures.**

**4. Safety Report (Upper Tier only)**
- Conduct hazard identification and risk assessment (HAZID, HAZOP, QRA).
- Describe lined rock shaft storage system and containment measures.
- Detail safety management system and organizational structure.
- Outline accident prevention and mitigation measures.
- Include environmental risk assessment.
- Justify site layout and safety distances.
- Develop emergency response plans.

**5. Emergency Planning**
- **Lower Tier: Prepare on-site emergency plan.**
- Upper Tier: Coordinate with local authority for off-site emergency plan.

**6. Public Information**
- Provide public information on substances stored and safety measures.
- Ensure regular updates and accessibility.

**7. Technical Considerations for Hydrogen in Rock Shafts**
- Assess geological integrity of lined rock shafts.
- Evaluate hydrogen embrittlement and material compatibility.
- Design ventilation and leak detection systems.
- Perform fire and explosion modelling.
- Implement monitoring and control systems.

## Planned Work for Alpha Phase

SR25 Safety Assessment for demonstrator site – Premtech

COMAH Implications for LRS – NGT

### 0.53T of Hydrogen storage demonstrator (Permit Free)

### 65T Commercial Units (Upper Tier)

**Lower Tier Responsibilities**

**Notification**: Operators of all establishments subject to COMAH/SEVESO must notify certain basic details to the Competent Authority (CA)

**Hazardous substances consent**: You will need to obtain consent from the hazardous substances authority (HSA) to store a significant quantity of a hazardous substance (N.B. the thresholds for consent for certain materials are lower than the COMAH/SEVESO thresholds, local Planning Regulations should be referenced)

**Prepare a MAPP**: Lower tier operators must prepare a document setting out their policy for preventing major accidents (a major accident prevention policy or MAPP).

**Take all measures necessary**: Requires that COMAH/SEVESO operators take all measures necessary to prevent major accidents and limit their consequences to people and the environment. Demonstration of compliance is generally supported through standard safety studies (HAZID / HAZOP / DSEAR etc.) and robust process safety management procedures.

# COMAH Regulations on H2 storage

- Ref: The Control of Major Accident Hazards Regulations 2015
- Permit Free <2tonnes
- A consent is required under the Planning (Hazardous Substances) Regulations 2015 (SI 2015/627) to store between 2-5tons of gaseous hydrogen( hydrogen-projects-regulation-and-consents.pdf (shlegal.com) pg 7).
- Hydrogen (gas): COMAH1 @5-50tonnes & COMAH2 @>50 tonnes (COMAH2015 pg87)
- Hydrogen (liquefied gas): COMAH1 @25tonnes & COMAH2@250 tonnes (COMAH2015 pg87)
- Must ensure aggregation does not apply for site (COMAH2015 pg 119)
- Material Safety Data Sheet (MSDS) for solid-state hydrogen storage material is required to comply with CLP/COMAH regulations, which are country specific. (Chemical classification: The GB CLP Regulation (hse.gov.uk))
- Hydrogen (gas) transport is prohibited through ten road tunnels in the UK based on its classification under the European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR). **Making tube trailer logistics difficult at scale**.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# Saftey Risk Register

- Considered over 200 applicable hydrogen related hazards identified in three hydrogen related HAZIDs utilising appropriate guidewords and consequences for H2 Teeside blending, brigg blending trial and PU EC.

| Node | Ref. | Guideword | Hazardous Event | Consequence | T | S | Safeguards | L | Risk | Action |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.001 | Fire | Potential for expected small releases (pinhole) from H2 network, e.g. valve stems, flanges, compressors, small bore fittings, corrosions etc. | Potential for open space ignition and non-visible fire leading to potential for major injury of onsite personnel from above ground leak. | S | S3 | Fire retardant PPE | B | Intolerable | The East Coast Hydrogen HAZID team identified that small (pinhole) Hydrogen releases from any future Hydrogen network (e.g. valve stems, flanges etc.) have the potential to result in non visible flames in the event of ignition with the potential to cause major injury to site operatives.<br><br>With Asset Engineering stakeholder buy in, develop a leak detection philosophy appropriate for Hydrogen service for the project to adopt through it's design in the absence of existing adequate policy for |
| | 1.002 | | Refer to scenario 1.001 | Refer to scenario 1.001 | S | S3 | Refer to scenario 1.001 | B | Intolerable | The East Coast Hydrogen HAZID team identified that small (pinhole) Hydrogen releases from any future Hydrogen network (e.g. valve stems, flanges etc.) have the potential to result in non visible flames in the event of ignition with the potential to cause major injury to site operatives. |

# Consumer perspectives

**We engaged with stakeholders to:**

- Understand academic, industrial and policy stakeholder views around hydrogen linepack.
- Assess the potential value of using Lined Rock Shaft technology to replace linepack for security of supply and resilience.
- Consider likely impacts to consumers and their perceptions of these impacts.

We interviewed stakeholders across the wider energy sector to understand their insights on the following topics:

**How linepack is currently used in the natural gas network.**

**How they see linepack being used in the future.**

**The potential role of linepack with hydrogen.**

**Perspectives on how costs for linepack should be allocated and possible payment mechanisms for linepack services.**

Hydrogen linepack will likely play a role (alongside other hydrogen technologies) in providing intraday supply demand balancing.

However, understanding the availability and operational parameters of hydrogen linepack will influence whether stakeholders will connect to a national network or source their hydrogen flexibility through other technologies or sources.

# Opportunities and Challenges Identified

Recognition of the **value of hydrogen linepack was broadly positive** across the interviews, however there were key themes that kept emerging around key aspects:

| | |
|---|---|
| Balancing, storage, and operation | Linepack will need to play a part in supply demand balancing, especially during intermittent generation. |
| | Understanding supply & demand profiles (off time, ramp rate, & line operational boundaries) will impact who can join the network alongside what other interim storage may be needed to ensure consistent supply. |
| | A whole system approach is required to ensure operability and resilience. |
| Local vs. National | Understanding the needs of various producers & end users will be crucial in defining operational parameters for linepack & determining if it is feasible for them to be part of a network. |
| System Integration and Market Challenges | Hydrogen linepacking must be competitive with other flexibility technologies and services. |
| | Exploring pricing structures (e.g. standing charges or flexibility tariffs) will help demonstrate the market and reduce perceived investment risk. |
| Economic uncertainty | Addressing uncertainty around market signals, government policies, and commitment will help to reduce the perceived risk of investment, but this doesn't answer who should pay for linepack – or how. |

# Additional exploration for consumer benefit

**Strengthen stakeholder engagement to enrich broaden and deepen findings,**

- **Wider stakeholder engagement** – may help to identify a particular group of stakeholders with a particular interest – or need – for access to hydrogen linepacking (and placing this in current and potential future context informed by known and hypothetical policy and hydrogen industry developments).
- **Consider wider stakeholder types** – working alongside other projects, such as Project Union/ FOGSI, would enable a wider understanding from stakeholders from other types of groups/bodies such as environmental groups and public perception groups. Whilst this would expand the stakeholder group(s) to a broader set, the data derived would be more context rich and provide a deeper understanding of external considerations for hydrogen linepack.

**Consumer contextualisation: understanding and articulating business case and value for money**

- Interview and reinterview participants with **more detailed projected financial costs for linepacking and operational needs** utilising the Catapults **Business Model Innovation** team- to help understand the perceived VfM and novel commercial ways that providers could approach provision of hydrogen linepack, alongside interested consumers.
- Undertaking a **pilot study using a current hydrogen hub or valley** would help demonstrate the business case for hydrogen linepacking.

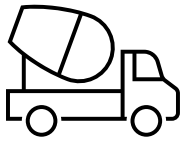
# Project Specific Conditions

D16 Scalability of LRS

D17 System deployment without a comprehensive GB energy system

national gas transmission

# No of LRS to Deploy per Industry in UK



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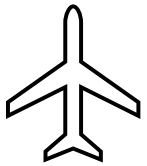

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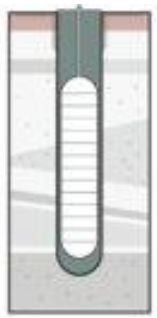

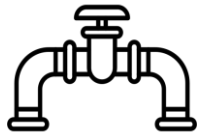

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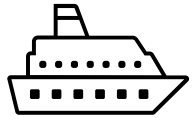

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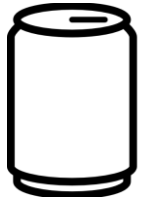


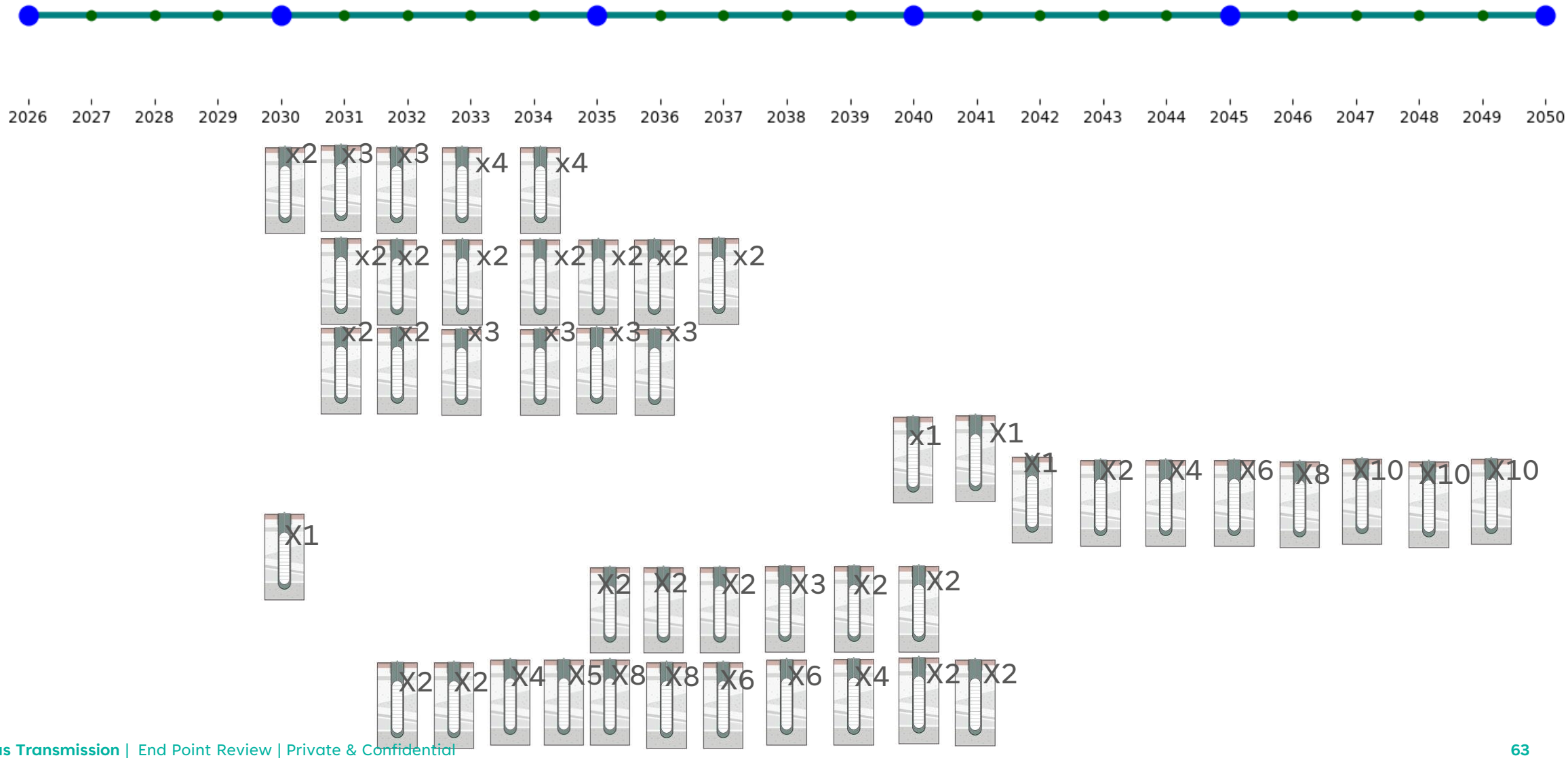
x1

**Total maximum** number of LRS systems we could deploy is **162 with a lower bound of 69 depending on %hydrogen storage needed for each industry;** therefore, we require a plan to scale and implement the proposed solution.

However, must stress and caveat that this is based on the operation and cycling of each LRS at **2 full cycles per week for 26 weeks (half) of a year.** Operational profiles may be more or less extreme for certain use cases resulting in less or more LRS deployment and any final determination will be based on site by site project analysis to determine how many LRSs will actually be required.

Total CAPEX to deploy would be dependent on if a system would need to be modified or a standard system based on geology in certain areas. This will also determine the exact number of shafts needed to be deployed for each industry, adding an extra layer of uncertainty.

# Timeline of Deployment for LRS

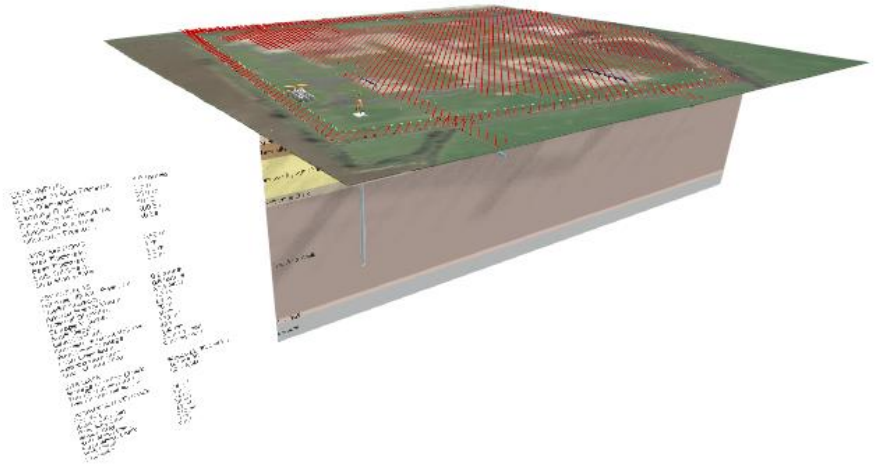


# Parametric Model Development

In Discovery, we explored the development of a **parametric model** which has the following benefits for scaling the solution and iterative design:

- Capturing the **design process** not just the final result
- Enables **design improvement feedback loop**
- Encodes **engineering knowledge**
- Enables **fast concept iteration, design optimisation and performance-based design**
- **Reduces cost** of changes
- Enables **product-oriented approach** to design

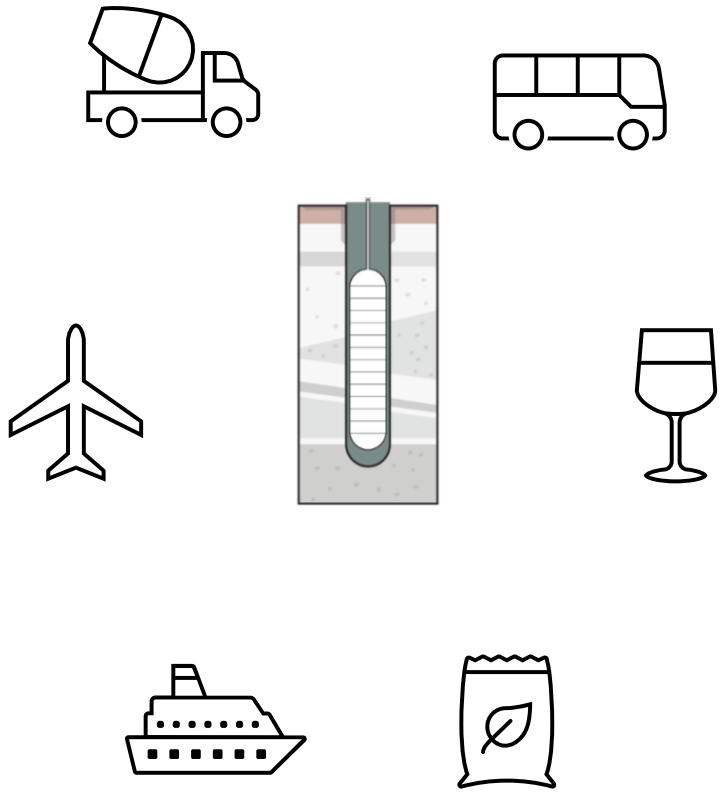
- The budget is not available to explore this further in Alpha or as part of a Beta bid but we may want to explore as a **RIIO-3 NIA** innovation project running alongside any Beta phase as is applicable to any project in our business and related to **DAM strategy**.



# LRS deployment without a comprehensive GB energy system

- End users outside of GB energy networks:

- Ammonia/fertiliser production
- Transport applications and hydrogen refuelling for HGVs or Buses
- Steel/cement production
- Glass furnacing
- e-SAF producers
- Maritime fuels and bunkering



# Summary Table

| Use Case | UK Volumes of Hydrogen demand per annum (tonnes) | Energy (TWh) | Hydrogen Storage Needed (%) | Hydrogen Storage (TWh) | No of Lined rock shafts (WG capacity 57tons, 2 cycles per week for 26 weeks per annum) |
|---|---|---|---|---|---|
| E-SAF | 340k | 11.3 | 0.3-2 | 0.034-0.226 | 1-2 |
| Steel | 0.75 - 1M | 25-34 | 3-4 | 0.75-1.36 | 8-14 |
| Cement | 200-250k | 8-10 | 10-15 | 1-1.5 | 9-16 |
| Maritime | 1-3M | 33-100 | 2-5 | 2-5 | 21-51 |
| Glass | 0.6-0.7M | 20-24 | 10-20 | 2.4-4.8 | 25- 49 |
| Aluminium | 10-12k | 0.33-0.4 | 1-3 | 0.004-0.012 | 1 |
| Fertiliser | 0.18-0.35M | 7.5-15 | 2-8 | 0.3-1.2 | 4-13 |
| **Total** | **3.08-5.652M** | **105.1-194.7** | **N/A** | **6.8-14.1** | **69-146** |

# Comms & Engagement Plan

| Event | When | Responsible |
|---|---|---|
| Online Dissemination Event | March End | Holly (NG) |
| Internal Asset Working Group (NGT) | March | Kelvin (NG) |
| Linkedin posts | March | All partners |
| UKES Conference (Uni of Ed) | April | Kelvin (NG) |
| 5th International Summer School on Underground Hydrogen Storage (UHS) | June | Kelvin (NG) |

To note, were unable to host a joint in person dissemination event with FOGSI as were unable to submit the 1 pager in time for HII deadline for funding due uncertainty at the time (October) about the project continuing to go ahead due to partner administration.

# Whats Next?

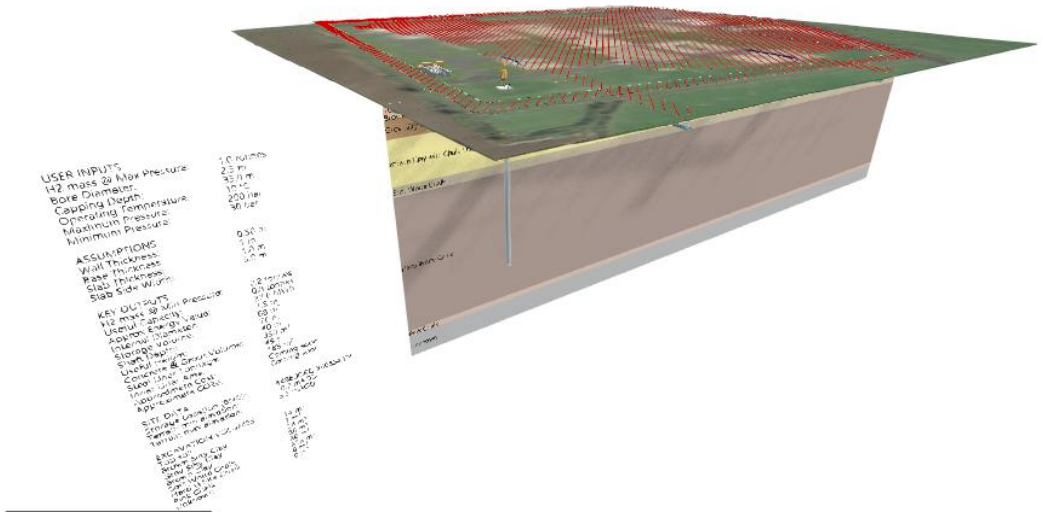
Beta Phase Plan/To do List

national gas transmission

# Beta Phase Development Bid Plan

- **To do:**
- Sourcing Quotes from various partners/suppliers/subcontractors based on SoW already out
- Suring up cost estimate and including sufficient contingency
- Beta application Qs
- Benefits Mapping
- Tweaking CBA
- Relevant Additional Appendices
- LoS supporting technology from BP and Centrica
- Confirm Third Party Validator of Technology
- Complete PMB with risk register, key info/skills and expertise etc

ENERGY TRANSITION ZONE



# Thank you and AOB

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# Design Note

Civils

| Document Number: | Project: | Revision: |
|---|---|---|
| 1102-002 | 1100 SIF-NG | 01 |

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## REVISION HISTORY

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|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |
| 01 | 15/09/2025 | Issued for Information | SK/NV | SK/NV | SK/NV |
| **Rev** | **Date** | **Reason for issue** | **Prepared** | **Checked** | **Approved** |

## CHANGE DESCRIPTION

01 First Issue

## 1 PURPOSE

This document provides information on the civil concept design for a 1t hydrogen storage technology demonstrator under the Ofgem Strategic Innovation Fund, B-Linepack+ Project, in partnership with National Gas.

## 2 CIVILS ENGINEERING TENDER

Civil engineering design for the Lined Rock Shaft demonstrator requires specialist support. Gravitricity has completed a competitive tendering process for the civils concept design and have provisionally favoured COWI based upon the strength of their proposal, value for money, and their experience and past delivery in the field. The scope of work for the civils design covers the unlined shaft, including methodology and temporary works, and the overburden plug together with the Ground Investigation (GI). COWI have extensive experience globally with shaft design, including the new pumped hydro storage scheme Coire Glas, near Invergarry, which includes a pressure shaft which is perhaps the closest current analogous technology to Lined Rock Shaft.

## 3 GI INVESTIGATION

Ground Investigation (sometime known as Site Investigation) is an essential step in the civil engineering design process. On-site penetrative GI is sometimes proceeded by an earlier phase of desk-based analysis which draws on available pre-existing information to make a preliminary assessment of the ground conditions which may be encountered at any given location. Desktop GI has the advantage of being relatively quick and inexpensive, but the output is highly dependent on the availability of information. For many locations around the UK there is sufficient information available regarding ground conditions to facilitate a detailed desktop GI which would allow specialist design engineers to develop a concept civils design.

The details of the GI specification will depend on the size, shape, and purpose of the structure to be constructed and, to a lesser extent, the known ground conditions at the location. The purpose of the GI is that once executed and completed it provides sufficient detail and confidence in the expected ground conditions such that the detailed design of the structure can be completed. There will remain some inherent natural risk as ground conditions can be subject to short-range variability, and this risk is usually factored in by the civils contractor when pricing the tender for the construction.

For the purposes of the Lined Rock Shaft demonstrator, the results of GI will primarily inform the design of the unlined shaft which will include the construction methodology and associated temporary works. The GI results will also support determination of the dimensions of the liner layers and the gas storage pressure. For most shafts the design would also include the lining and installation methodology but as Lined Rock Shafts feature a bespoke lining system which is not simply to ensure shaft stability through lifespan, the liner design and installation is out of scope for civil engineering.

Gravitricity commissioned a GI specification for an identical shaft in terms of dimensions and methodology in 2022. Discussions with COWI, favoured civil engineering design contractor, indicate that this GI specification is largely appropriate for this project irrespective of location. Some minor modifications may be made once the contract for the civils design is awarded.

This GI specification includes boreholes and trial pits with associated sample collection and geophysical surveying, groundwater and gas monitoring, and laboratory testing of samples with additional specialist testing, the requirement for which will be confirmed by the Investigation Supervisor.

The specification outlines the known and relevant information for the site and surrounding area which characterises the ground conditions and describes the reporting requirements once all data and information has been collected.

# 4 SHAFT SINKING METHODOLOGY

## 4.1 Technology Demonstrator – Auger Piling

The technology demonstrator has been intentionally sized to maximise technology validation and minimise cost, in particular, shaft sinking costs. The 2.5m external shaft diameter and depth of up to 47m are driven by the proven capabilities of a large Auger piling rig.

*Figure 1 Typical Auger Pilling Rig*

The two primary types are Continuous Flight Auger (CFA), which uses a hollow-stem auger to simultaneously drill and pump concrete, and Rotary Bore Piling, which uses a short auger to create a bore that is then concreted. Auger piling has the advantage of being fast, economical and is a relatively low vibration drilling method, making it suitable for varying ground conditions, maintaining a competent shaft wall and will be advantageous with regards to planning and consenting.

The shaft will be constructed in two stages. The first stage is to construct and install a 2.6m internal diameter steel liner through the site superficial deposits and to found this at the top of the first rock layer to provide suitable ground support for the drilling rig during deeper excavation. This part of the shaft will be constructed by vibratory and/or oscillating techniques, typically adopted for tubular steel piles. Alternatively, this stage could be constructed by caisson methods using pre-cast concrete segments.

The second stage would see the shaft constructed to its full depth using a rotary piling rig. During shaft construction a fluid will be pumped into the shaft cavity to stabilise the hole and to assist installation of the internal and external liners.

There is a wide range of experience using Auger piling within the UK and equipment is readily available. Specialist parts, such as the Kelly Bar may need to be sourced from Europe depending

on final depth on shaft. Details regarding installation of cementitious and steel liners will be provided in the construction plan.

### 4.2 Full scale systems – Blind Boring: Direct or Reverse circulation drilling

Following the technology demonstration of Lined Rock Shafts, the technology is ready for commercialisation. Full-scale shafts will be up to 7m in diameter and 430m in depth. Each shaft will be capable of storing up to 100t of hydrogen. The shaft dimensions mean that the Auger piling method used for technology demonstration is not suitable. Following significant engagement with shaft sinking contractors, blind boring, in particular, direct circulation or reverse circulation drilling has been identified as the most suitable shaft excavation method.

The major difference between direct circulation and reverse circulation drilling is related to the direction of movement of drilling fluid. For this design note, information on reverse circulation drilling only has been provided in section 4.2.1

#### 4.2.1 Reverse Circulation Drilling

Flooded reverse circulation drilling is a mechanised drilling method that is ideal for unconsolidated ground conditions and water bearing geology but can be deployed effectively in a wide range of ground conditions.

The excavated material is removed from the shaft via the drill pipe. This is achieved by filling the shaft with fluid. Compressed air is injected below water to a pre-determined depth. The compressed air expands in the drill pipe on the way back up (due to reducing water pressure) until it relieves at the altitude of the gooseneck to approximately atmospheric pressure. This results in a reduced density in the drill pipes. The original density in the annulus remains the same. Therefore, the pressure differential between the annulus and inner pipes allows the fluid and cuttings to flow from the anulus to the drill pipe and be removed from the shaft.

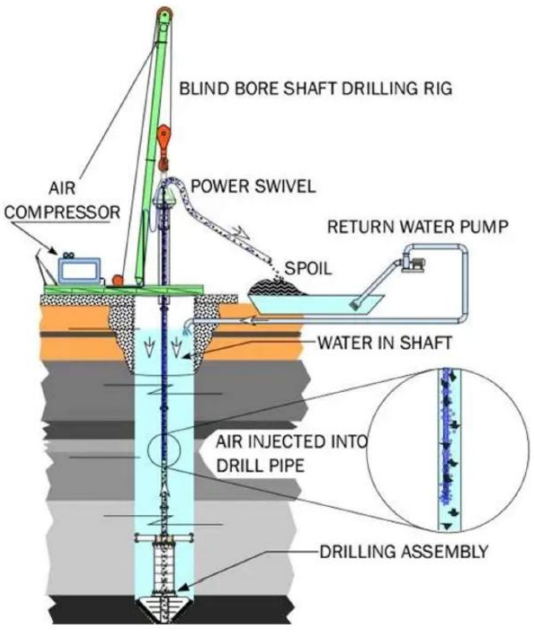


*Figure 2 Typical Reverse Circulation Drilling Set-Up*

Typical stages of reverse circulation drilling:

**Ground consolidation** – this consists of drilling holes to a pre-determined depth and back-filling with grout.
**Piling** – a range of piling is excavated and constructed to a pre-determined depth.
**Concrete pad construction** – a concrete pad is constructed on the shaft centre and reinforced with steel rebar. The concrete is then tied to the piles. All underground piping and utilities are constructed into the shaft collar to accommodate return and overflow lines.
**Pilot hole drilling** – the pilot hole will go through the centre pile. Pumps will be used to flush out the cuttings of the hole. Once the pilot hole has reached the intended depth, a gyroscopic surveying instrument will be used to survey the vertical alignment of the drilled hole. The pilot hole is then reamed to the size of the reverse circulation drill rods, accounting for any misalignment detected in the survey.
**Excavation of pre-sink** – A pre-sink hole is excavated to a predefined diameter and depth based on ground conditions. The pre-sink allows for installation of the downhole assemble and to facilitate the fluid pressures during the reverse circulation drilling.
**Machine assembly** – the down hole equipment and reverse circulation drill rig is assembled, and utilities are connected. Typical down hole equipment consists of cutterhead, stinger assembly, non-rotating stabilizer, weight collars and crossover.
**Reaming** – The shaft is reamed to the predetermined depth. Once this depth is reached, a gyroscopic survey is performed to check that the reaming has followed the pilot hole successfully and not deviated from the centre line. After completion and verification, the downhole assembly is removed from the hole. Drilling fluid will be maintained at near-surface level providing shaft stability until the multi-layer liner is installed.
**Dewatering** – Dewatering will take place during the installation of the multi-layer liner.
**Demobilisation** – all drilling and ancillary equipment will be removed from over the shaft head to allow for liner installation and site welding.

Reverse circulation drilling is ideal for Lined Rock Shaft construction due to its relatively fast drill rates, cost effectiveness and ability to be deployed in a wide range of geological conditions.

# Ofgem SIF B-Linepack+

# Electrical, Controls and Instrumentation Design Note

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## 1.0 Summary

This document provides a design overview of the electrical, controls and instrumentation (EC&I) design for the Lined Rock Shaft (LRS) technology demonstrator, developed as part of the Ofgem SIF B-Linepack+ storage demonstration project. The scope of the controls system is for all above ground and sub-surface equipment. The scope of the electrical and instrumentation design is for the sub-surface equipment only excluding the containment pressure and temperature monitoring which is covered in LGG-L057401-R08 Sub-Surface Process Design Note.

The controls system will provide the operator with six different modes of operation. Injection, withdrawal, stand-by, commissioning/decommissioning, maintenance and emergency shut-down. Operation will be automated where possible and the operator will receive real-time monitoring information regarding mechanical, thermal and process characteristics of the system. Only in maintenance mode can safety interlocks be deactivated by the operator. This will require sign-off from appropriate authority and integration with a permit-to-work system.

The control system architecture will provide the operator the ability to select the required mode of operation and then perform that operation in a safe manner. This will be achieved by using a supervisory controller to monitor and manage the interface between the process equipment and external machines. A programmable logic controller will use the information received from the monitoring and process equipment to determine what adjustments to the process equipment are required to achieve the desired outcome of the operational mode and maintain the system within operational limits. This is achieved using a combination of feedforward and proportional-integral-derivative control. A high-level system control diagram is provided which illustrates the main control hardware and communication signals.

The alarm system design will follow a hierarchy to prevent overload and provide clarity to the operator. A cause-and-effect matrix (appendix A) has been developed to highlight scenarios which require the operator to be alerted and when emergency shutdown procedures should be automatically activated. The controls system design shall aim to make alarms obvious, unambiguous, and actionable. The controls safety management system should integrate with the wider safety system of the site. Following HAZID/HAZOP activities, appropriate measurements of the systems safety performance (safety integrity levels) can be applied in conjunction with an analysis of the layers of safety protection in the system. The LRS technology demonstrator will be a first-of-a-kind installation and therefore the additional risks associated with the unknown behaviour of the system should be factored into safety case analysis and control system/monitoring design.

The grid requirements for the technical demonstrator are expected to be a maximum of 0.5MW. The site owner has suggested a new sub-station will be built at the site and the LRS import requirements included as part of the design and connection. A bespoke electrical power unit will be manufactured to containerise the required control panels and drives. A control cabin will contain the necessary operating equipment used to monitor and control the LRS system. In addition, the control cabin will contain a manual emergency push button.

The purpose of the monitoring system is to achieve operational safety and provide behaviour and performance characteristics of the sub-surface storage. Data from the monitoring system will be used to automatically activate/deactivate other system components to manage system behaviour and prevent an unsafe event. Gathering quantitative data on the mechanical response of each liner material and the rock mass will provide the opportunity to validate modelling predictions and optimise the operation and future design of the sub-surface storage. The requirements register LGG-L057401-R01 provides a list of requirements for the EC&I sub-system of the LRS. In addition, the instrumentation design should account for the unique environment and behaviour of the sub-surface storage. A table and supporting figures, outlining the instrumentation design, is provided.

## 2.0 Introduction

This document provides a high-level overview of the EC&I design for the deployment of a LRS technology demonstrator. The project aims to validate and de-risk the storage technology such that on completion, the technology is ready for a commercial pilot and is suitable for Linepack+ storage on the gas network. The B-Linepack+ project is at the “Alpha” stage of development and funded by Ofgem SIF in collaboration with National Gas Transmission (NGT).

For more information regarding the technology demonstrator aims and requirements, see the document LGG-L057401-R04-Rev00 Basis of Design (Sub-Surface Containment).

### 2.1 Abbreviations

Abbreviations used in this report are outlined in *Table 1.*

*Table 1: Abbreviations*

| | |
|---|---|
| ***LRS*** | *Lined Rock Shaft* |
| ***NGT*** | *National Gas Transmission* |
| ***EC&I*** | *Electrical, Controls and Instrumentation* |
| ***PFD*** | *Process Flow Diagram* |
| ***PCV*** | *Pressure Control Valve* |
| ***FCV*** | *Flow Control Valve* |
| ***ETZ*** | *Energy Transition Zone* |
| ***SL*** | *Structural Liner* |
| ***BoD*** | *Basis of Design* |
| ***ALARP*** | *As Low As Reasonably Practicable* |
| ***WRA*** | *Well-Reasoned Argument* |
| ***GTL*** | *Gas-tight Liner* |
| ***SL*** | *Structural Liner* |
| ***MOP*** | *Maximum Operating Pressure* |
| ***HAZID*** | *Hazard Identification* |
| ***HAZOP*** | *Hazard and Operability Study* |

## 3.0 System Overview

The LRS technology demonstrator is a hydrogen gas storage system and will demonstrate the ability to perform linepack storage for future use on the UK gas network. A high-level Process Flow Diagram (PFD) can be seen in Figure 1, highlighting the major components of the system. The system will consist of a compressor for increasing the LRS storage pressure to 200barg, a cooler, heater, and recirculation blower for thermal management and ancillary storage for facilitating the demonstration of linepack capabilities and allowing pressure cycling of the sub-surface storage. The pressure control valve (PCV) is used to control the pressure in the ancillary storage. The 2-off flow control vales (FCV) control the flow of gas into the compressor and out of the LRS.

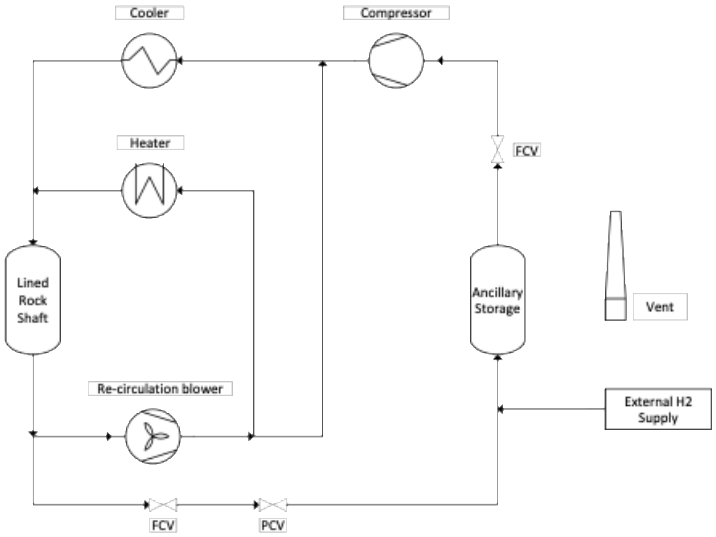


*Figure 1: Simplified system PFD*

The demonstration site will not be connected to the national gas network. Hydrogen will be delivered to site via a tube trailer and injected into the system. Once hydrogen has been supplied to the system, the demonstrator will work as a closed loop with hydrogen being cycled between the sub-surface storage and the ancillary storage. The demonstrator will be connected to the electricity grid to provide power to the topside process equipment, monitoring systems, site ancillaries, and control system.

Figure 2 shows the major sub-systems of the LRS system. The surface and sub-surface equipment will be controlled by a high-level supervisory controller which will remotely monitor and control the process operations. It is expected that each process component will include its own pre-commissioned control system which will then communicate with, and receive direction form, the supervisory controller.

The intended site for the demonstration is the Energy Transition Zone (ETZ) in Aberdeen. This is a technology development facility with other projects deployed within the site. Therefore, specific site safety/communication requirements for the control system may be required. In addition, to validate linepack performance, the control system may need to demonstrate sending and receiving data packets to an external system that acts as a network operator. In this scenario, the supervisory controller would receive a data packet requesting the system to inject or withdrawal hydrogen, simulating the ability to balance the gas pressure on the grid. The LRS control system will then respond appropriately and in a timely manner before sending a data packet back to the external system to demonstrate the work has been completed successfully and within tolerance. Further development of the linepack testing programme will be carried out in the next phase of design, which will determine the requirements for external communication (if required).The following sections of this report assume no external communication is required.

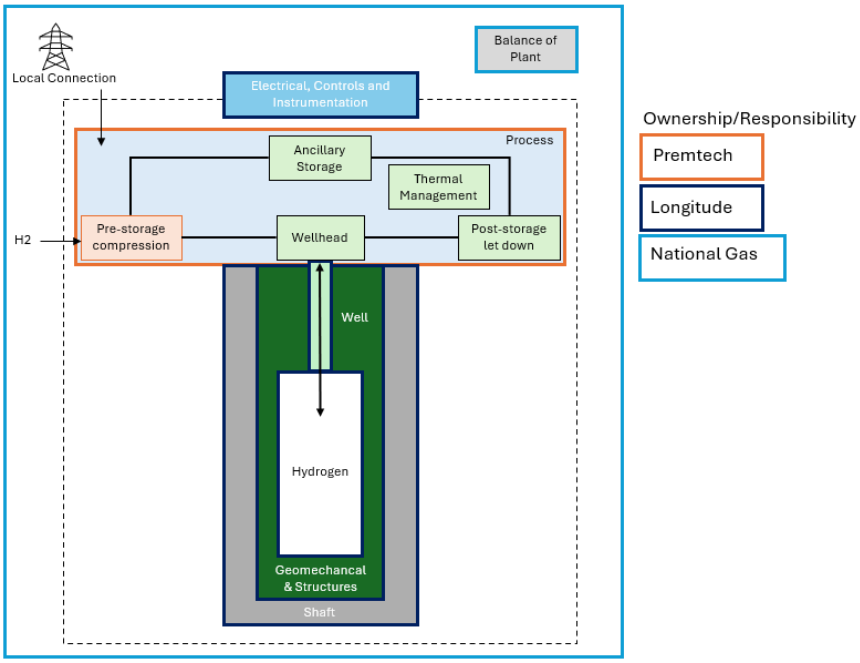


*Figure 2: Sub-system breakdown*

## 3.1 Modes of Operation

The controls system will provide the operator with six different modes of operation. A description of the modes of operation is given below.

### 3.1.1 Injection (Sub-surface)

This is an automated process, with operator oversight, where the gas flows from the ancillary storage to the sub-surface storage. The pressure in the sub-surface storage is raised to a desired set-point with the maximum operating pressure (MOP) being 200barg. The pressure increase is achieved using a surface mounted compressor and thermal management system. During pressurisation, the operator is presented with real-time information on process, thermal and mechanical characteristics of the system. All safety interlocks are active with automated temperature, strain, pressure and flow management used to keep the system within operational limits.

### 3.1.2 Standby (Sub-surface and ancillary)

Gas pressure is monitored and maintained within expected pressure and temperature fluctuations in the sub-surface storage and ancillary storage. There may be a scenario where both the sub-surface storage and ancillary storage are required to be safely controlled in standby mode at the same time. During storage, the operator is presented with real-time information on process, thermal and mechanical characteristics of the system. All safety interlocks are active.

Recirculation heating may be required to maintain the internal sub-surface gas temperature at an acceptable level. If this is required, the system will automatically start the re-circulation blowers and heater, allowing gas to circulate via the production and injection tubes.

### 3.1.3 Withdrawal (Sub-surface)

This is an automated process, with operator oversight, where the gas flows from the sub-surface storage to the ancillary storage via the production tube. During withdrawal, the operator is presented with real-time information on process, thermal and mechanical characteristics of the system. Recirculation heating may be required to

maintain the internal sub-surface gas temperature at an acceptable level. If this is required, the system will automatically start the re-circulation blowers and heater allowing gas to circulate via the production and injection tubes. The compressor is not required for this process. Withdrawal will continue until internal sub-surface storage pressure reaches a desired set-point or 30barg (whichever is achieved first) or stopped manually by the operator. All safety interlocks are active.

#### 3.1.4 Commissioning and Decommissioning

This is a semi-automated mode of operation and only accessed via a password protected login to the human-machine interface (HMI). The operator will have the ability to adjust set-points and perform individual isolation and operation of process equipment. All safety interlocks remain active and the operator is presented with real-time monitoring data.

#### 3.1.5 Maintenance

This is a semi-automated mode of operation and only accessed via a password protected login to the HMI. The operator will have the ability to perform individual isolation and operation of surface process equipment. This mode of operation can be used for priming the system with gas and purging with nitrogen. Gas is delivered to the ancillary storage via tube trailer and allowed to flow into the LRS system. The operator can control when and how the gas is transferred from the tube trailer and stored in the ancillary storage. The operator can also vent and flare gas from the system should there be a need to do so. Safety interlocks can be deactivated by the operator but require sign-off from appropriate authority and integration with a permit-to-work system.

#### 3.1.6 Emergency Shutdown

The purpose of this mode is to protect people, the facility and the environment. Should a monitoring characteristic reach a critical value the system will automatically begin to shut down the system until it reaches a safe state. All personnel will be warned of the unsafe environment and directed to evacuate the site.

### 3.2 High level system architecture

The LRS control system must provide the operator the ability to select the required mode of operation and then perform that operation in a safe manner.

The supervisory controller and data acquisition (SCADA) is used to monitor and manage the plant process equipment. This is likely to be a software-based system that acts as the interface between the various LRS process equipment and any external industrial machines and/or the HMI. The data acquisition collects data from the system sensors, processes the information and displays this information on the HMI for monitoring and analysis.

A programmable logic controller (PLC) is a piece of hardware designed to control complex industrial processes. The system PLC used by the LRS SCADA receives real-time data from the topside and sub-surface sensors and the HMI inputs. This data is then processed by the PLC state machine using a pre-programmed internal logic. The state-machine models the system behaviour as a series of unique states (See 3.1). Specific actions are performed in each state and the system transitions to another state only when predefined conditions are met from the monitoring data and/or the HMI. Based on the known state, the input data from the sensors and the desired process conditions (setpoints), the PLC uses controls logic to correct deviations, ensuring efficiency, quality and safety of the LRS system. It is expected that the PLC will use a combination of feedforward and proportional-integral-derivative (PID) control to manage deviations and maintain the desired system setpoints. The new setpoints and currents will then be sent to the individual process equipment PLCs followed by the electrical system which in turn either activates/deactivates a component or varies the output parameters. This process is continuous throughout the operation of the LRS system.

In the event of pressure, flow or hydrogen being detected by the leak management monitoring system, the state machine will automatically enter emergency shutdown. This will trigger a series of process equipment responses, controlled by the PLC and SCADA to minimise the risk to health and safety, environment and equipment.

## 3.3 Alarms and Operator Interface

The alarms should follow a hierarchy to prevent overload and provide clarity to the operator. Table 1 highlights a simplified alarm hierarchy used for gas storage systems and the associated control system actions. IEC 68682 *Management of alarms for the process industries* should be used during the next stages of controls design. Typically, high-level alarms will trigger system interlocks to be activated, e.g., stop compressor, however equipment should be designed to failsafe where possible.

*Table 2: Alarm Hierarchy*

| Alarm | Control system actions |
|---|---|
| **Advisory/Warning** | • Operator awareness<br>• No automatic shutdown |
| **High/Emergency** | • Audible + visual alarms<br>• Automatic safety actions |
| **Critical (all automatic)** | • Emergency shutdown<br>• System isolation<br>• Area evacuation signal |

The controls system design should aim to make alarms obvious, unambiguous and actionable to the operator. Guidance should be taken from relevant codes and standards including IEC 68682 and IEC 61511 *Functional safety – safety instrumented systems for the process industry sector*. The current operating mode will be clear and obvious to the operator, and any change of operating mode, other than emergency shutdown, will require confirmation from the operator. Visual aids, such as diagrams of the system will be utilised where possible. The operator should have the visibility of trends and history, current set points and any active alarms.

## 3.4 Cybersecurity

Ofgem implements and enforces the Network and Information Systems Regulations 2018 (NIS Regulations) for gas and electricity operators. The project will not fall under the classification of operators of essential services (OES) but will look to implement, were practicable, the core requirements of this regulation, namely:

- Take appropriate and proportionate technical and organisational measures to manage risks to security network and information systems
- Prevent and minimise the impact of cyber incidents
- Have regard to relevant guidance from Ofgem
- Consider supply chain cyber risks

Should the control system need to communicate externally, then additional cyber security requirements will need to be met.

# 4.0 Electrical System

The requirements for the electrical system can be found in LGG-L057401-R01 Requirements Register. In addition, the following key legislation and standards will be consulted during design:

- Electricity at Work Regulation 1989
- Electricity Supply, Quality and Continuity Regulations 2002
- BS7671:2018 Requirements for Electrical Installations

## 4.1 Grid Connection

The LRS system will be deployed at the Energy Transition Zone (ETZ) in Aberdeen. The site owner has suggested a new sub-station will be built at the site and the LRS import requirements included as part of the design and connection. It is estimated that the LRS site will require a maximum of 0.5MW during construction and operation.

## 4.2 Electrical Power Unit

A bespoke electrical power unit (EPU) will be designed to containerise the PLC, variable frequency drives (VFDs) and associated control panels. In addition, an uninterruptible power supply (UPS) and the required power distribution equipment will be included in the EPU. The container will require appropriate ventilation and cooling for the VFDs and a dehumidifier to prevent condensation on the electrical equipment.

This is a stand-alone piece of equipment which is likely to be installed in a standard shipping container depending on the quantity and size of hardware required. The EPU and wider system electrical design is anticipated to be in line with BS7671.

## 4.3 Control Cabin

For commissioning and testing, the system will be operated from an on-site control cabin. The cabin will contain the necessary operating equipment used to monitor and control the LRS system. In addition, the control cabin will contain a manual emergency push button. The cabin will be located a safe distance from the process equipment and at a location where the operator has as clear a view as possible of the entire site. If this is not possible, then cameras will be installed with monitoring equipment located within the control cabin.

## 5.0 Safety and Interlocks

Functional safety is part of the overall safety of plant and equipment that depends on the correct functioning of safety-related systems and other risk reduction measures such as safety instrumented systems (SIS), alarm systems, and basic process control systems (BCPS).

The SIS, with regards to the LRS, are the sensors and controls logic that detect dangerous conditions and manage process equipment to achieve a safe state. The controls system safety should take guidance from BS EN 61511. This is the benchmark standard for the management of functional safety in the process industry. The key principles of this standard relating to the LRS system are:

- specify the required function, integrity and other requirements of the SIS
- design and implement the SIS to satisfy the requirements of LGG-L057401-R1 Requirements Register
- install, commission and validate the SIS
- operate, maintain and periodically proof-test the SIS
- manage modification to the SIS
- decommission the SIS as part of the wider system decommissioning

The controls safety management system should integrate with the wider safety system of the site. Following HAZID/HAZOP activities, appropriate measurements of the systems safety performance (safety integrity levels) can be applied in conjunction with an analysis of the layers of safety protection in the system. The LRS technology demonstrator will be a first-of-a-kind installation and therefore the additional risk associated with the unknown behaviour of the system should be factored into safety case analysis and control system/monitoring design.

### 5.1 Leak management

The LRS technology demonstrator design includes a sub-surface leak management system. This will be designed to detect, capture and vent/flare in the event of a hydrogen leak in the sub-surface area of the system. It will be located appropriately to prevent migration of the gas to surface and have a sensitivity level which will highlight the presence of hydrogen before an unsafe concertation of hydrogen can occur. This safety system will be tested periodically by dosing the sub-surface environment with a mixture of nitrogen and helium (such as 10% helium, 90% nitrogen) to ensure the seeking nature of hydrogen is replicated. This test will be performed after each significant step in the commissioning and test programme. For further information on the leak management system, see LGG-L057401-R08 Sub-surface Process Design Note.

The controller PLC will have a dedicated monitoring system for leak detection. Should a leak be detected then the state machine will force the system into emergency shutdown.

### 5.2 Emergency Shutdown

Based on the cause and effect matrix, an emergency shutdown procedure will be initiated due to the following causes:

- High high pressure (max design pressure exceeded)
- High high strain in gas-tight liner (significantly above expected strain)
- Low low strain in gas-tight liner (negative strain)
- High high strain in structural liner (significantly above expected strain)
- Low low strain in structural liner (negative strain)
- Excessive overburden movement
- Dangerous seismic activity
- Leak detected
- Emergency push button activated

- Fire/smoke detected
- Passive safety feature activated

During an emergency shutdown, the control system will close all isolation valves and deactivate topside process equipment. Audible and visual operator/site alarms will be activated and all remaining gas in the containment vented and flared at surface. Should the emergency shutdown be activated due to the passive sub-surface safety valves closing, then only the remaining gas in the topside process equipment will be vented and flared.

# 6.0 Sub-Surface Monitoring

## 6.1 Overview

The primary purpose of the monitoring system for the LRS is to achieve operational safety. The monitoring must provide reliable and resilient feedback on the behaviour of the system to detect and warn the operator if mechanical, thermal, or structural boundaries are approached or exceeded. Data from the monitoring system will be used to automatically activate/deactivate other system components to manage system behaviour and prevent an unsafe event.

In addition to safety, the monitoring system will provide behaviour and performance characteristics of the sub-surface storage. Gathering quantitative data on the mechanical response of each liner material and the rock mass will provide the opportunity to validate modelling predictions and optimise the operation and future design of the sub-surface storage. This section of the report will consider the instrumentation required to monitor the characteristics highlighted in Table 3. Containment pressure and temperature monitoring is not covered in this section of the report as it is expected this will be achieved using standard process monitoring.

*Table 3: Sub-surface monitoring*

| Sub-system | Characteristics to monitor |
|---|---|
| **Multi-layer liner** | • Gas tight liner and structural liner strain<br>  ○ Vertical strain over full height of steel structures<br>  ○ Radial strain over full circumference<br>  ○ Localised strain at areas of interest (e.g., high fatigue welds)<br>• Gas tight liner and structural liner temperature |
| **Casing string** | • Radial strain<br>• Longitudinal strain<br>• Temperature |
| **Overburden** | • Radial strain<br>• Longitudinal strain<br>• Vertical displacement<br>• Rock mass to overburden shear |
| **Rock mass** | • Rock mass temperature<br>• Rock mass strain |

Ideally, the monitoring system would provide feedback on the temperature, strain and cracking behaviour of the concrete and grout layers. However, following discussion with monitoring experts, it has been suggested that due to the relatively small thickness of both the concrete and grout layers, it may be difficult to provide accurate and reliable results. Longitude will continue to engage with industry partners to review potential options. The concrete behaviour will therefore be tested and analysed in a multi-layer liner lab experiment prior to the technology demonstrator deployment.

## 6.2 Design Considerations

The GTL is expected to exceed yield strain during initial overpressure testing. Following the overpressure and depending on ground conditions, the material is expected to cycle within the elastic limit during pressurisation and depressurisation. As the initial overpressure will exceed yield, this aspect of the design will require alternative validation as opposed to typical legislation. Because the system will operate with hydrogen, a materials testing programme will be performed to first optimise material and weld procedure selection and then ultimately derive design data which will be used to ensure the demonstrator and future full-scale designs are within factored material limits.

The instrumentation and monitoring system must have the coverage and capability to provide appropriate sensitivity and an adequate number of data points to deliver a complete picture of the system and rock mass behaviour to the operator. The requirements register LGG-L057401-R01 provides a list of requirements for the EC&I sub-system of the LRS. In addition, below are design considerations that should be accounted for due to the unique environment and behaviour of the sub-surface storage.

- Instrumentation within the lining system will be subjected to high compression and abrasion due to expansion and contraction of the liner layers during operation.
- Voids in the concrete, grout or rock may induce localised stresses on liner elements which may compromise localised results
- High strength wires or cables may induce stress on lining elements by unfavourably constraining the lining during expansion
- Concrete and grout are designed to crack radially under radial strain. This may cause local movement and stress reduction at sensor locations. In addition, cracks could result in excessive local loading on fibre optic cables.
- Plastic deformation of the gas-tight liner, structural liner, and rock mass may occur on initial pressurisation.
- Cyclic loading may generate minor plastic deformation on each cycle. The amount of the plastic deformation is expected to reduce for each cycle as the rock mass consolidates.
- Instrumentation should, where relevant, be suitable for service in the presence of hydrogen. This is unlikely to occur but must be considered in case of a leak
- Redundancy should be considered throughout the monitoring system design for safety critical elements.
- Calibration and ground truthing should be performed in the installation of instrumentation. There may be no access to sub-surface instrumentation once the LRS is installed.

## 7.0 Bibliography

ANSI 2016*18.2 Management of Alarm Systems for the Process Industries*

British Standards 2018 *BS7671 Requirements for Electrical Installations*

British Standards 2024 *BS7671 Requirements for Electrical Installations*

HSE 1989 *The Electricity at Work Regulations*

IEC 2016 *61511-1 Functional Safety - Safety instrumented systems for the process industry sector*

IEC 2022 *68682 Management of alarm systems for the process industries*

# Ofgem SIF B-Linepack+

## Test Plan

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## 1.0 Summary

This document presents a comprehensive commissioning and testing plan for the Lined Rock Shaft (LRS) technology demonstrator, developed as part of the Ofgem SIF B-Linepack+ storage demonstration project.

The principal objective of the test plan is to verify the safety, performance, and commercial viability of the LRS, with the intention of closely replicating full-scale operational conditions to support future commercial deployment. Furthermore, the testing is planned to generate sufficient evidence to enable third-party technology qualification, and to demonstrate the value that LRS technology can offer in supplementing linepack for emerging hydrogen gas networks. For each test detailed in this report, a test procedure will be produced, each with specific aims/targets. Tests reports detailing results will be created to form the evidence for technology validation. This test plan is the overview of all the testing that needs to be performed.

The testing is comprised of five different stages which are; non-containment commissioning, containment commissioning, operational testing, accelerated life testing, and decommissioning testing. It is estimated that the commissioning stage will take 113 days, the operational and accelerated life testing stages 528 days, and the decommissioning testing six days. The total programme therefore takes 647 days. This does not consider further time required for down time, maintenance, and other activities. Testing is performed both with water for hydro-testing and using hydrogen. As the maturity of the technology demonstrator progresses, more or less tests may be required.

# 2.0 Introduction

## 2.1 Scope and Purpose

The purpose of this document is to provide the commissioning and test plan for the technology demonstrator LRS as part of the Ofgem SIF B-Linepack+ storage demonstration project.

The technology demonstrator shall be used to test and validate the safety, performance, and commercial value of the LRS. The system is being designed such that the testing shall, as close as possible, demonstrate the behaviour of a full-scale LRS so that the technology can enter commercial deployment thereafter.

For more information regarding the technology demonstrator aims and requirements, see the document LGG-L057401-R04-Rev00 Basis of Design (Sub-Surface Containment).

To inform this test plan, both the *Guideline For Pressure Testing of Field-Installed Piping and Equipment* (European Industrial Gases Association AISBL, 2024) and the BSI Standards Publication *PD5500 2024 Specification for unfired pressure vessels* (BSI, 2024) were reviewed. Both documents provide guidance for commissioning testing for pressure equipment. It is however noted that due to the novel nature of the LRS technology, not all requirements stated in the documents are applicable. In these cases, engineering best practice is applied and risk as low as reasonably practicable (ALARP) alternatives proposed.

## 2.2 Testing aims

The test programme has three key aims:

1. Demonstrate the safety, performance, and commercial value of LRS technology to enable the deployment thereafter of full-scale commercial systems.
2. Provide sufficient evidence for technology qualification from a third-party certification authority.
3. Demonstrate the capability of the LRS technology in supplementing linepack to show the value it could provide to support future hydrogen gas networks.

## 2.3 LRS Technology development

Prior to the test programme detailed hereafter, a comprehensive technology development programme will have been completed. The technology demonstrator is the last stage of the physical testing required. The key aspects of the LRS technology that require physical testing as part of the development process are:

- Gas-tight liner (GTL) exposure to LRS hydrogen service conditions
- LRS multi-layer lining design
- Rock mass support

To test the GTL for exposure to hydrogen service conditions, a materials testing programme will have been completed. To test the LRS multi-layer lining design, lab scale testing of the full lining system will have been completed with artificial rock support. The purpose of the technology demonstrator therefore is to test the LRS system with rock mass support that is representative of future deployment conditions.

## 2.4 Testing stages

The test programme is split into different stages which have been detailed in Table 1. Each stage is described in more detail in the later sections. For each testing stage, downtime for maintenance, rework etc. has been excluded. Additional time would need to be added to account for these.

*Table 1: Testing stages*

| Test stage | Aim |
|---|---|
| Commissioning (non-containment) | Test that all sub-systems (excluding the containment) are operating safely and as expected – first with each in isolation, then all operating together (where applicable). Test that all controls and communication systems are working as expected. Test all safety and emergency procedures. Tests shall include those required to show compliance with regulatory requirements. |
| Commissioning (containment) | Test that the containment is gas-tight and operating safely. This shall first be performed with water (hydro-testing), then hydrogen thereafter. Tests shall include those required to show compliance with regulatory requirements. The equipment commissioned during the non-containment commissioning phase will be used to facilitate this testing phase. |
| Operational testing | Test the LRS system with hydrogen as would be expected for in-service conditions. Demonstrate the safety, performance, and commercial value of the system. Complete linepack supplementation testing to demonstrate how LRS systems can support a future hydrogen gas network. |
| Accelerated life testing | Perform accelerated life testing, taking the LRS system to 5,000 full pressure cycles (the expected service life of a full-scale system). To be performed via hydro-testing to facilitate faster cycling. |
| Decommissioning testing | Perform any required tests to facilitate the decommissioning of the LRS. |

## 2.5 Test data

For the testing to satisfy the aims detailed in Section 2.2, the following behaviours must be monitored and data of sufficient quality recorded throughout. The instrumentation, monitoring equipment, and control system used to achieve this is detailed in LGG-L057401-R02-Rev00 EC&I Design Note.

- Containment and casing string gas pressure and temperature
- GTL strain
- Structural liner strain
- Overburden displacement
- Rock mass response
- Hydrogen gas purity
- Gas flowrates
- Gas detection
- System temperatures

## 2.6 Abbreviations

Abbreviations used in this report are outlined in Table 2.

*Table 2: Abbreviations*

| | |
|---|---|
| ***LRS*** | *Lined Rock Shaft* |
| ***GTL*** | *Gas-Tight Liner* |
| ***SSSV*** | *Sub-Surface Safety Valve* |
| ***ASV*** | *Annular Safety Valve* |
| ***ALARP*** | *As Low As Reasonably Practicable* |

## 3.0 Commissioning (non-containment)

The commissioning (non-containment) stage is to test that all sub-systems other than the containment are working safely and as expected. Following isolated sub-system testing, all sub-systems (excluding containment) will be tested together to confirm safe operation. The summary of the test stage is given in Table 3, then the full test breakdown is given in Table 4. Considerations for the testing stage are as follows:

- Prior to any tests starting, checks shall be performed to ensure that all relevant documentation is completed and available. All procedures and safety information/equipment/signage etc. shall also be checked to ensure risk ALARP commissioning will take place.
- Commissioning testing of the non-containment sub-systems includes everything other than the gas containment sub-surface. The interface between containment and non-containment is defined as the sub-surface safety valve (SSSV) in the injection tube, and the annular safety valve (ASV) in the production tube.
- All commissioning shall be performed in a way that ensures risk ALARP testing. Where possible, individual components/parts/processes etc. shall be tested in isolation before including additional components/parts/processes etc.
- Testing in Table 4 is detailed as being performed in sequential order. It may be that some tests could be performed in parallel if practical and safe to do so.

For all commissioning testing (non-containment and containment), there shall be strict control of security and personnel on site. A specific commissioning team shall perform the tests, which may differ from the team that perform the tests thereafter.

At this stage, high level tests have been defined in Table 4. Further detail shall be added as the system design maturity progresses, with specific detail relating to topside process equipment commissioning to be provided/owned by Premtech.

*Table 3: Commissioning (non-containment) summary*

| | |
|---|---|
| Test regime duration | 34 days |
| No. of tests | 15 |
| Total full pressure cycles | 0 |

*Table 4: Commissioning (non-containment) test breakdown*

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | time (days) | Cumulative time (days) |
|---|---|---|---|---|---|---|---|
| 1 | 01 System | Gas detection and fire suppression equipment tests | Test that all gas detection and fire suppression equipment/systems are in full working order. | Ensure all gas and fire safety equipment is working. Compliance with regulation. | 48 | 2 | 2 |
| 2 | 07 Electrical & Controls | Electrical continuity and insulation test | Test that all electrical systems are correctly connected and suitably insulated. | Ensure safety of electrical system. Compliance with regulation. | 48 | 2 | 4 |
| 3 | 07 Electrical & Controls | Control system and communication check | Test functionality of all control system actions and responses. Test integration between all sub-system controls. Test communication of internal system and with external systems. | Ensure control system and communication operating as expected. Compliance with regulation. | 168 | 7 | 11 |
| 4 | 04 Well & Sub-Surface Process | Production tube and safety valve test | Production tube pressurised with water and held at pressure. | Test integrity of production tube and safety valve. Compliance with regulation. | 24 | 1 | 12 |
| 5 | 04 Well & Sub-Surface Process | Injection tube and safety valve test | Injection tube pressurised with water and held at pressure. | Test integrity of injection tube and safety valve. Compliance with regulation. | 24 | 1 | 13 |
| 6 | 04 Well & Sub-Surface Process | Sub-surface safety valves functional test | Test function of opening and closing of valves. | Test that control of safety valves work. Compliance with regulation | 24 | 1 | 14 |
| 7 | *Owned by Premtech* | Wellhead and top-side flow control valves test | Pressurise all valves and test function of opening and closing of valves. | Test integrity and that wellhead and valves work. Compliance with regulation. | 24 | 1 | 15 |

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | time (days) | Cumulative time (days) |
|---|---|---|---|---|---|---|---|
| 8 | *Owned by Premtech* | Top-side piping pressure test | Pressure tests of all top-side piping. | Test integrity of all top-side piping. Compliance with regulation. | 24 | 1 | 16 |
| 9 | *Owned by Premtech* | Top-side monitoring and metering test | Calibration and function testing of all monitoring and gas metering equipment. | Ensure correct operation of all monitoring and metering equipment. Compliance with regulation. | 24 | 1 | 17 |
| 10 | *Owned by Premtech* | Top-side process equipment commissioning test | Commissioning testing required for all additional process equipment such as compressor, heating/cooling etc. | Ensure correct operation of all top-side process equipment. Compliance with regulation. | 168 | 7 | 24 |
| 11 | 06 Instrumentation | Containment monitoring equipment calibration and test | Calibration and function testing of pressure and temperature containment monitoring equipment. | Ensure correct operation of all monitoring equipment. Compliance with regulation. | 48 | 2 | 26 |
| 12 | 06 Instrumentation | Structural monitoring equipment calibration and test | Calibration and function testing of structural monitoring equipment. | Ensure correct operation of all monitoring equipment. Compliance with regulation. | 48 | 2 | 28 |
| 13 | 06 Instrumentation | Ground monitoring equipment calibration and test | Calibration and function testing of ground monitoring equipment. | Ensure correct operation of all monitoring equipment. Compliance with regulation. | 48 | 2 | 30 |
| 14 | 04 Well & Sub-Surface Process | Test leak management system | Dose system with seeking gas. Test leak management system functionality and wider system response. | Ensure leak management system operating as expected. Compliance with regulation. | 24 | 1 | 31 |
| 15 | 01 System | Emergency shutdown and safety procedures test | Test all emergency shutdown and safety procedures. | Ensure procedures work and are suitable for wider system. Compliance with regulation. | 72 | 3 | 34 |

## 4.0 Commissioning (containment)

Having completed the non-containment commissioning, the containment will be commissioned. The testing shall check for gas-tightness of the containment, and that it operates safely and as expected. This will first be performed using water (hydro-testing). Once completed, the containment shall be de-watered, dried, and then commissioned for hydrogen containment.

The summary of the test stage is given in Table 5, then the full test breakdown is given in Table 6. Considerations for the testing stage are as follows:

- The test breakdown assumes that the containment is already filled with water used during the installation procedure. If this water is deemed unsuitable for hydro-testing, then it must first be de-watered, then re-filled with suitable water. The high-level de-watering procedure is detailed in LGG-L057401-R07-Rev00 Construction Sequence.
- Prior to the use of hydrogen within the LRS system, it shall first be purged with nitrogen.

*Table 5: Commissioning (containment) summary*

| | Test regime | Full test programme |
|---|---|---|
| Duration | 67 days | 101 days |
| No. of tests | 13 | 28 |
| Total full pressure cycles | 25 | 25 |

*Table 6: Commissioning (containment) test breakdown*

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | No. of tests | No. Pressure Cycles | time (days) | Cumulative time (days) | Total Pressure cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 16 | 01 System | Overpressure test (hydro-test) | Gradually increase the pressure of the containment beyond the maximum operating pressure using water. Return to cushion gas pressure. | Test the integrity of the containment. Test response of rock mass, lining and overburden to containment pressure. Compliance with regulation. | 72 | 1 | 1 | 3 | 37 | 1 |
| 17 | 04 Well & Sub-Surface Process | Leak management system test | Dose system with seeking gas. Test leak management system functionality and wider system response. | Ensure leak management system operating as expected following overpressure test. | 24 | 1 | 0 | 1 | 38 | 1 |
| 18 | 01 System | Pressure hold test (hydro-test) | Increase pressure of the containment from cushion pressure to maximum operating pressure. Hold pressure for one week. Return to cushion gas pressure. | Test leak tightness of the containment. Test the long duration response of the rock mass, lining and overburden. | 192 | 1 | 1 | 8 | 46 | 2 |

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | No. of tests | No. Pressure Cycles | time (days) | Cumulative time (days) | Total Pressure cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 19 | 01 System | Pressure cycle test (hydro-test) | Increase pressure from cushion pressure to maximum operating pressure over 24 hours. Hold pressure for 12 hours. Return to cushion pressure over 12 hours. Hold pressure for 12 hours. | Test the cyclic response of the rock mass, lining and overburden. | 60 | 5 | 5 | 13 | 59 | 7 |
| 20 | 01 System | Injection and withdrawal rate test (hydro-test) | Increase rate of injection and withdrawal from 24 hour injection and 12 hour withdrawal to 30 minute injection and 30 minute withdrawal (unless monitoring data shows rates are too fast) | Test system response to varying rate of liner displacement. Check whether faster cycling can be performed to enable accelerated life testing. | 168 | 1 | 10 | 7 | 66 | 17 |

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | No. of tests | No. Pressure Cycles | time (days) | Cumulative time (days) | Total Pressure cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 21 | 04 Well & Sub-Surface Process | Leak management system test | Dose system with seeking gas. Test leak management system functionality and wider system response. | Ensure leak management system operating as expected. | 24 | 1 | 0 | 1 | 67 | 17 |
| 22 | 01 System | De-water containment | Pump water out from containment. Circulate hot inert gas to fully de-water. Test gas mix for moisture content. | To facilitate operation with gas. | 168 | 1 | 0 | 7 | 74 | 17 |
| 23 | 01 System | Leak test (inert gas) | Increase containment pressure to maximum operating pressure. Hold pressure for one week. Reduce pressure to cushion pressure. | Test containment for gas tightness. Test pressure equipment and instrumentation for gas use. | 192 | 1 | 1 | 8 | 82 | 18 |

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | No. of tests | No. Pressure Cycles | time (days) | Cumulative time (days) | Total Pressure cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 01 System | Pressure hold test (hydrogen) | Increase pressure of the containment from cushion pressure to maximum operating pressure. Hold pressure for one week. Return to cushion gas pressure. | Test leak tightness of the containment. Test the thermodynamic response of the system and the gas. Test for safe operation with hydrogen | 192 | 1 | 1 | 8 | 90 | 19 |
| 25 | 01 System | Pressure test (hydrogen) | Increase pressure from cushion pressure to maximum operating pressure over 24 hours. Hold pressure for 12 hours. Return to cushion pressure over 12 hours. Hold pressure for 12 hours. | Test the integrity of the containment. Test response of rock mass, lining and overburden to containment pressure. Test for safe operation with hydrogen. | 60 | 1 | 1 | 3 | 92 | 20 |

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | No. of tests | No. Pressure Cycles | time (days) | Cumulative time (days) | Total Pressure cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 01 System | Pressure cycle test (hydrogen) | Increase pressure from cushion pressure to maximum operating pressure over 12 hours. Hold pressure for two hours. Return to cushion pressure over 12 hours. Hold pressure for two hours. | Test the cyclic response of the rock mass, lining and overburden. Test for safe operation with hydrogen. | 28 | 5 | 5 | 6 | 98 | 25 |
| 27 | 01 System | Cushion pressure test (hydrogen) | Reduce pressure from cushion pressure to atmospheric pressure over six hours. Hold for two hours. Increase pressure back up to cushion pressure over six hours. Hold for two hours. | Test impact of dropping pressure below cushion gas pressure. Test for safe operation with hydrogen. | 16 | 3 | 0 | 2 | 100 | 25 |

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | No. of tests | No. Pressure Cycles | time (days) | Cumulative time (days) | Total Pressure cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 28 | 04 Well & Sub-Surface Process | Leak management system test | Dose system with seeking gas. Test leak management system functionality and wider system response. | Ensure leak management system operating as expected. | 24 | 1 | 0 | 1 | 101 | 25 |

## 5.0 Operational testing

On completion of all commissioning testing, with all relevant tests/check/producers etc. reviewed and deemed appropriate/acceptable, operational testing can begin. The operational testing will continue to test for the safe operation of the LRS, however it will also focus on validating the performance and commercial value of the system.

The summary of the test stage is given in Table 7, then the full test breakdown is given in Table 8. Considerations for the testing stage are as follows:

- Details regarding the testing to demonstrate linepack supplementation shall be defined in greater detail as the system maturity progresses. As detailed below, it may be that a tube trailer or other temporary/permanent storage is used to simulate a hydrogen user or producer to further demonstrate the system capabilities.
- A focus of the operational testing will be to understand the thermodynamic behaviour of the hydrogen and validate thermodynamic/process models of the system.

*Table 7: Operational testing summary*

| | Test regime | Full test programme |
|---|---|---|
| Duration | 114 days | 215 days |
| No. of tests | 5 | 33 |
| Total full pressure cycles | 75 | 100 |

*Table 8: Operational testing breakdown*

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | No. of tests | No. Pressure Cycles | time (days) | Cumulative time (days) | Total Pressure cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 29 | 01 System | Flow rate test (hydrogen) | Increase rate of injection and withdrawal from 24 hour injection and 12 hour withdrawal to six hour injection and six hour withdrawal (unless monitoring data shows rates too fast). | Demonstrate that required flow rates can be achieved. Test the thermodynamic response of the system and the gas. Determine the rate that hydrogen cyclic testing can be performed. | 168 | 1 | 10 | 7 | 108 | 35 |
| 30 | 01 System | Pressure cycle test (hydrogen) | Increase pressure from cushion pressure to maximum operating pressure over 24 hours. Hold pressure for 12 hours. Return to cushion pressure over 12 hours. Hold pressure for 12 hours. | Test the integrity of the containment. Test the thermodynamic response of the system and the gas. | 60 | 10 | 10 | 3 | 133 | 45 |
| 31 | 01 System | Linepack supplementation test (hydrogen) | Perform tests cycling hydrogen between the LRS and the ancillary storage to represent linepack supplementation. This may include the use of additional storage to represent a hydrogen user/producer on the network. Test detail to be defined as the system maturity progresses. | Demonstrate the performance of an LRS in providing storage to supplement a gas network. Test the thermodynamic response of the system. | 1,440 | 1 | 30 | 60 | 193 | 75 |

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | No. of tests | No. Pressure Cycles | time (days) | Cumulative time (days) | Total Pressure cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 32 | 01 System | Pressure cycle test (hydrogen) | Increase pressure from cushion pressure to maximum operating pressure over 12 hours. Hold pressure for one hour. Return to cushion pressure over six hours. Hold pressure for one hour. | Test the cyclic response of the rock mass, lining and overburden. Test the thermodynamic response of the system. | 20 | 25 | 25 | 21 | 214 | 100 |
| 33 | 04 Well & Sub-Surface Process | Leak management system test | Dose system with seeking gas. Test leak management system functionality and wider system response. | Ensure leak management system operating as expected. | 24 | 1 | 0 | 1 | 215 | 100 |

## 6.0 Accelerated Life Testing

The accelerated life testing aims to take the LRS to 5,000 full pressure cycles which is the expected service life of a full scale system. The testing will be performed using water for hydro-testing. This is because faster cycling can be achieved. It is also because the behaviours that are of interest from life testing are only structural, therefore the thermodynamic response of hydrogen is not required. Instead the structural response of the system can be generated by applying internal pressure with water.

The summary of the test stage is given in Table 9, then the full test breakdown is given in Table 10. Considerations for the testing stage are as follows:

- To transition from hydrogen testing in the operational testing stage to hydro-testing in the accelerated life testing stage, the system shall be purged of hydrogen using nitrogen, then filled with water of suitable quality.
- It is assumed that one cycle can be performed in two hours. The acceptability of this is to be reviewed as part of the commissioning test 20. If for any reason the duration for one cycle must be increased, then the time taken to complete the life testing will increase. If the overall accelerated life testing stage takes too long to complete, then it may not be possible to test to 5,000 cycles which would limit the learnings that the technical demonstrator could provide. It may also be found that one cycle can be performed quicker than in two hours, meaning the time taken to complete the accelerate life testing could reduce.
- It may be that on completion of testing up to the end of the accelerated life testing (test 34), that more tests not yet defined would be of value. It may be that these would be using water for hydro-testing or using hydrogen gas. The scope for any additional testing would need to be reviewed at the appropriate time.
- If more pressure tests are performed during the previous commissioning and testing stages than is currently stated, the number of pressure tests required to achieve the full 5,000 cycles may decrease.
- Additional tests, checks, inspection, maintenance etc. may be performed at desired intervals during the accelerated life cycle test (test 34). This may include testing the leak management system to ensure that it is operating as expected throughout.

*Table 9: Accelerated life testing summary*

| | Test regime | Full test programme |
|---|---|---|
| Duration | 418 days | 633 days |
| No. of tests | 5 | 38 |
| Total full pressure cycles | 4,900 | 5,000 |

*Table 10: Accelerated life testing breakdown*

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | No. of tests | No. Pressure Cycles | time (days) | Cumulative time (days) | Total Pressure cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 34 | 01 System | Pressure cycle test (hydro-test) | Increase pressure from cushion pressure to maximum operating pressure over 45 minutes. Hold pressure for 15 minutes. Return to cushion pressure over 45 minutes. Hold pressure for 15 minutes. | Test the cyclic response of the rock mass, lining and overburden. | 2 | 4,900 | 4,900 | 410 | 625 | 5,000 |
| 35 | 01 System | Addition tests as required (hydro-test) | As required | N/A | N/A | N/A | N/A | N/A | 625 | 5,000 |
| 36 | 01 System | De-water containment | Pump water out from containment. Circulate hot inert gas to fully de-water. Test gas mix for moisture content. | To facilitate operation with gas. | 168 | 1 | 0 | 7 | 632 | 5,000 |
| 37 | 04 Well & Sub-Surface Process | Leak management system test | Dose system with seeking gas. Test leak management system functionality and wider system response. | Ensure leak management system operating as expected. | 24 | 1 | 0 | 1 | 633 | 5,000 |
| 38 | 01 System | Addition tests as required (hydrogen) | As required | N/A | N/A | N/A | N/A | N/A | 633 | 5,000 |

## 7.0 Decommissioning tests

On completion of all required testing, the system will be decommissioned. Options for decommissioning include backfilling or re-certifying and de-rating for alternative use. For all decommissioning options, the system may be re-tested for pressure integrity beforehand.

The summary of the test stage is given in Table 11, then the full test breakdown is given in Table 12. Considerations for the testing stage are as follows:

- It is expected that additional testing will be required as part of the decommissioning process which will be detailed as the system decommissioning plan matures.

*Table 11: Decommissioning testing summary*

| | Test regime | Full test programme |
|---|---|---|
| Duration | 2 days | 635 days |
| No. of tests | 2 | 40 |
| Total full pressure cycles | 0 | 5,000 |

*Table 12: Decommissioning test breakdown*

| Test No. | Sub-System | Test | Description | Justification | Duration (hr) | No. of tests | No. Pressure Cycles | time (days) | Cumulative time (days) | Total Pressure cycles |
|---|---|---|---|---|---|---|---|---|---|---|
| 39 | 04 Well & Sub-Surface Process | Production tube and safety valve test | Production tube pressurised with water and held at pressure. | Test integrity of production tube and safety valve. | 24 | 1 | 0 | 1 | 634 | 5,000 |
| 40 | 04 Well & Sub-Surface Process | Injection tube and safety valve test | Injection tube pressurised with water and held at pressure. | Test integrity of injection tube and safety valve. | 24 | 1 | 0 | 1 | 635 | 5,000 |

## 8.0 Summary

A summary of the test plan is given in Table 13. The system will complete 5,000 pressure cycles, of which 82 will be using hydrogen gas. The full programme will take 635 days.

*Table 13: Test plan summary*

| Test stage | Duration (days) | Cumulative duration (days) | Pressure cycles (non-hydrogen) | Pressure cycles (hydrogen) | Pressure cycles total |
|---|---|---|---|---|---|
| Commissioning (non-containment) | 34 | 34 | 0 | 0 | 0 |
| Commissioning (containment) | 67 | 101 | 18 | 7 | 25 |
| Operational testing | 114 | 215 | 0 | 75 | 100 |
| Accelerated life testing | 418 | 633 | 4,900 | 0 | 5,000 |
| Decommissioning testing | 2 | 635 | 0 | 0 | 5,000 |

Considerations for the test plan are as follows:

- The time stated to complete the full test programme does not account for down time between tests. Therefore, it is likely that the time taken to complete the programme will be longer than 635 days (assuming the full test programme is completed).
- As stated previously, the time taken to complete the accelerated life testing stage assumes that a full pressure cycle can be completed in two hours. If this needs to increase, then the time taken for this stage would increase. Likewise if it can be completed in less than two hours, the time taken to complete the stage may decrease.
- For the accelerated life testing to be performed with a two-hour pressure cycle, it is assumed that water can be used as the working fluid. To confirm that this would demonstrate representative behaviour of a system using gas, further modelling is required.
- The test programme assumes that all tests performed are successful or allow for the next test to take place. If tests are unsuccessful or show that the test programme must be modified or stopped, then this will affect the remaining test programme. This would likely result in a change to the schedule and the test programme may need to be amended.
- Additional tests may be required as specified by a third-party certification authority or a member of the Ofgem SIF B-Linepack+ storage demonstration project consortium.
- It is noted that hydrogen is not required for entire test programme (estimated at 133 days and 82 pressure cycles). This is because for the tests that take the longest (primarily accelerated life testing), hydrogen is not required as the working gas. The technical justification for this has been detailed in Section 6.0.

## 9.0 Bibliography

BSI 2024 *PD5500:2024 Specification For Unfired Pressure Vessels*

European Industrial Gases Association AISBL 2024 *Guideline For Pressure Testing Of Field-Installed Piping And Equipment Doc 254/24*

REPORT.

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# Ofgem SIF B-Linepack+

# Basis of Design (Sub-Surface Storage)

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## 1.0 Summary

This document provides a design overview of the sub-surface storage for the Lined Rock Shaft (LRS) technology demonstrator, developed as part of the Ofgem SIF B-Linepack+ storage demonstration project. This document should be used in conjunction with PRZ0025-REP-0000-0001 which acts as the upper-level basis of design report and provides wider project scope.

The LRS system stores pressurised gas, typically hydrogen, in a sub-surface storage vessel. The liner of the vessel is designed to allow load transfer to the surrounding geology, resulting in material and cost savings compared to above-ground storage solutions. The project aims to validate and de-risk the storage technology such that on completion, the technology is ready for a commercial pilot and is suitable for Linepack+ storage on the gas network. At a high level the design should:

- Demonstrate the safety, performance, and commercial value of LRS technology to enable the deployment thereafter of full-scale commercial systems.
- Provide sufficient evidence for technology qualification from a third-party certification authority.
- Demonstrate the capability of the LRS technology in supplementing linepack to show the value it could provide to support future hydrogen gas networks.

The development of the LRS technology comprises three major stages:

- Stage 1 is a material testing programme to determine the most suitable parent, weld filler material and weld procedure for the gas-tight liner, then determine design data for the technology demonstrator. This material testing program will determine the material and weld behaviour with regards to the system cycle life and exposure to pressurised hydrogen.
- Stage 2 will verify and correlate the pressurised LRS liner behaviour to the design calculations and geomechanical modelling. The test will be performed by mechanically loading a section of lining with equivalent diameter of the technology demonstrator.
- Stage 3 is the deployment of the technology demonstrator underground to achieve the design aims discussed previously.

The LRS system is designed to store gaseous hydrogen with a total capacity of 0.53 tonnes, comprising 0.09 tonnes of cushion gas and 0.44 tonnes of working gas, with a maximum operating pressure of 200 Barg and a cushion gas pressure of 30 Barg. The internal storage volume will be 35 $m^3$, with an overall shaft depth of 47m.

The requirements of the system are driven by safety and the need to demonstrate the operational and lifetime performance of the LRS. LGG-L057401-R01 provides a detailed breakdown of system and sub-system requirements including the design stage at which evidence of compliance is required.

The demonstrator sub-surface design will follow the as low as reasonably practicable (ALARP) process for risk management and be completed in accordance with internal ABL/Longitude procedures and policies. In addition, the design will follow, where applicable, appropriate industry legislation and adhere to all relevant safety legislation throughout the project life.

# 2.0 Introduction

## 2.1 Scope and Purpose

This Basis of Design (BoD) provides the design overview for the sub-surface storage of a LRS, seen in **Error! Reference source not found.**, being developed under the Ofgem SIF B-Linepack+ project. It provides specific design information related to the design and development of the sub-surface containment. This BoD should be used in conjunction with PRZ0025-REP-0000-0001 which acts as the upper-level BoD report and provides wider project scope.

The LRS system stores pressurised gas, typically hydrogen, in a sub-surface storage vessel. The liner of the vessel is designed to allow load transfer to the surrounding geology, resulting in material and cost savings compared to above-ground storage solutions. The LRS is deployed in purpose sunk shafts allowing the end user to locate the sub-surface storage where it provides most value.

The project aims to validate and de-risk the storage technology such that on completion, the technology is ready for a commercial pilot and is suitable for Linepack+ storage on the gas network.

## 2.2 Related Documents

System engineering documents referenced in this report are outlined in Table 1.

*Table 1: System Engineering Documents*

| Document Name | Document Number | Scope |
|---|---|---|
| **Basis of Design (General)** | PRZ0025-REP-0000-0001 (Premtech) | Outlines the fundamental principles, assumptions, and design criteria for the overall project. To be used in conjunction with this BoD which provides specific information regarding the sub-surface design. |
| **Requirements Register** | LGG-L057401-R01 (Appendix A) | Defines the functional requirements of each subsystem and indicates at which point in the project compliance shall be demonstrated. |
| **Interface Register** | PRZ0025-REG-0000-00002 (Premtech) | Tracks major interfaces between sub-systems and highlights interface ownership and design evidence. |
| **Risk Register** | B-Linepack+ LRS Safety Risk Register (National Gas Transmission) | Tracks design, budget, schedule and safety risks across the project, and their planned and implemented mitigations. |
| **Load Case definitions** | To be created at next stage of design | Defines through-life load conditions to be considered during the technical analysis of the design. |
| **Test plan** | LGG-L057401-R03 | Defines the commissioning and testing plan used to verify the safety, performance, and commercial viability of the system. |

## 2.3 Abbreviations

Abbreviations used in this report are outlined in *Table 2.*

*Table 2: Abbreviations*

| | |
|---|---|
| ***NGT*** | *National Gas Transmission* |
| ***LRS*** | *Lined Rock Shaft* |
| ***LRC*** | *Lined Rock Cavern* |
| ***SSSV*** | *Sub-Surface Safety Valve* |
| ***ASV*** | *Annular Safety Valve* |
| ***GTL*** | *Gas-Tight Liner* |
| ***SL*** | *Structural Liner* |
| ***BoD*** | *Basis of Design* |
| ***ALARP*** | *As Low As Reasonably Practicable* |
| ***WRA*** | *Well-Reasoned Argument* |
| ***PFD*** | *Process Flow Diagram* |
| ***PCV*** | *Pressure control valve* |
| ***FCV*** | *Flow Control Valve* |

# 3.0 Development Methodology and Objectives

## 3.1 Methodology

LRS technology is novel. It implements, and builds upon, design principles used for the development of Lined Rock Caverns (LRC). The major difference being that LRS systems can be deployed in a wide range of typical geologies compared to LRCs that can only be deployed in hard rock conditions. In addition, the storage is installed in a vertical, rather than horizontal, excavation. Following a 2-year accelerated life testing programme, LRC technology has reach a high TRL and is now ready for industrialisation. This achievement provides a reliable platform for the LRS technology to base a technology readiness pathway.

There are three major stages to the technology development programme, shown in Figure 1 and outlined below.

**Determination of design data for gas-tight liner**

The GTL has been designed to exceed the yield strain of the material, meaning the design of the GTL does not comply with pressure vessel design standards. A materials testing programme will be performed to first optimise material and weld procedure selection and then ultimately derive design data which will be used to ensure the demonstrator and future full-scale designs are within factored material limits. The testing will account for hydrogen service conditions with a focus on fatigue behaviour of the parent and weld material.

**Verification and correlation of multi-layer behaviour under pressure**

The LRS liner is made up of multiple layers which work together to transfer load to the surrounding rock mass. The multi-layer liner consists of a “sandwich” of different materials and material thicknesses. The steel and cementitious layers strain to transfer the load to the rock mass. A numerical model has been built to replicate and assess the behaviour of the liner as the layers respond together. The aim is to fabricate a welded ring section of the liner and pressurise this in a lab or workshop environment to replicate the hoop stress expected during operation. The rock mass resistance will be replicated mechanically. This test will provide the opportunity to de-risk modelling uncertainties for the technical demonstrator and provide design data with regards to material behaviour and monitoring techniques.

**Verification and correlation of rock mass behaviour**

Following material and multi-layer testing, the next step is to deploy the system underground. This will provide the only viable opportunity to de-risk the remaining uncertainly of rock-mass behaviour as the system is pressurised and de-pressurised for up to 5000 cycles. A key behaviour to observe is how the liner reacts at points where rock mass changes strength. This will provide critical evidence regarding the stress/strain behaviour of the liner with respect to variations in rock strength and can be used to correlate and verify the numerical models.

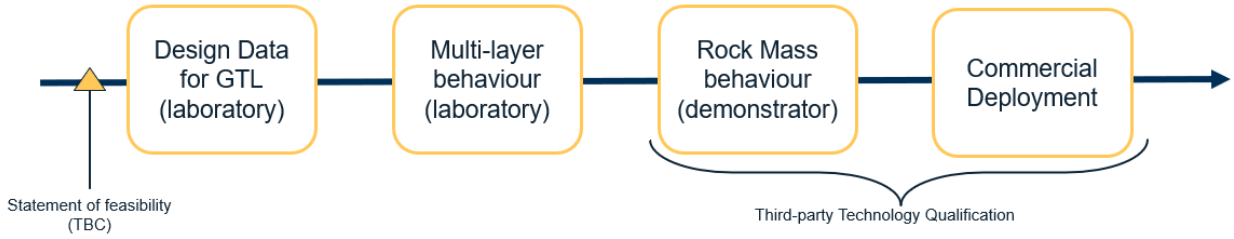


*Figure 1: Technology Development Programme*

To compliment the technology development programme, Longitude will engage with a third-party certification body to implement and deliver a technology qualification process. Should it be deemed necessary or advantageous, a statement of feasibility can be issued by the third-party following review of initial engineering documentation. For technology qualification, the third-party will assess the relevance and completeness of the

technology development programme and perform independent analyses and tests to verify the qualification evidence and conclusions. In addition, it will provide an opportunity to highlight risks and confirm compliance with specified standards. The completed technology qualification will provide proof of readiness to the market, confirmation of system reliability and insurance to the end user that the system will perform as stated.

## 3.2 Objectives

The B-Linepack+ project will see the LRS system move through the technology development programme and ultimately be ready for commercial deployment at the completion of testing and demonstration. In addition to validating the safety and performance for the LRS system, the project will provide evidence of a robust supply chain and provide an opportunity to validate and improve on construction and installation techniques.

At a high level the design should:

- Demonstrate the safety, performance, and commercial value of LRS technology to enable the deployment thereafter of full-scale commercial systems.
- Provide sufficient evidence for technology qualification from a third-party certification authority.
- Demonstrate the capability of the LRS technology in supplementing linepack to show the value it could provide to support future hydrogen gas networks.

In addition, the following demonstrator design considerations should be made when assessing alternative design options:

- Designs should aim to maximise continuity with full-scale system design intent and seek modularity where possible.
- Solutions which provide a range of potential suppliers should be preferred and single-source suppliers avoided where possible.
- Where lifetime cost is not a substantial factor between two options, the option resulting in lower embodied carbon emissions and/or longer operational life should be preferred.
- Design options which allow for normal road transport of modular sections for final assembly at site should be preferred.
- Local suppliers should be preferred where possible.

Further design considerations will be implemented in Longitude Design Review Checklists.

# 4.0 Requirements

## 4.1 Project and System Requirements

The requirements of the system are driven by safety and the need to demonstrate operational and lifetime performance of the LRS. LGG-L057401-R01 provides a detailed breakdown of system and sub-system requirements including the design stage at which evidence of compliance is required. A summary of the project and system requirements is shown in Table 3.

*Table 3: High-level Requirements*

| Requirement | Compliance plan |
|---|---|
| **Safety** | Evidence that all materials, equipment, and components are suitable for all though-life aspects of the project. |
| **Commercial Value** | Scalable test data which demonstrates the value of LRS technology for Linepack+ and its wider commercial value to industry. |
| **Performance** | Scalable test data which sufficiently demonstrates performance characteristics of the demonstrator and future full-scale systems. |
| **Constructability and supply chain** | Installation procedure which demonstrates, as near as possible, the methods and suppliers used for a full-scale system deployment. |
| **De-risking and learnings** | Test plan which provides suitable learning to de-risk future systems. |

## 4.2 Site Requirements

A comprehensive list of requirements and assessment criteria for site down-selection can be found in 1101-004-02 Practicalities of Test Locations. For the purpose of shaft sinking and the installation of the sub-surface storage a construction footprint of approximately. 2 acres (TBC) is required.

The ground conditions of the site will have a significant impact on the ability of the system to demonstrate the expected mechanical and geo-mechanical behaviours of a full-scale system. Ground conditions at the site should meet the following high-level requirements:

- Sufficiently competent to provide support for the sub-surface storage
- Suitable for shaft excavation using an augur piling rig
- Strata sequencing within the height of the containment such that the multi-layer lining behavior across rocks with different engineering properties is demonstrated.
- As worst case, representative in-situ stress conditions and geothermal, hydrostatic, and lithostatic gradients for UK geology.
- No high-risk ground conditions, e.g., geological faults, pressurized gas horizons, pressurized ground water horizons.

# 5.0 Sub-System Naming Convention and Boundaries

The sub surface design of the LRS has been divided into five sub-systems for the purpose of tracking requirements and interfaces. Each sub-system has a specific set of design requirements found in LGG-L057401-R01. Each requirement highlights at which stage of the design that evidence should be provided for compliance. The five sub-systems are:

- Civils: Includes preliminary civil works, shaft sinking and overburden
- Sub-surface Process: Includes casing string, safety valves and leak management
- Geomechanical & Structures: Includes steel liners, structural concrete, grout, and transition from GTL to casing string
- Electrical and Controls: Includes electrical power requirements for subsurface monitoring and system level controls system
- Instrumentation: Includes sub-surface monitoring equipment and gas/seismic monitoring at surface

## 5.1 Major System Components

### Casing String

The casing string connects the GTL to the topside process equipment. It comprises an injection tube which runs to the bottom of the GTL and a production tube which connects to the top of the GTL. It is a pipe-in-pipe construction with separate individual flanged connections at surface for injection and production.

### Safety Valves

Two safety valves are located sub-surface and inside the casing string. A sub-surface safety valve (SSSV) is located in the injection tube and an annular safety valve (ASV) located in the production tube. The purpose of both valves is to prevent the flow of gas in emergencies. Each valve will be held open using hydraulic pressure from a surface control line. When pressure in this control line is lost, a spring forces the valve to close and therefore fail in a safe manner.

### Overburden

The overburden is a column of concrete which prevents uplift of the containment and provides structural support to the GTL at the top hemisphere. The overburden will surround the casing string and leak management pipes. The overburden acts like a concrete pile in that it provides uplift resistance through the friction created at the interface to the rock mass shaft wall.

### Leak Management

The leak management system consists of a perforated tube, used to provide a low resistance migration pathway for hydrogen, Two vent tubes which deliver the leaked hydrogen to surface for collection/flaring and a dosing pipe which is used for regular integrity testing of the leak management system. A similar leak management system has been successfully used and tested for the development of LRCs.

### Gas-Tight Liner

This is a steel structure used to contain the hydrogen gas. It is resistive to long term degradation caused by exposure to hydrogen and when under pressure will strain to allow load transfer towards the rock mass.

### Concrete Liner

The structural concrete is poured between the structural steel liner (SL) and the GTL. It transfers the load to the rock mass and resists ground and hydrostatic pressure when the internal gas is low. The concrete liner and the SL reduce stress concentrations on the GTL by distributing loads caused by cracks opening in the rock mass.

### Structural Liner

The SL is a steel structure that provides stiffness in resisting the internal gas pressure, transfers load to the rock mass and resists ground and hydrostatic pressure loading when the internal gas pressure is low.

### Grout Liner

The grout liner bonds the lining system to the rock mass, provides a uniform interface between the structural liner and the rock mass and transfers the load to the rock mass.

## 5.2 System Boundaries and Responsibilities

The demonstration site is a standalone site with the hydrogen flowing through a closed loop system. Therefore, the only external interfaces are power from the local grid, an initial delivery of hydrogen, and water during testing.

The project has three main partners involved with the ownership, design, construction, operation and decommissioning of the system. Figure 2 and Table 4 show the boundaries and responsibilities of each partner at each given project stage.

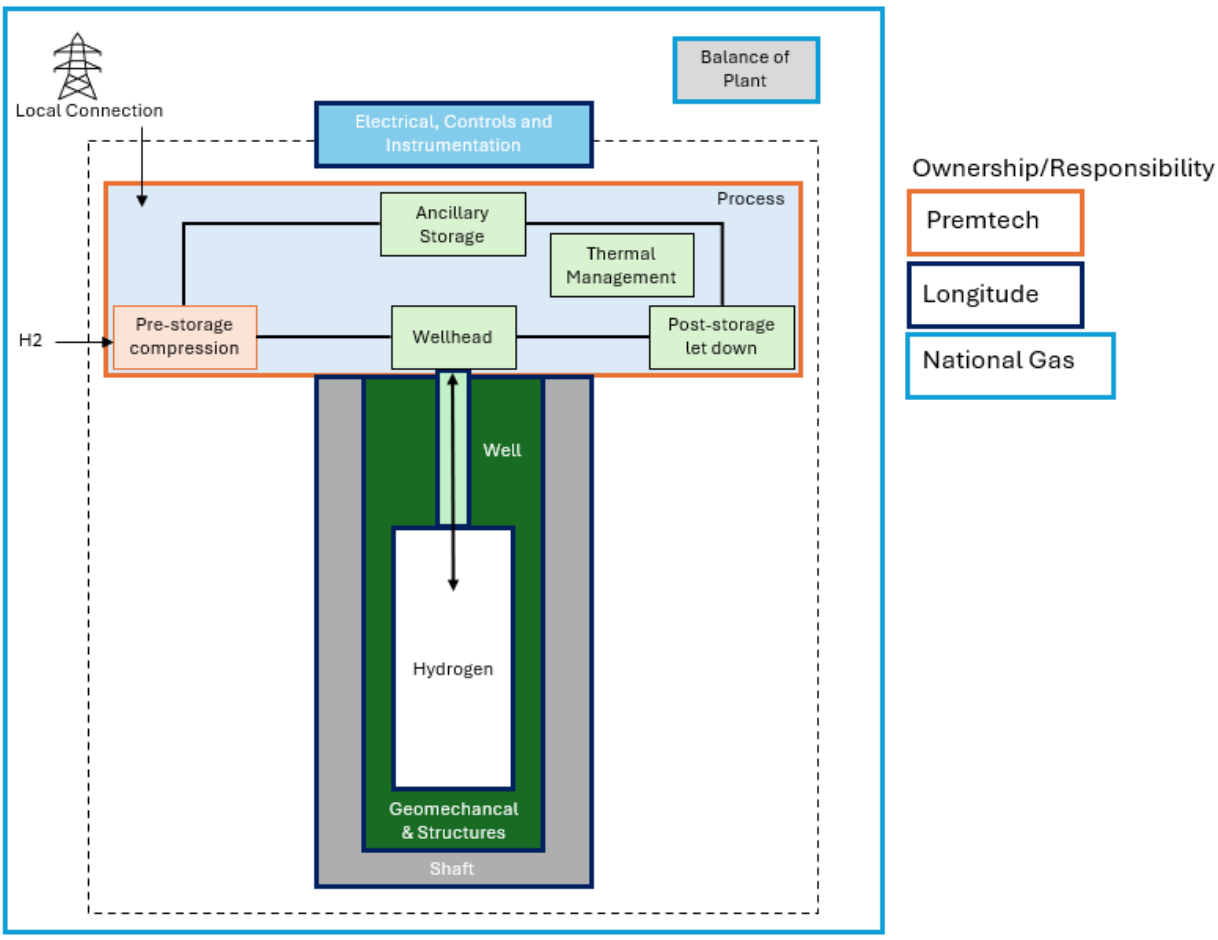


*Figure 2: System Responsibilities*

*Table 4: High-level Responsibilities*

| | Planning/Engineering | | | | | | Construction & Commissioning | | | | Operations | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Responsible** | Topside Process | Sub-surface storage | Planning & Consenting | Legal | Cost-Modelling | BOP | Topside Process | Sub-surface storage | BOP | Site Operator | Operations &Testing | Maintenance | Technical Support | BOP | Cost Control | Site Operator |
| **National Gas Transmission** | | | x | x | x | x | | | x | x | x | x | | x | x | x |
| **Premtech** | x | | | | | | x | | | | | x | x | | | |
| **Longitude** | | x | | | | | | x | | | | x | x | | | |

## 5.3 Basic Process Flow Diagram

A high-level Process Flow Diagram (PFD) can be seen in Figure 3 highlighting the major components of the process system. The system will consist of:

- A compressor for increasing the LRS storage pressure to 200barg
- A cooler, heater and recirculation blower for thermal management
- Ancillary storage for facilitating the demonstration of linepack capabilities and allowing pressure cycling of the sub-surface storage
- A pressure control valve (PCV) used to control the pressure in the ancillary storage
- 2-off flow control vales (FCV) to control the flow of gas into the compressor and out of the LRS

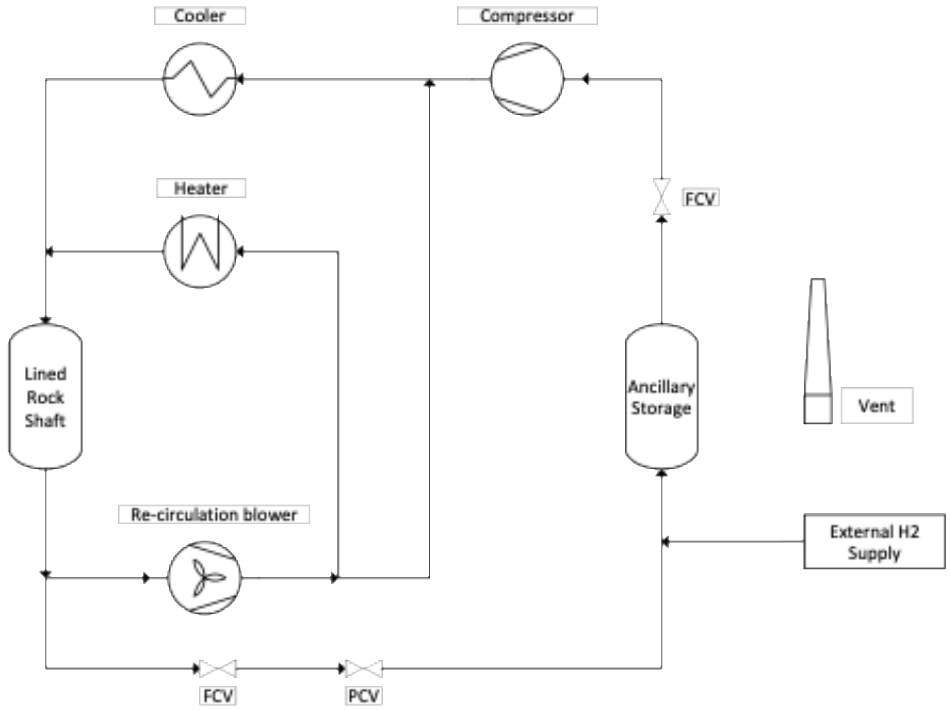


*Figure 3 High Level PFD*

# 6.0 System Properties

## 6.1 Sub-surface Storage Properties

The sub-surface storage properties are driven by the requirement to gain maximum technology validation at minimal cost whilst maintaining system integrity and safety. This philosophy drives many of the properties of the sub-surface storage shown in Table 5.

As a result of this design philosophy, an auger piling rig has been selected for the shaft excavation. Auger piling rigs are readily available in the UK and due to the relatively simplistic equipment set-up, costs can be minimised. Following discussion with civil contractor, a maximum shaft diameter of 2.5m has been suggested. This will be utilised for the demonstration project. The depth of the shaft is driven by the required length of GTL needed to validate system modelling. As a result of ASMEVIII pp.463, which states “Vessel side plates with aspect ratios less than 4 are strengthened by the interaction of the end closures”, the minimum length of the GTL must be 4 x the GTL inner diameter plus an additional 20m of liner section to allow sufficient GTL length to cross stratification in the rock mass.

The overburden depth is driven by the diameter of the GTL and the storage pressure due to the loading mechanism discussed in 5.1. The overburden height will be finalised following ground investigation results and analysis.

The mass of cushion gas required is driven by the total mass of gas stored. Cushion gas is the amount of gas which remains in the GTL at all times. This prevents unwanted external loading on the liner structure from hydrostatic pressure and the load of the rock mass.

*Table 5: Storage Properties*

| Property | Value | Notes |
|---|---|---|
| **Storage capacity** | 0.53 tonnes | Total hydrogen gas storage capacity assuming average storage temperature of 20 degrees Celsius. |
| **Cushion gas** | 0.09 tonnes | The amount of gas which is permanently stored in the sub-surface containment. It prevents unwanted loading on the liner and shaft walls when the working gas has been removed. |
| **Working gas** | 0.44 tonnes | Available gas for injection and withdrawal. |
| **Maximum Operating Pressure** | 200 Barg | Maximum operating storage pressure. During commissioning this pressure will be incrementally increased from atmospheric pressure and liner/geological strains assessed before pressure is increased. |
| **Inner storage diameter** | 1.26 m | Internal diameter of the gas-tight liner |
| **Inner storage length** | 29 m | Internal length of the gas-tight liner |
| **Internal storage volume** | 35 $m^3$ | Internal volume of the gas-tight liner |
| **Overburden depth** | 12 m | Depth of backfill in competent rock to provide resistance to vessel uplift pressure. |
| **Shaft diameter** | 2.484 m | Excavated diameter of shaft prior to liner installation |

| | | |
|---|---|---|
| **Shaft depth** | 47 m | Excavated depth of shaft prior to liner installation assuming 5m of superficial deposits. |

## 6.2 System Life

Table 6 provides the number of cycles (a cycle defines as empty-full-empty) which should be assumed for the design of the demonstrator equipment. As can been seen, only eight-two cycles are expected to be performed with hydrogen gas and one cycle with inert gas. The remaining cycles, which are used to validate the life of the liner, will be performed with water. This is because faster cycling can be achieved. It is also because the behaviours that are of interest from life testing are only structural, therefore the thermodynamic response of hydrogen is not required. In addition, exposure to hydrogen over the expected testing duration isn't long enough to see hydrogen embrittlement effects. Instead the structural response of the system can be generated by applying internal pressure with water.

*Table 6: System Life*

| Project stage | Pressure cycles (non-hydrogen) | Pressure cycles (hydrogen) | Pressure cycles total |
|---|---|---|---|
| Commissioning (containment) | 17 | 7 | 24 |
| Operational testing | 0 | 75 | 100 |
| Accelerated life testing | 4900 | 0 | 5000 |

## 6.3 Co-ordinate System

Figure 4 shows the definition of the LRS co-ordinate system. The Z-axis is aligned with the shaft axis (nominally vertical) and positive is upward. The negative direction of the X-axis is aligned with production interface flange and the co-ordinate system origin at ground level. The Y-axis is oriented to complete an orthogonal right-hand co-ordinate system.

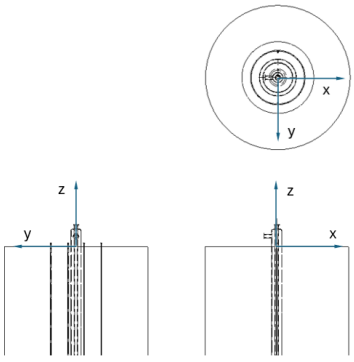


*Figure 4: Co-ordinate System*

# 7.0 Compliance

## 7.1 Design

Design reviews and preparation of engineering documentation (including drawings) shall be completed in accordance with internal ABL/Longitude procedures and policies. Only once a completed checklist of evidence is presented to, and accepted by the design review authority shall the design pass to the next design phase. In addition, the sub-surface design will be third-party verified for legislative and safety compliance.

The design will follow the as low as reasonably practicable (ALARP) process for risk management. At each design review, the team will challenge the design to determine if it has reached a suitable level of ALARP. A transparent and traceable record of reasoning will be appropriately documented and stored to form a Well-Reasoned Argument (WRA) for each major design decision. The design shall use equipment, materials and components that comply with any relevant standards, carry required conformity marks, and are suitably certified.

## 7.2 Legislation

A list of legislative documentation and hydrogen specific standards, specifications, and guidance documents relating to the design of the topside process equipment can be found in PRZ0025-REP-0000-0001. Due to the nature of the design, the LRS does not strictly conform to traditional pressure vessel codes and standards hence the use of ALARP and WRAs noted in section 7.1. The sub-surface storage will follow, where applicable, the following legislation in addition to all relevant safety legislation local to the site:

Energy Act 2023

Gas Act 1986

Planning Act 2008

Town and Country Planning Act 1990

Control of Major Accident Hazards (COMAH) Regulations 2015

Planning (Hazardous Substance) Regulations 2015

Health and Safety at Work Act (HSWA) 1974

Pipelines Safety Regulations 1996

Construction Design and Management (CDM) Regulations 2015

Dangerous Substances and Explosive Atmosphere Regulations (DSEAR) 2002

The Borehole Sites and Operations Regulations 1995

Confined Space Regulations 1997

Joint Service Safety Regulations for the Storage and Handling of Gases (JSP 319)

Gas Safety (Management) Regulations 1996

Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2004

Building Regulations 2010

Alternative Fuels Infrastructure Regulations 2017

Offshore Installations and Wells (Design and Construction, etc.) Regulations 1996

Pressure Equipment (Safety) Regulations (PESR) 2016

Pressure Systems Safety Regulations 2000 (PSSR)

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# Lined Rock Shaft – Construction Storyboard

LGG-L057401-R06

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# Lined Rock Shaft
# Technology Demonstrator
# Construction Storyboard

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# Lined Rock Shaft – Overview

## Document aims

- Pictorial overview of the sequence to construct a Lined Rock Shaft technical demonstrator.
- Note, this storyboard should be viewed in conjunction with written document LGG-L057401-R07 ‘Lined Rock Shaft – Construction Sequence’. Numbers on captions refer to relevant sections in that document.
- Cartoons in the storyboard are indicative only, not to scale, and with significant horizontal exaggeration.

## Key assumptions

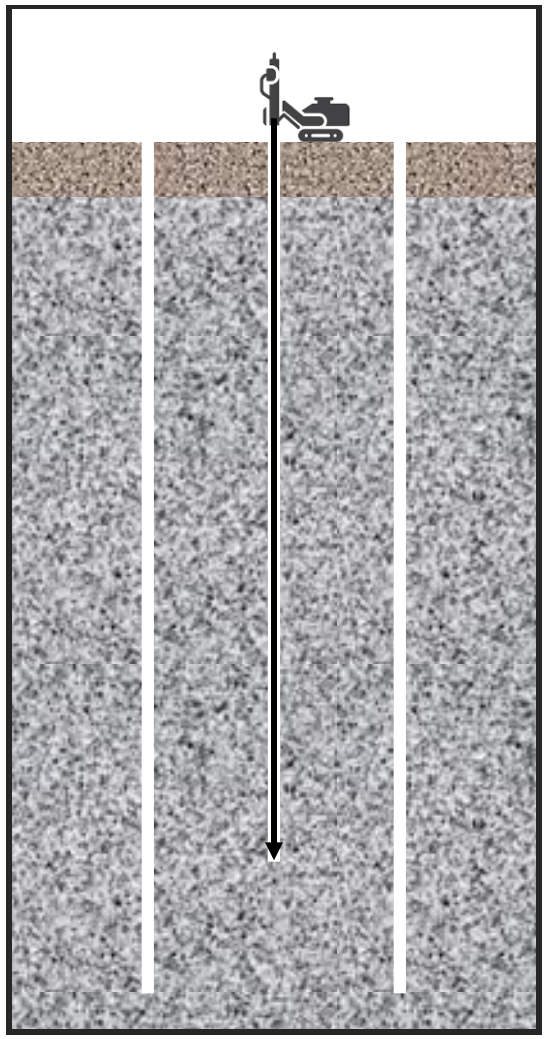
- Lined Rock Shaft (LRS) technology demonstration.
- Principal lining layers to be gas-tight liner, structural concrete, structural liner, grout.
- 2.5m dia. x 47m depth target dimension.

## Abbreviations

- GTL – Gas-tight Liner
- SL – Structural Liner

# **Lined Rock Shaft Construction** – ground preparation and pre-collar

2.2.1 Pre-grouting holes drilled



2.2.1 Pre-grouting stabilises ground

2.2.2 Pre-sink, piling, and collar

2.2.2 Collar and foundation construction

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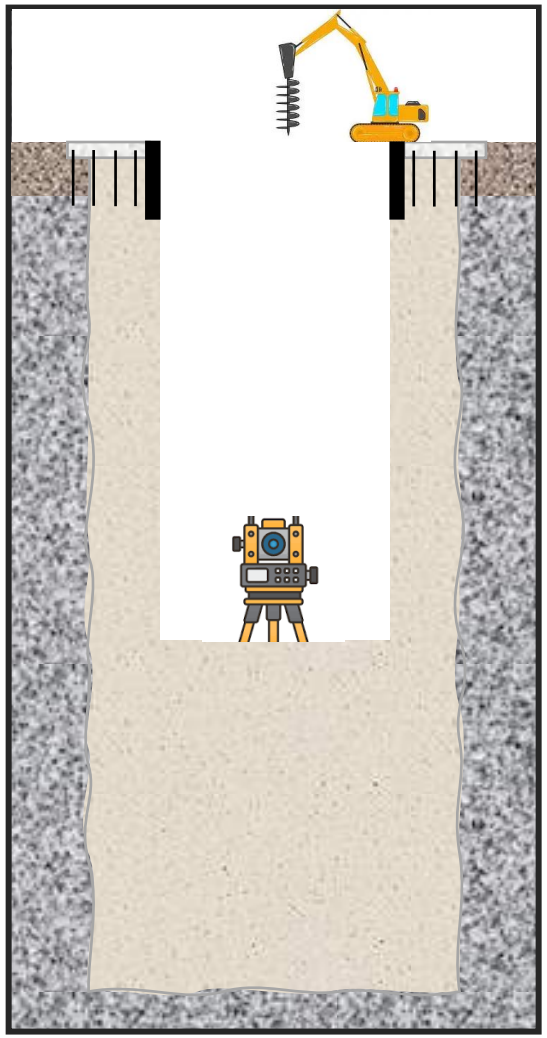
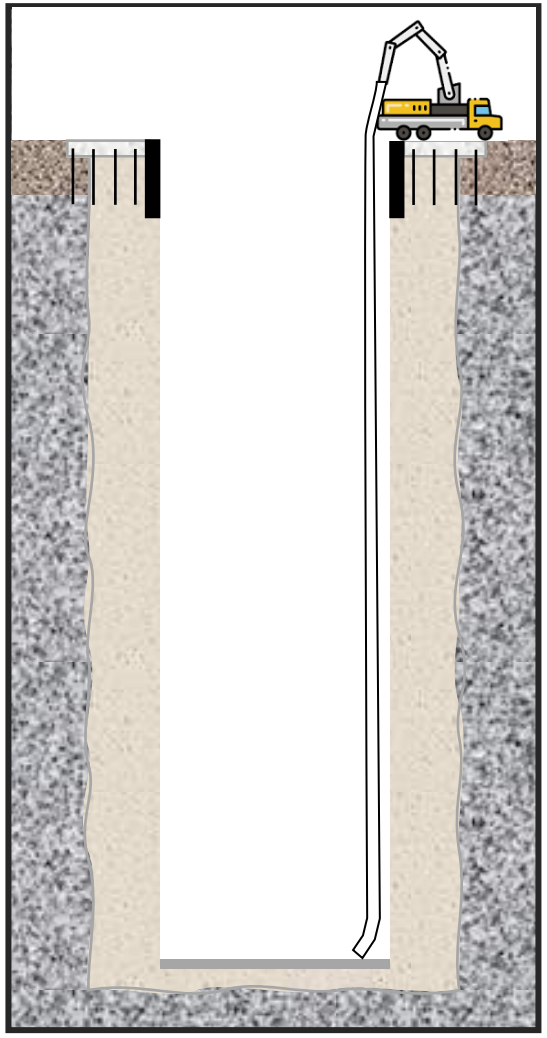
# **Lined Rock Shaft Construction** – shaft boring and finishing

2.3 Shaft construction

2.3 Survey shaft tolerances



2.3 Pour basal grout plug

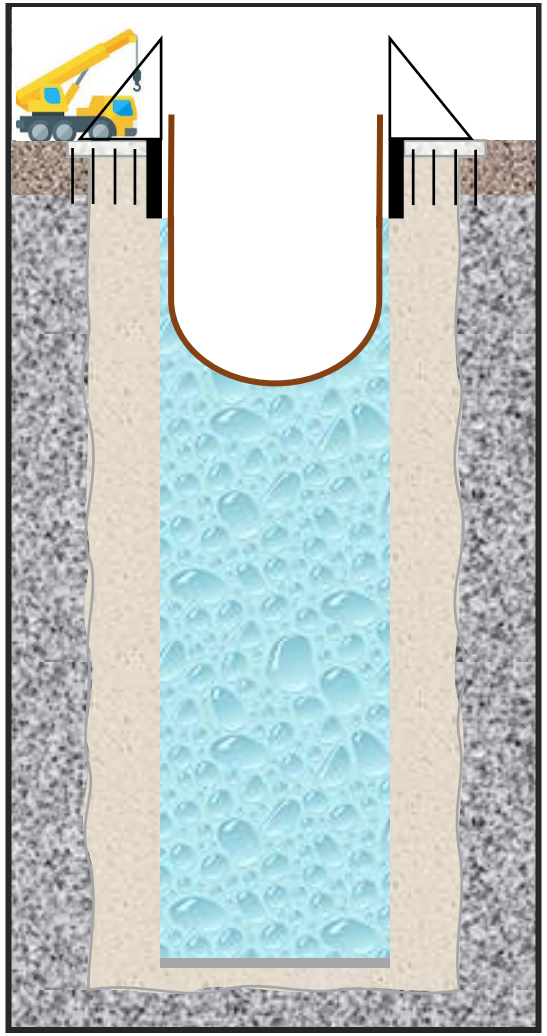


2.3 Flood completed shaft

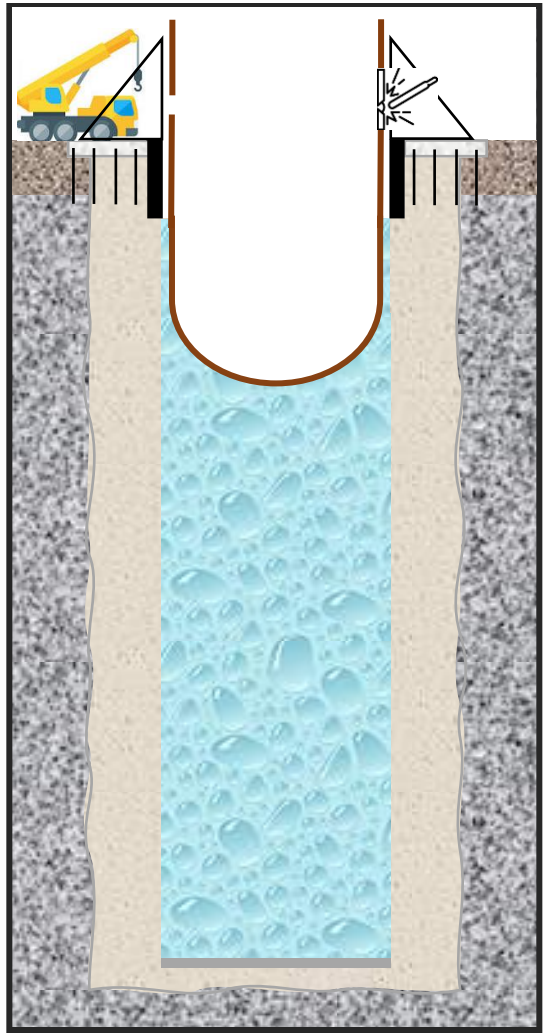
# **Lined Rock Shaft Construction** – temporary works and structural liner install

2.4.1 Temporary works installation

2.4.2 Structural liner install section 1



2.4.2 First external weld section 1 and 2



2.4.2 First internal weld section 1 and 2

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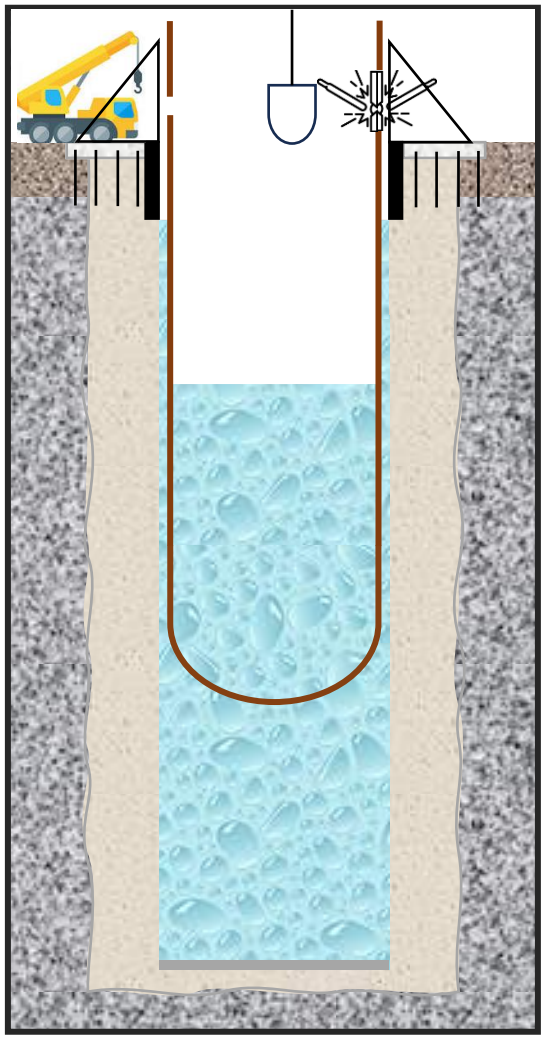
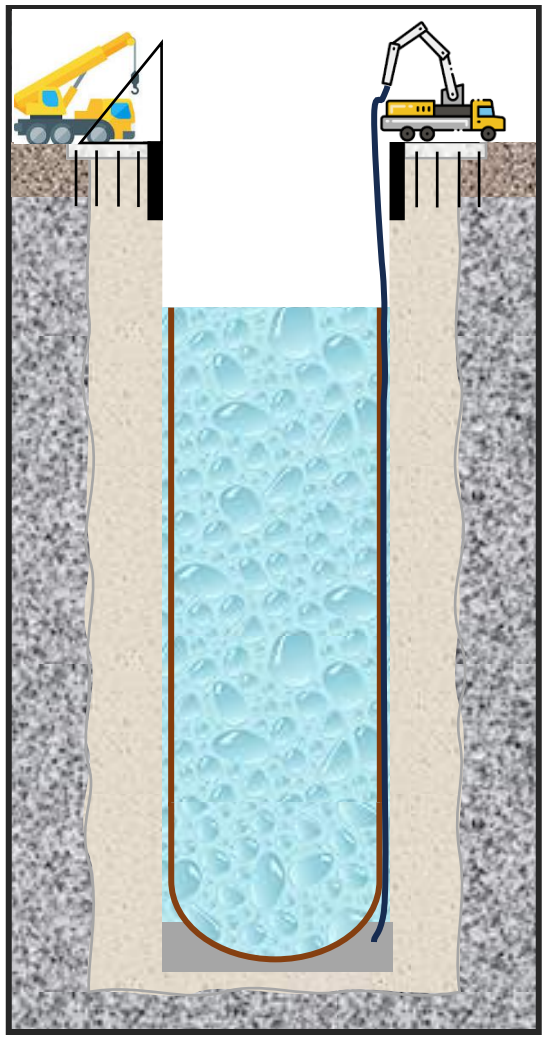
# **Lined Rock Shaft Construction** – structural liner finish, grout pour and GTL install

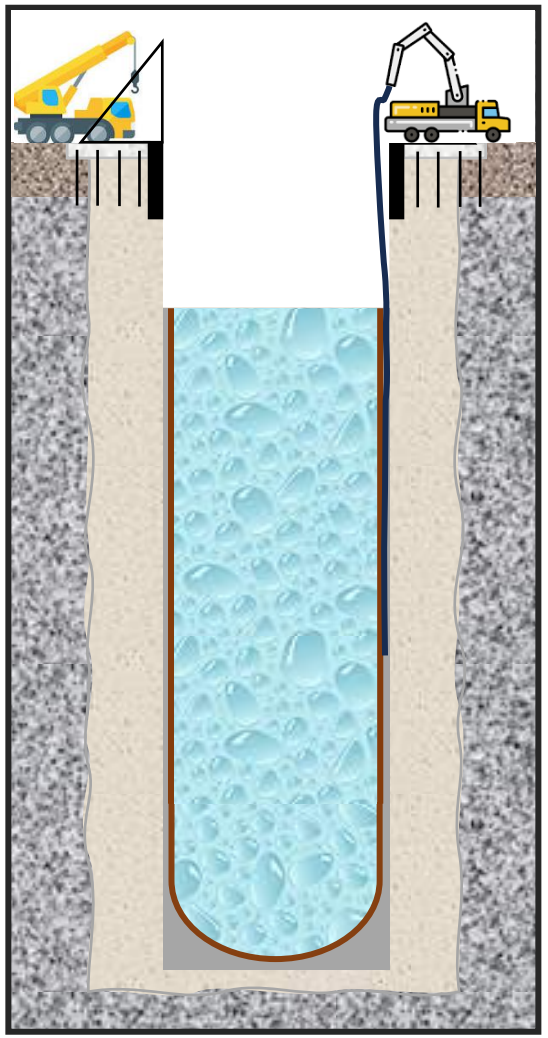
2.4.2 Second welds sections 2 and 3



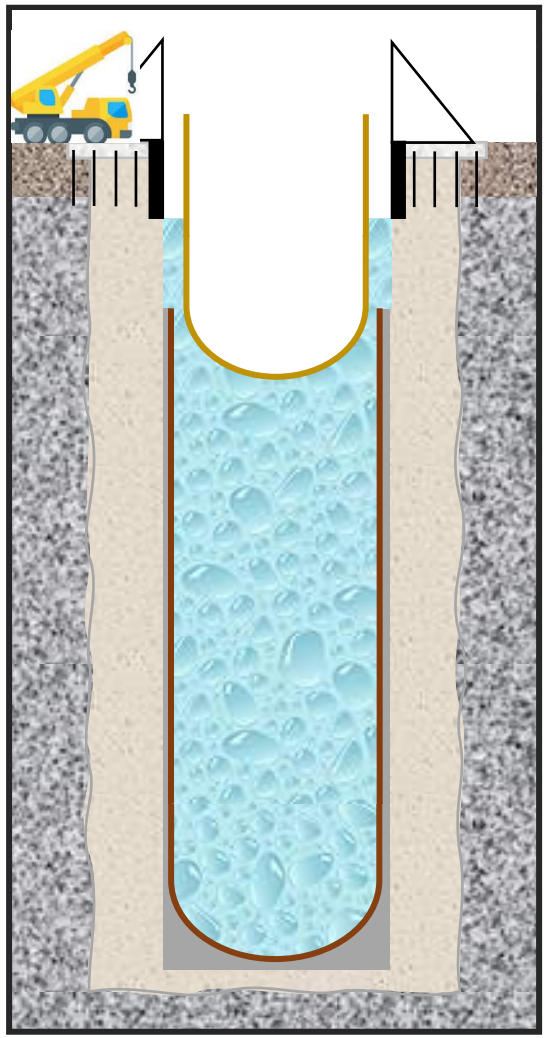
2.4.4 Grout anchor plug pour



2.4.4 Grout pour btw SL and rock mass



2.5 Gas tight liner (GTL) install section 1





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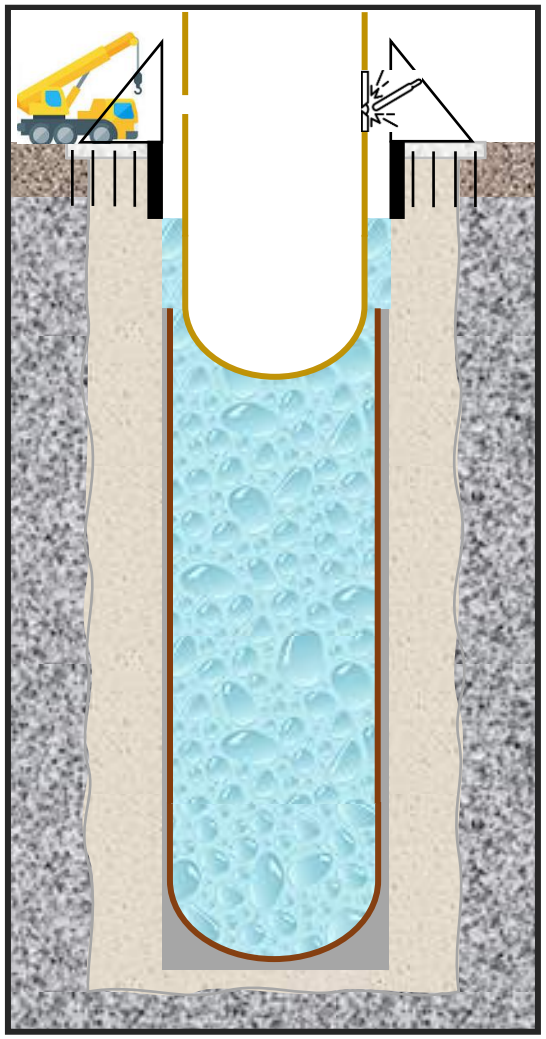
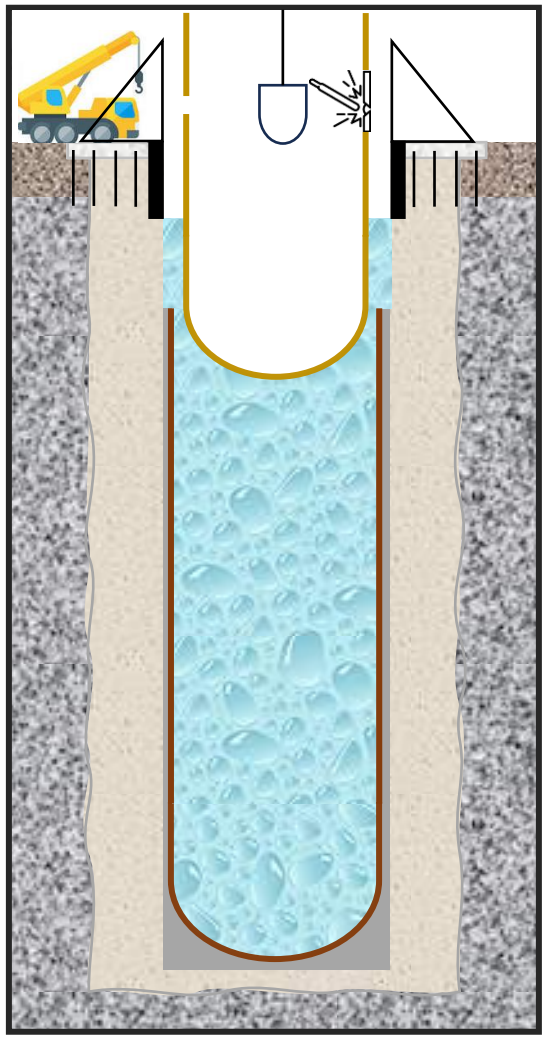
# **Lined Rock Shaft Construction** – gas-tight liner install

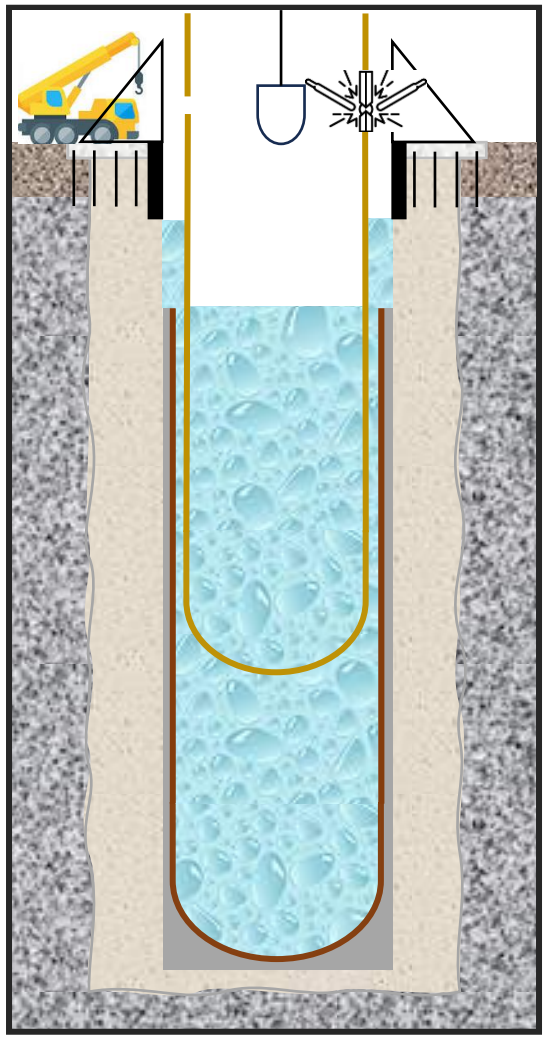
2.5 GTL first external weld sections 1 & 2



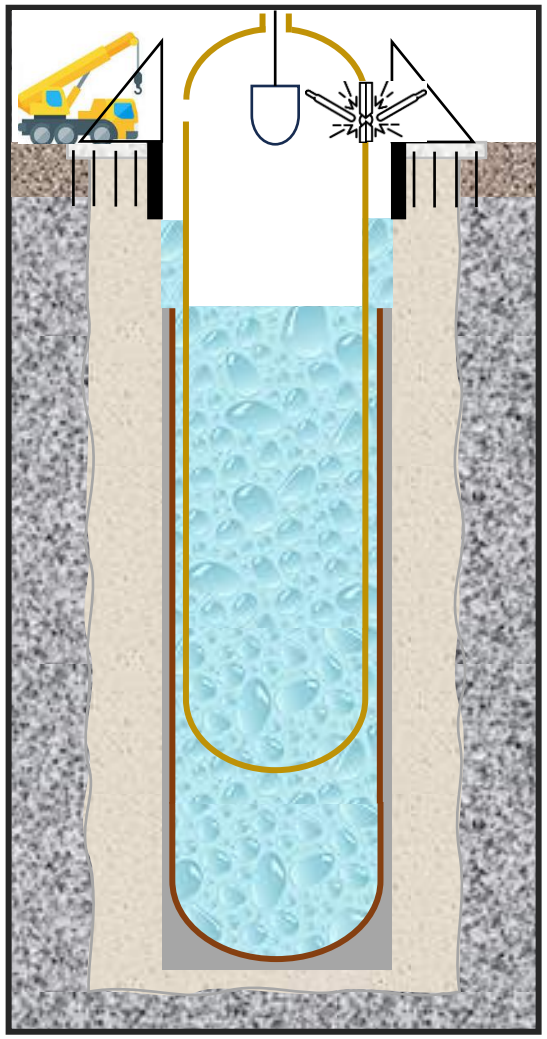
2.5 GTL first internal weld sections 1 & 2



2.5 GTL weld sections 2 & 3



2.5 GTL weld sections 3 & top-cap





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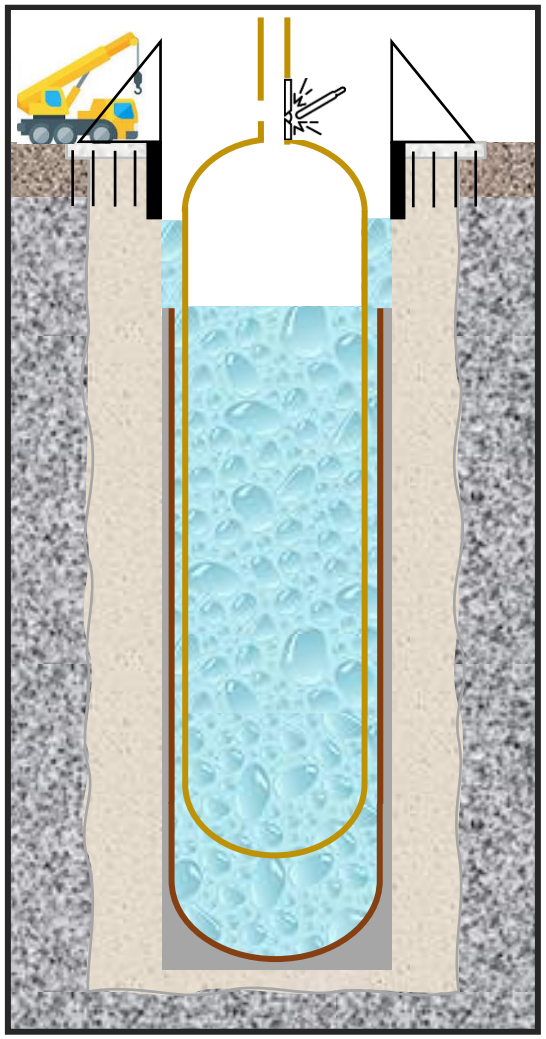
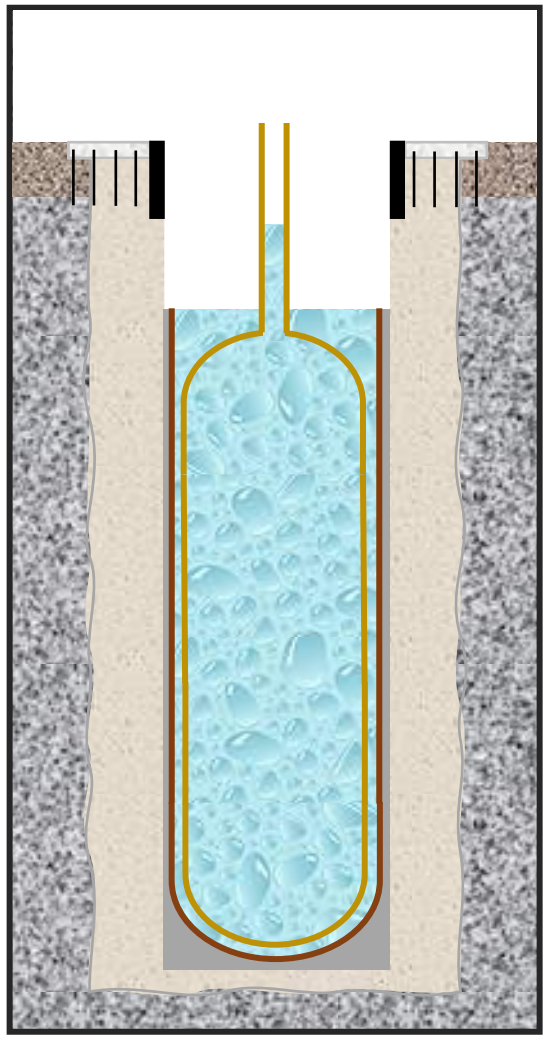
# **Lined Rock Shaft Construction** – GTL install and concrete

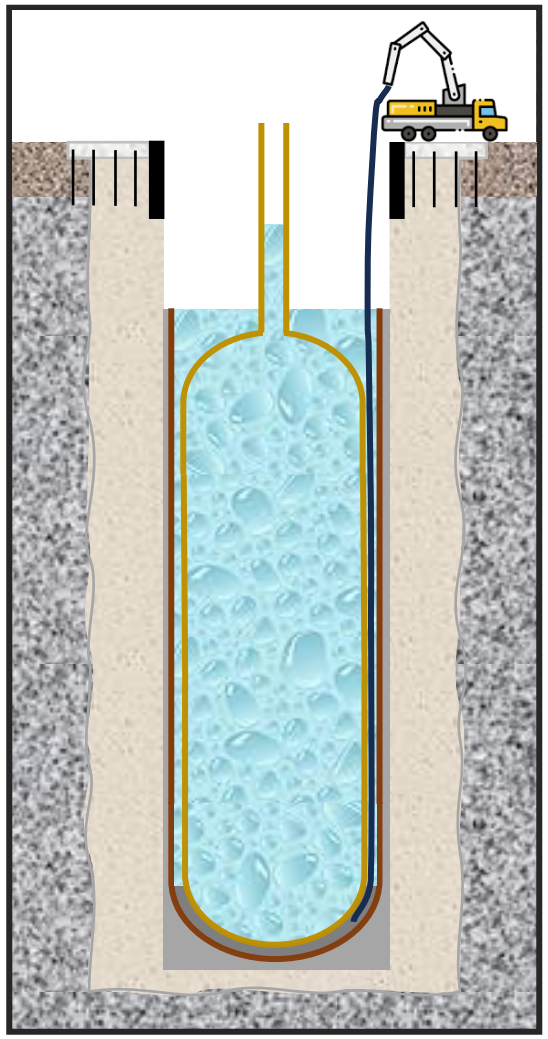
2.5 GTL top-cap and casing string weld



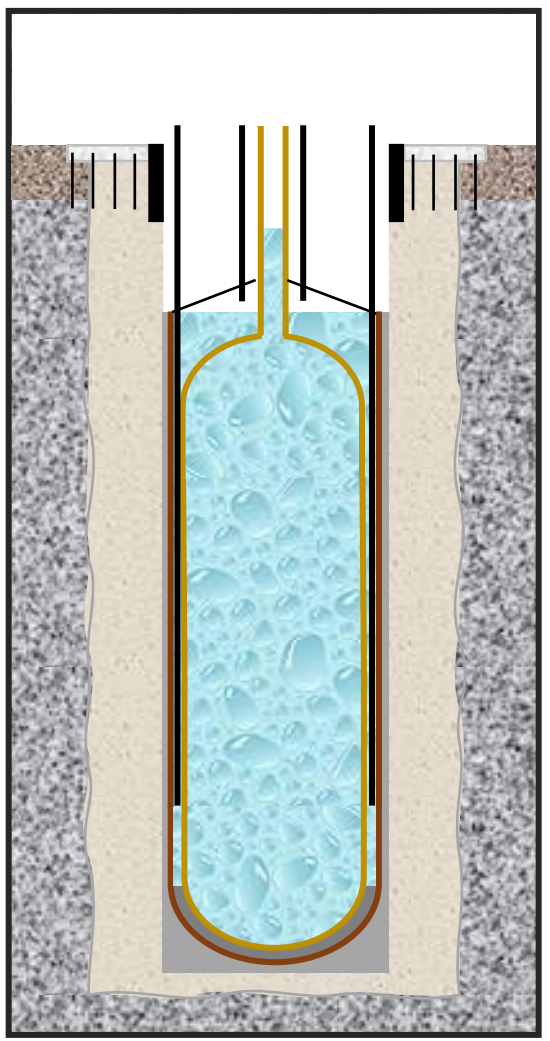
2.5 GTL (inc. casing string) fully installed



2.5 Concrete anchor pour to secure GTL



2.5 Install leak management





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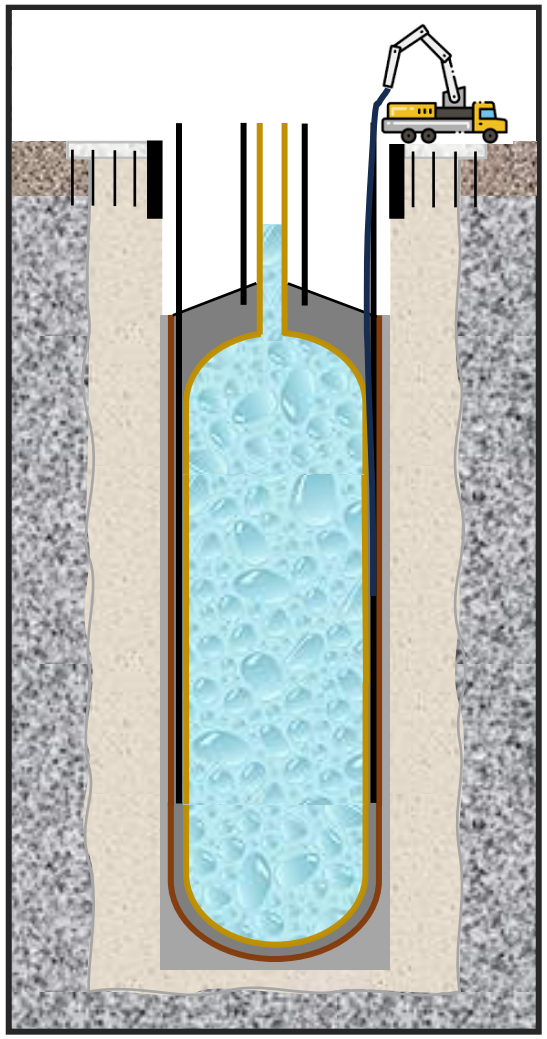
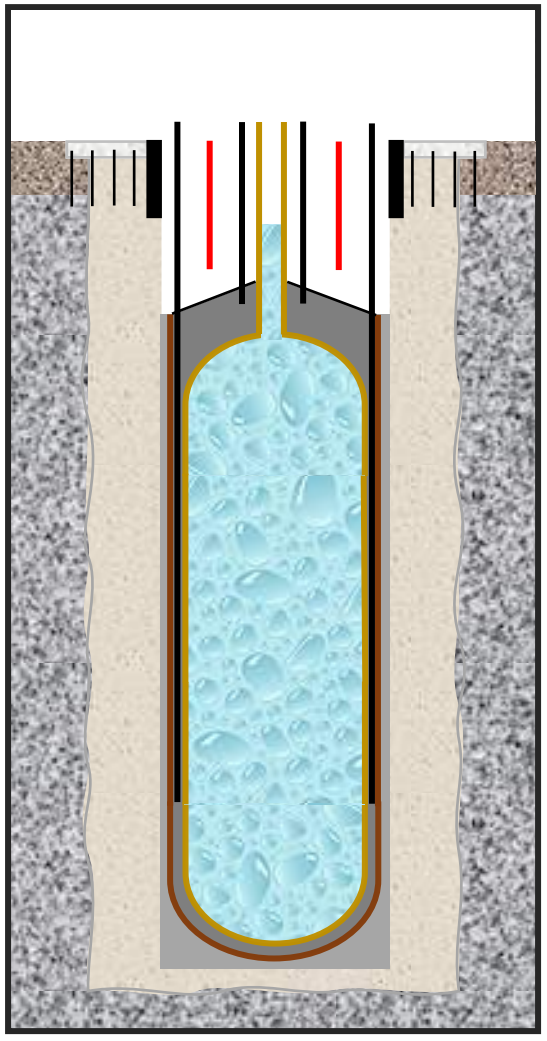
# **Lined Rock Shaft Construction** – Leak management and overburden

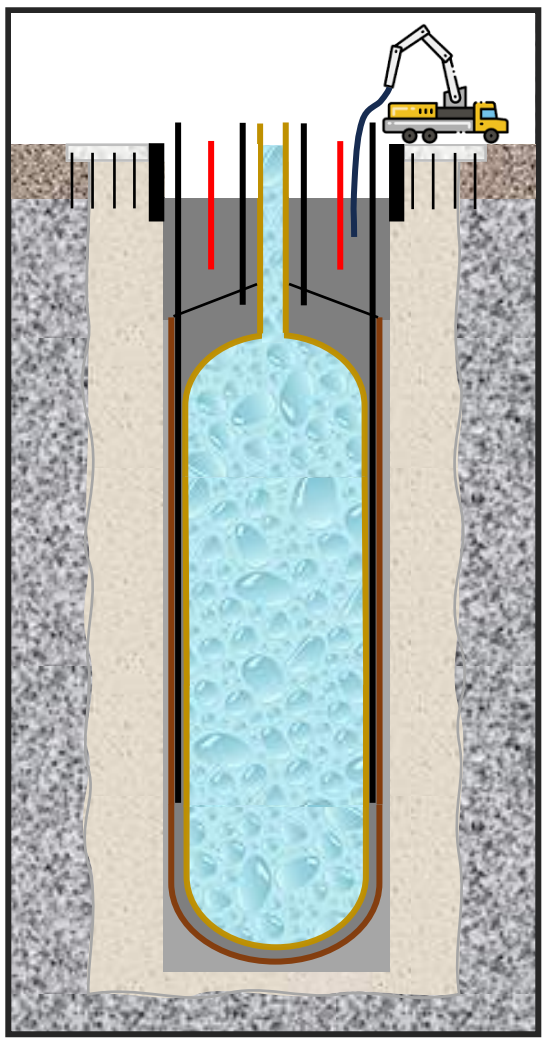
2.5 Finish concrete pour btw GTL & SL



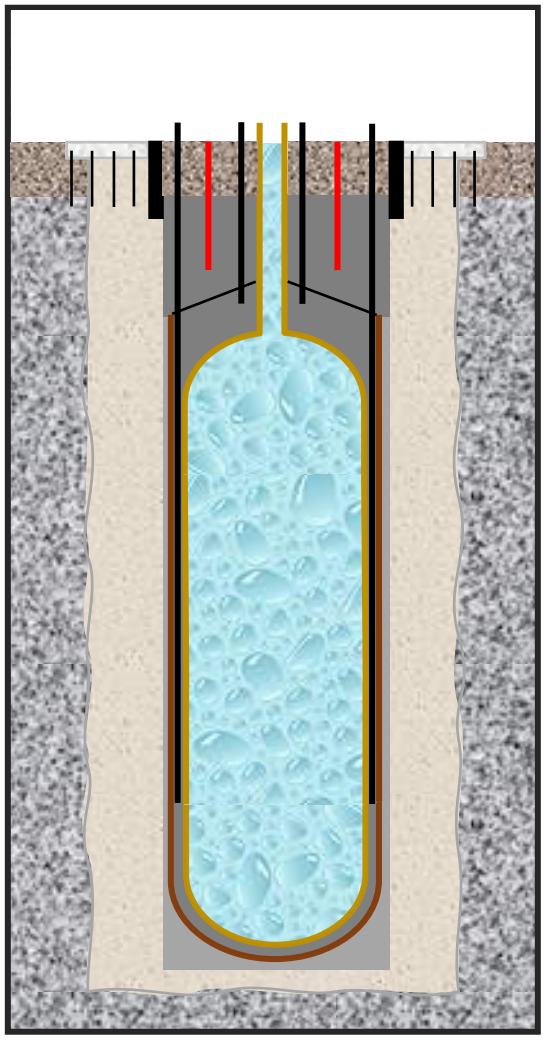
2.6 Install overburden geotechnical monitoring



2.6 Overburden install

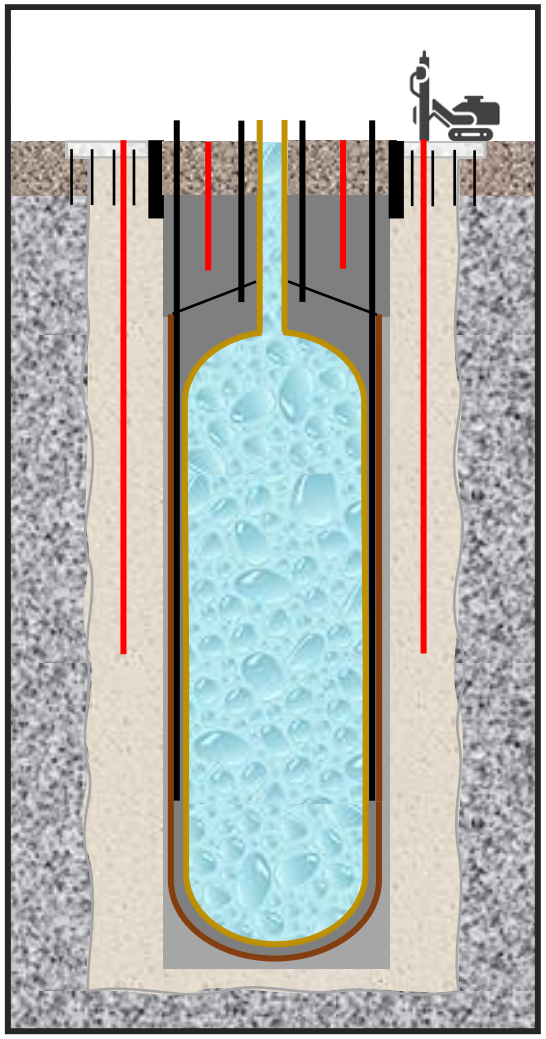


2.6 Reinstate superficials inc. topsoil

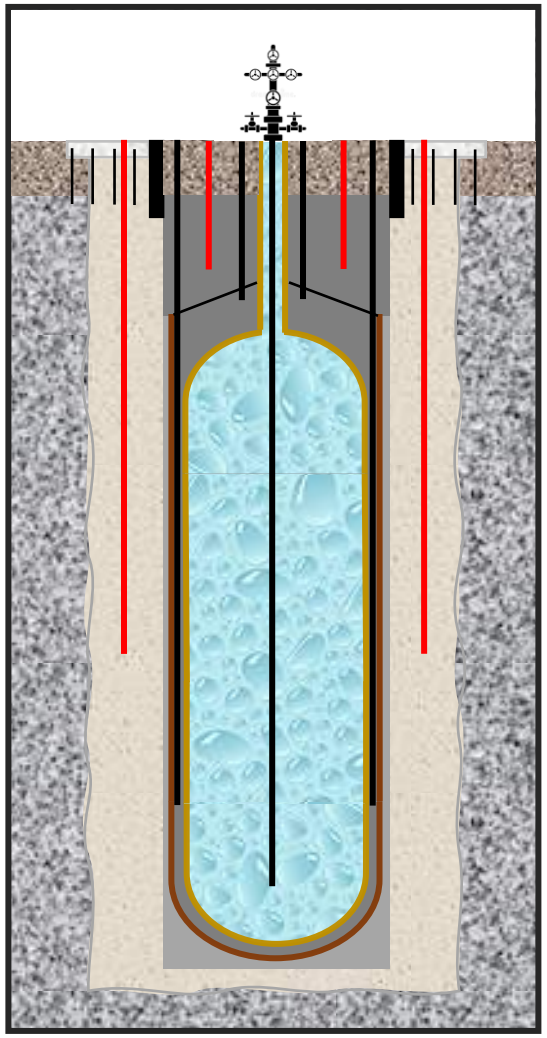


# **Lined Rock Shaft Construction** – monitoring and process equipment

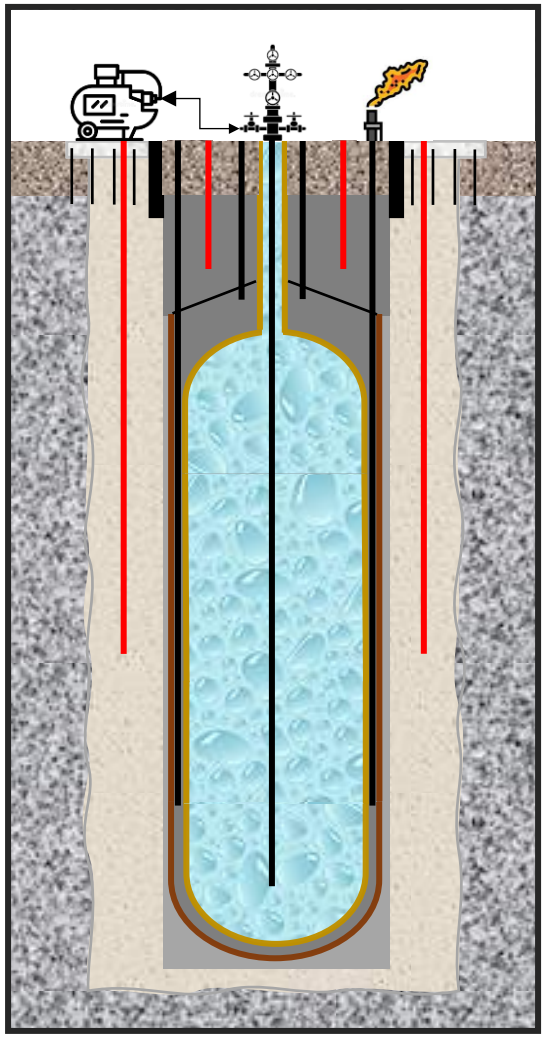
2.7 Install geotechnical monitoring



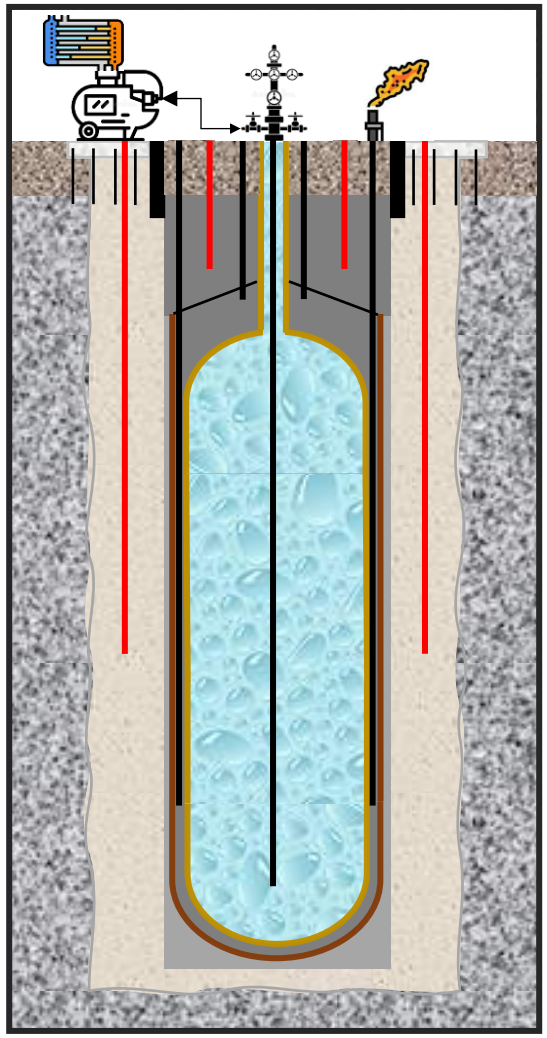
2.8 Install wellhead & injection tube



2.8 Install flare & compression/letdown



2.8 Install cooling/heating equipment





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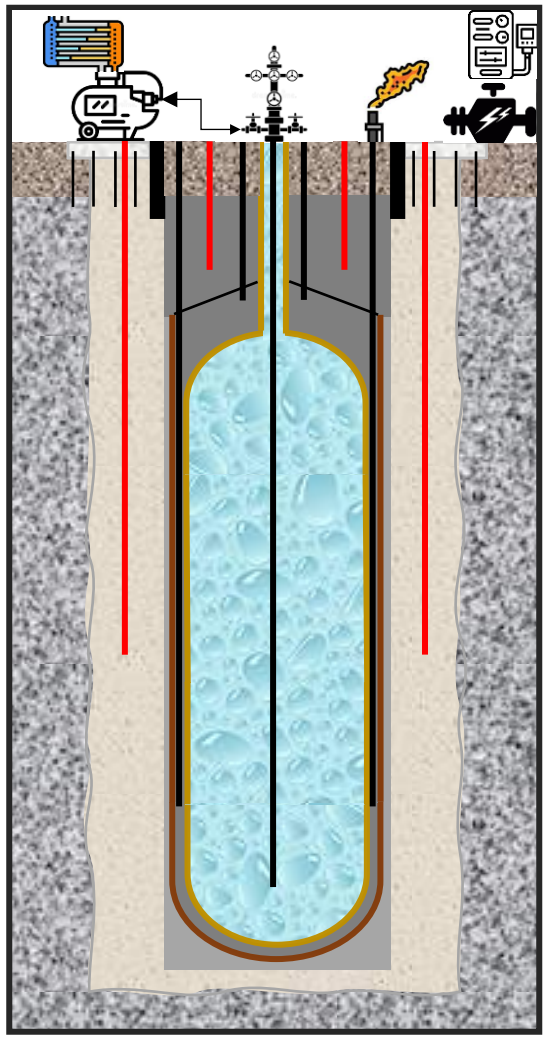
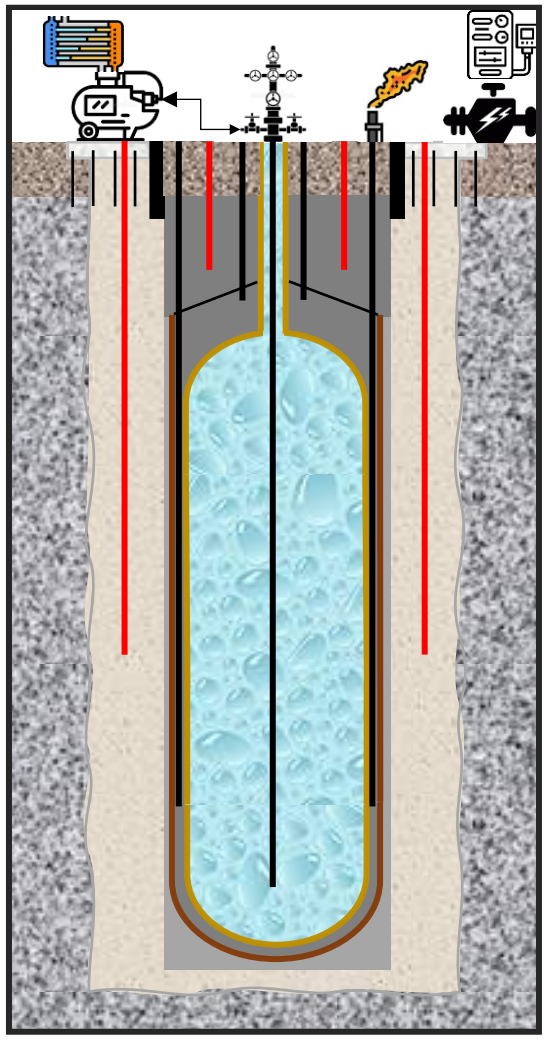
# **Lined Rock Shaft Construction** – Electrical, controls, and dewatering

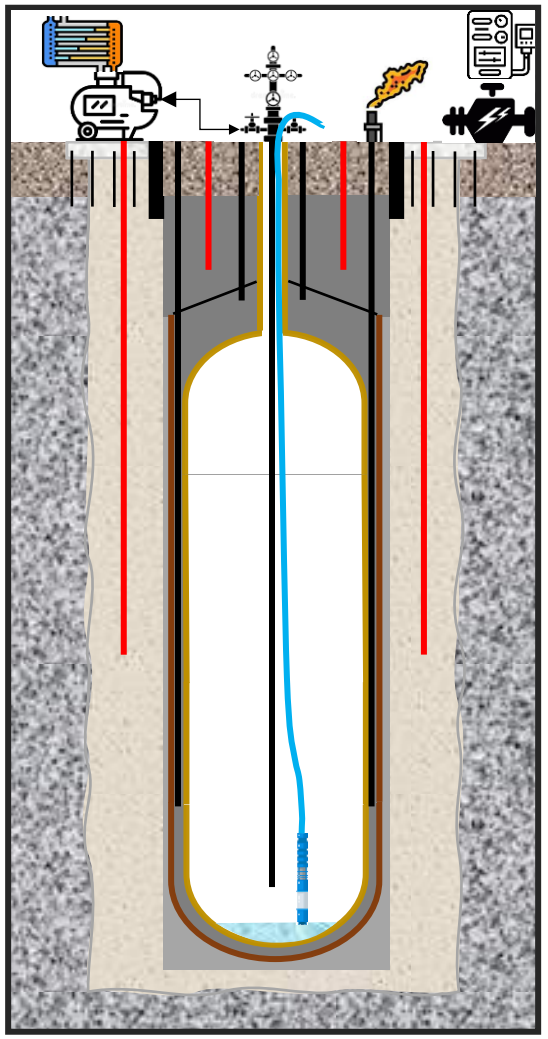
2.8 Control system & elec. connection



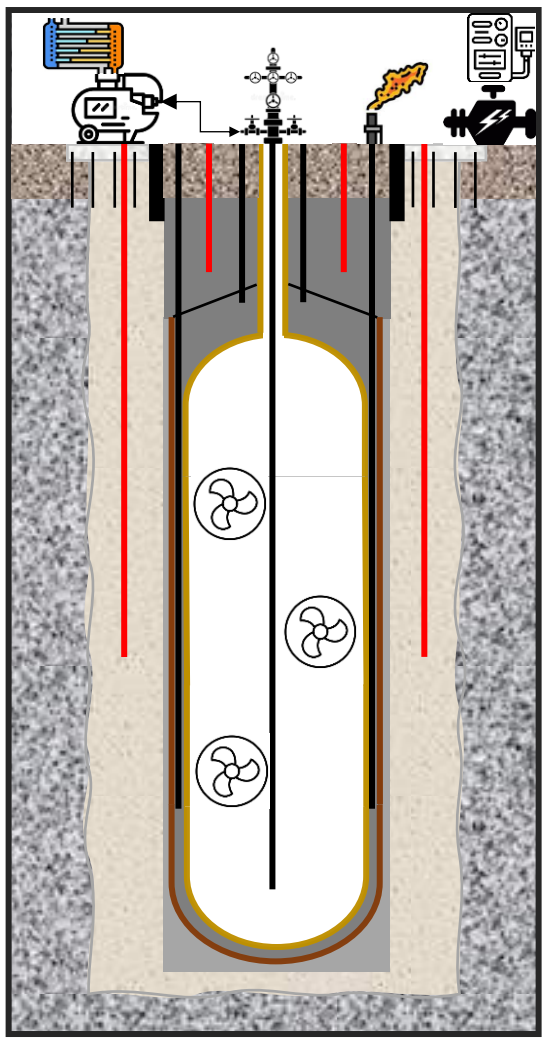
2.8 Commissioning & phase 1 testing



2.9 Dewatering (water pumping)



2.9 Dewatering (gas circulation)





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REPORT.

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# Ofgem SIF B-Linepack+

# Lined Rock Shaft – Construction Sequence

| REPORT DETAILS | | | |
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| Revision | Revision number 00 | Client Reference | |
| Author | Nigel Voaden | Issue Date | 06-Jan-2026 |
| Task Name | Construction Plan | Task Number | 106 |

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| Rev | Details of Changes | Page |
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## Executive Summary

Longitude Engineering, in partnership with National Gas, intend to deliver a technical demonstration of Lined Rock Shaft underground hydrogen storage. This partnership and project is funded by the Ofgem Strategic Innovation Fund.

The Lined Rock Shaft technical demonstration is a complex construction project with multiple stages, disciplines, and parties involved. Each stage needs to be satisfactorily completed in the correct sequence before the subsequent stage can commence. This Construction Sequence document, alongside the pictorial Construction Storyboard, provides a detailed description of the steps involved throughout the construction phase with reference also to the preceding fabrication and procurement stages. The document is correct according to the current level of design maturity, will form the basis for discussions with partaking third parties, and will be updated as the design matures and greater resolution and confidence in the methodology are obtained.

The planned demonstration site is the Aberdeen Energy Transition Zone's green hydrogen testing facility. Stage one of construction will prepare the site including safety and security, offices and welfare, access and parking and electrical connection to the on-site substation.

Pre-grouting of the rock mass is not expected for this project, shaft sinking will commence with any required concrete slabs for heavy equipment followed by collar installation through unconsolidated material. The main shaft will be excavated with a rotary piling rig fitted with a large augur drill bit. The shaft will be surveyed at regular intervals allowing for reaming and correction of verticality and other tolerance issues.

Once complete, the shaft will be filled with fluids and a temporary structure to support installation of the liner sections will be constructed. The outer structural liner sections will be welded together in turn and slowly descended to the base of the shaft before the annulus between the liner and shaft is grouted. The inner gas-tight liner and casing string will be installed in the same way as the structural liner following which the leak management system will be positioned before the annulus between the structural and gas-tight liners is filled with concrete.

An overburden plug comprised of concrete will be poured over the installed liners setting the casing sting and leak management system in place. Superficial soil and/or rock and topsoil will be reinstated on top of the overburden to complete the sub-surface containment. Geotechnical monitoring equipment will then be installed in the surrounding rock mass adjacent to the containment. Finally, processing equipment, control systems and power units, and instrumentation will be emplaced on surface and interconnected.

Construction is expected to be completed within 12 months allowing for four weeks of hydrotesting and subsequent dewatering of the system. Longitude will act as EPC for the fabrication, procurement, and construction phases. A robust procurement process will be adopted with competitive tendering and quantitative comparison before selection. Preferred suppliers for design, materials, fabrication, and construction are however already identified and in most cases have been supporting the project for considerable time already. The critical path for the fabrication and construction is the gas-tight liner due to lead times on the specialist steel required from the sole supplier.

This document provides a reasoned and detailed approach to the construction of the Lined Rock Shaft demonstrator which provides significant value to the technical understanding of the project and a basis which can be built upon with collaborating partners as design maturity increases.

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# 1.0 Introduction

## 1.1 Scope and Purpose

This document provides details of the proposed construction sequence for the Lined Rock Shaft (LRS) hydrogen storage system technical demonstration. This will be completed as part of the Ofgem SIF-funded B-Linepack+ project led by National Gas Transmissions (NGT). The document also outlines the proposed procurement and fabrication strategy for the demonstration. The intended site for the demonstration is the green hydrogen testing facility owned by Aberdeen Energy Transition Zone (ETZ). This document should be read in conjunction with the LGG-L057401-R06 Construction Storyboard to which it adds written commentary and further details. The numbering system of figures in the storyboard corresponds directly to this document.

## 1.2 Reference

[1.] *LGG-L057401-R06-Rev00 Construction Storyboard*

[2.] *LGG-L057401-R02-Rev00 EC&I Design Note*

[3.] *LGG-L057401-R09-Rev00 Geomechanical & Structural Design Note*

## 1.3 Abbreviation

*Table 1: List of abbreviations*

| | |
|---|---|
| ***LRS*** | *Lined Rock Shaft* |
| ***GTL*** | *Gas-tight Liner* |
| ***ETZ*** | *Energy Transition Zone (Aberdeen)* |
| ***DFOS*** | *Distributed Fibre Optic Sensing* |
| ***JGL*** | *Joseph Gallagher Limited* |
| ***EPC*** | *Engineering, Procurement, and Construction* |
| ***NDT*** | *Non-destructive Testing* |
| ***ECA*** | *Engineering Critical Assessment* |
| ***A2AM*** | *A-squared Advanced Monitoring (LTD)* |

# 2.0 Lined Rock Shaft Construction Sequence

## 2.1 Site preparation

Before construction can begin the site will require preparation. This stage is not depicted in the storyboard but will include several elements as follows.

### 2.1.1 Security

Temporary fencing e.g. Heras fencing, may be installed around the entire site to facilitate both security and safety against unauthorised access. Further security measures such as cameras, motion sensors, security staff etc. will be specified following detailed site assessment.

### 2.1.2 Safety

All required signage, barriers, segregation, pedestrian and plant routing, unauthorised areas, vehicle parking etc. will be installed based on detailed safety planning. Hazardous area zoning may be required, and may vary

depending on the phase of construction and the specific ongoing activities. This will be assessed in advance and implemented as required.

#### 2.1.3 Grid Connection (Electrical)

A 0.5MW import connection is required for the construction and operation of the technical demonstrator. The connection needs to be available at the start of site preparation to facilitate subsequent stages. Current understanding is that a new substation will be installed at the site by the ETZ and this project's requirements will be considered during the sizing of this.

#### 2.1.4 Offices and Welfare

Office and welfare units will be installed as required and will be appropriate to the level of staffing on site.

#### 2.1.5 Site Setup

Laydown areas will be appropriately located and established, parking areas will be defined with appropriate signage. Depending on ground conditions there may need to be temporary upgrades to the site for safety and logistical purposes. This may include the addition of hardcore, matting for vehicles and plant to move around and concrete slabs (with or without piling) for heavy plant such as cranes and a piling rig to be situated. Ground conditions will only be fully established once penetrative site Ground Investigation (GI) studies and associated laboratory testing are completed before detailed design. Note that GI will be conducted as a discrete activity *c*. 8-10 months before construction begins.

### 2.2 Ground Preparation and Pre-collar

Ground conditions can be broadly subdivided into two categories; competent rock mass and an overlying superficial layer comprising unconsolidated soils, rocks, and sediments.

Detail of the shaft construction will be finalised once GI has been completed and ground conditions are best understood. The following is an example of the likely sequence based on current understanding.

#### 2.2.1 Pre-grouting

Pre-grouting of the ground is designed to stabilise and upgrade the superficial deposits and rock mass and render the rock mass impermeable so that drilling fluids are retained. This will be standard practice for full-scale LRS systems for which the shafts will be sunk using a blind boring or reverse circulation method. For the purposes of the technology demonstrator, a rotary piling rig is the intended equipment and methodology for the shaft construction. Based on currently available information, the ground conditions at the demonstration site are believed to be relatively favourable and, combined with the relatively shallow depth of the demonstrator, it is less likely that pre-grouting will be required.

However, if pre-grouting is required, it is achieved by drilling narrow diameter diamond core holes to a depth just beyond the planned final shaft depth and pumping low-viscosity grout into these. The total number, density, and pattern of grouting holes will be defined by the results of GI, and may be increased depending on how the grouting of the initial holes responds. The grout will spread through fracture networks in the rock mass and superficial layer before setting. Once set, the rock mass will be significantly strengthened and upgraded, the primary function of this is to support the shaft construction process but there may also be some associated benefits to the completed LRS. These are however unlikely to be relied upon or reflected in the design as they will be difficult to quantify with confidence.

#### 2.2.2 Pre-sink and Collar

Surface foundation slabs may be installed at this stage to support the plant for the main shaft sinking, these may require piling, but the detailed design of these is dependent on the results of the GI.

Topsoil and the rest of the superficial layer will be removed and stockpiled separately for reinstatement once construction is completed.

Once again, until GI has been completed the details of this stage cannot be finalised, but it is likely that a pre-sink and collar will be required to stabilise the upper portion of the shaft ahead of the main shaft sinking operations. This is because in most locations there is an overburden of unconsolidated material before competent rock mass is reached. The depth at which competent rock is reached can vary significantly but currently it is expected to be approximately 5m at Aberdeen ETZ. Construction of the collar may be through vibratory or oscillating techniques typical of driven tubular steel piles and using a single section of tubing (Figure 1).

*Figure 1: Vibratory/oscillating unit driving temporary outer casing through superficial deposits*

## 2.3 Shaft Sinking

Before shaft sinking commences the drill rig and ancillary equipment will be set up, this may include equipment for recycling fluids if required which in turn includes equipment for separation and drying of sediments.

The shaft itself will be constructed using a rotary piling rig (e.g. Bauer BG45 or equivalent see Figure 2) with a large drill bit and a long Kelly Bar fitted to ensure that required diameter (2.5m) and depth (47m) are achieved. The aim is to construct the shaft dry but this will depend on the specific ground conditions. It may be necessary to flood the shaft during construction so that the hydrostatic pressure from the contained fluid supports the unlined shaft walls. This will also prevent ingress from any pressurised groundwater that may be intersected. Depending on the specific characteristics of the ground conditions encountered, additives may be introduced to the water in the shaft, these are typically benign and environmentally-friendly but occasionally e.g. bentonite may be required to provide additional stabilisation if ground conditions are very poor.

*Figure 2: Large diameter piling rig*

The shaft will be drilled in stages and after each stage the shaft will be surveyed to verify it remains within tolerances for verticality, ovality, and straightness, otherwise it will be reamed and recentred to correct before proceeding to the next stage.

If the shaft is drilled under dry conditions cuttings can be largely removed by lifting the auger drill bit back to surface, those that fall to the base of the shaft can be returned using compressed air circulation or vacuum suction. If the shaft is drilled under flooded conditions cuttings from the drilling will be pumped to the surface as a slurry where they will be separated from the fluids which can be recycled back to the shaft for reuse. Cuttings will be dried and if possible then used in a nearby construction or landscaping project where benign fill material is required, or otherwise taken to landfill for disposal in accordance with regulations.

Once tolerances from the final stage of drilling have been achieved, the base will be cleaned of cuttings and a basal grout plug will be poured using a self-levelling grout, the grout may also be reinforced. The rotary piling rig and ancillary equipment will be removed from site and if the shaft was constructed in dry conditions it will now be flooded to preserve stability and assist with the next stages.

## 2.4 Structural Liner Installation

The first stage of the installation of the LRS is the Structural Liner, but before this can commence temporary works are required to facilitate.

### 2.4.1 Temporary Works

The structural liner will be comprised of three sections, these will henceforth be referred to as ‘cans’. As the technology demonstrator has an external diameter of 2.5m, the liner cans will be road transportable in terms of width, length, and mass, therefore longitudinal welds will be completed in the factory. Site welding will thus be restricted to circumferential welds joining the cans together, end to end. Nonetheless these will be technically challenging welds and the cans must be supported vertically both within and above the shaft with safe access to the joint provided in a weatherproof environment. The temporary works to achieve this have yet to be finalised but will feature clamps to hold the cans securely in place ensuring they are both vertical and straight. Temporary alignment plates and flanges welded to each can will likely be used to assist with alignment, these can be burnt off once welding is completed. A tent will be erected over the temporary works with a weatherproof seal fitted against each can in turn. The tent will likely be constructed of a space frame and a tensile, coated membrane. The tent will be positively pressurised to create a clean, controlled environment which is integral to the weld quality and will also provide a safe and comfortable working area. There will be a structure that can be lowered

inside the cans to complete double-sided welding. This will feature a basket or similar that will be suspended via a cable that once in position will be fixed in place to provide a stable working platform for the welder and their equipment.

### 2.4.2 Structural Liner Installation

The ends of the three cans forming the Structural Liner will be matched at the fabricators to ensure best fits for the welded joints and the sequence preserved for the installation at site. The first can forming the Structural Liner will be the bottom one and as such this will come pre-welded with a hemispherical end. Temporary lifting points will be welded to the can by the fabricators and these will be used to lift and vertically lower the first can into the shaft using a large crane(s). As the shaft will be full of fluid at this stage the can will be buoyant, clean water will be slowly added to the inside of the can so that it is gradually lowered into the shaft, displaced fluids will be pumped out from the annulus between the Structural Liner and the rock mass. Alignment will be key to ensure it does not snag the shaft walls, temporary guides may be attached to the outside of the can to ensure it remains centralised. The mass of the liner will be measured throughout the process as this will provide an indication if it has collided with the shaft wall. Descent of the can will halt when the top of the can is protruding above surface at an appropriate height for welding . The can will be held in place using wedges between the liner and the shaft wall, and/or using horizontal clamps.

The next can will be introduced vertically above the first can, lifted by cranage, and then clamped in place using horizontal clamps when the correct positions have been achieved. Clamps will need to be adjustable to make the fine adjustments required to achieve alignment. It will be critical that the cans are well aligned before welding commences so that the joint is flush. The cans will then be welded together, details of which can be found in LGG-L057401-R09 Geomechanical & Structural Design Note. Welds will be subjected to non-destructive testing and inspection with any remediation work subsequently undertaken before the two weld-jointed cans will be lowered into the shaft by further introducing fluids inside until the top of the second can reaches the appropriate height for welding. The weld of the second and third (final) cans will then be completed. The final assembly of the Structural Liner will be descended fully to the bottom of the shaft to rest on the pre-poured grout plug (see 2.3). During this process it will remain under careful control to ensure its final resting place is centred with a uniform width external annulus.

### 2.4.3 Monitoring Equipment

Distributed fibre optic sensing (DFOS) for strain and temperature measurement together with localised strain gauges and temperature sensors will be installed on the outside of the Structural Liner (and the GTL). These will be installed in the factory and arrive on-site as part of the Structural Liner can assembly ready for construction. Monitoring equipment associated with each section of can will be mostly independent however vertical arrays will need to be joined together after each weld join has been completed.

### 2.4.4 Grout Pumping

The annulus between the rock mass and the Structural Liner will be filled with grout using a tremie pipe which will be retracted as the grout level rises, grout will be introduced below the level of the fluids throughout to minimise the risk of voids developing. Multiple tremie pipes will be available to ensure redundancy should blockages in the pipes occur. Free falling grout should be avoided to reduce the risk of settling and separation. The height of the pour will be measured throughout to avoid overspill. Material properties will be monitored during the pour as will the quantity of grout delivered and the position of the liner to ensure that it does not move. Grout pumping will be undertaken very slowly or in stages to minimise buckling stress on the Structural Liner due to a pressure differential between fluids on the inside of the liner and grout on the outside. The first stage of the pour will be to create an anchor plug to secure the Structural Liner. Grout will displace fluids from the annulus which will be captured, cleaned, and disposed according to regulations (or recycled for further site use). Once the annulus is fully grouted the Structural Liner installation is complete.

## 2.5 Gas-tight Liner Installation

Much of the installation of the GTL is similar to the procedure for the Structural Liner. The temporary works and lowering of cans will be the same. There may be some variation in the welding methodology as the GTL is stainless rather than carbon steel. It will be imperative during lowering of the GTL that it does not impact against

the Structural Liner. Temporary guides may be added to the GTL cans to assist with centring the assembly during installation, alternatively fenders or similar could be lowered into the annulus and suspended from the temporary works, these would be simply recoverable after the installation is complete. The mass of the GTL will be monitored throughout the install as this may provide indication of collision . This is a last-resort mitigation and a non-preventative barrier.

Clean water is paramount for sinking the GTL to minimise contamination of the gas chamber. This may involve cleaning of fluids used for the Structural Liner install, or use of fresh water, and will depend on factors such as the ease and cost of fluid cleaning versus the availability and cost of sourcing fresh water.

The top hemispherical end of the GTL will likely be delivered to site with the interface to the casing string already connected (factory-welded joint). The final weld will be the casing string to the top of the GTL hemispherical end. Upon completion of this weld the final lowering of the GTL can be completed.

The GTL will be lowered to a position such that the annulus between it and the Structural Liner is a uniform width including between the hemispherical ends at the base. Once in position the GTL will be held securely in place.

Monitoring equipment installed on the outside of the GTL will be similar to that installed on the Structural Liner but will extend to cover the hemispherical top cap. This will again be installed at the factory with equipment attached to each can. There will be some vertical fibre optic cable joins to make on-site after each welded join of cans is made. Additionally DFOS strain and temperature measurement will extend up the length of the casing string alongside further localised strain gauges and temperature sensors.

Concrete will be poured to fill the annulus between GTL and Structural Liner at the base, this will then be allowed to cure and will secure the GTL in place. Free falling concrete during pumping should be avoided as concrete is at a higher risk of settling and separating than grout.

Next two dosing pipes (for helium testing) will be installed in the annulus between the Structural Liner and the GTL.

A perforated gas-collecting pipe and vent pipes (forming the leak management system) will also need to be emplaced ahead of the final concrete pour as will a gas-tight membrane that will cap the concrete. These may form a single connected structure that will be lowered into the shaft. Holes will be left in the membrane to insert tremie pipes for concrete pour and allow fluids to escape.

The remaining void between the GTL and Structural Liner will be filled with concrete to the membrane cap displacing remaining fluids. At this point the LRS is fully in place, but the GTL remains filled with fluids.

All temporary works, cranes etc. provided for the liner welding and installation can now be removed from site.

## 2.6 Overburden Installation

The overburden forms a plug to resist uplift for containment pressure, it will consist of a concrete pour filling the void above the containment to the base of superficial deposits. The remaining space will be backfilled with stockpiled superficial deposits and top soil. There may be some additional complexity to the design which depends on the findings of the GI. The installation sequence and method for these will be defined once a detailed design is completed. Due to the height, the overburden concrete pour will be completed in multiple stages. Tremie pipes or similar will be required and freefall of the concrete must be avoided to prevent separation. Settlement cells, which will measure vertical displacement and form part of the monitoring system, will be embedded within the overburden and must be emplaced before the concrete pour begins.

Note there will be the casing string, dosing pipes, vent pipes, as well as the settlement cells already in place before the overburden is installed so care must be taken during the pour to ensure these are not damaged.

## 2.7 Monitoring System

The monitoring system will capture the characteristics and behaviour of constituent parts of the LRS including the Structural Liner, GTL, casing string, concrete, grout, overburden, and surrounding rock mass. Instrumentation will be placed at strategic points to capture data and some of these have already been outlined in sections 2.4.3, 2.5, and 2.6. Following completion of the overburden pour there will be a borehole extensometer together with piezometer and thermistor strings installed in narrow diameter boreholes in the rock mass immediately adjacent to the LRS. These should be emplaced as close as possible to the lining without risking damage during the drilling. Directional drilling may be required to enable this.

## 2.8 Process Equipment Installation

With all sub-surface installation complete, the process equipment can be installed. Firstly the injection tube will be installed. This will be pre-fitted with an internal safety valve and an external annular safety valve for the production tube. These valves will be operated by hydraulic control lines which will run to surface. Next the wellhead will be installed and connected to the production and injection tubes. The compression and expansion equipment, and recirculation cooling/heating equipment will be sited on surface according to design and interconnected including to the wellhead. All required valves, flow control, and instrumentation will be installed as part of this process. Process equipment will include venting and flaring which will be connected to the leak management system. Finally, the control system/PLC, power management system and electrical connections will be completed.

Most of the equipment used in the construction that still remains on site at this point can now be removed. The system will then be commissioned and the first phase of testing undertaken whilst it is filled with water before the final stage of the construction sequence.

## 2.9 Dewatering

The first phase of testing will be completed using water but the second phase involves testing with gas. Therefore the system must be dewatered before the second phase can start. Water must be fully removed to prevent corrosion of the system and to meet hydrogen purity requirements.

The bulk of the water can be removed using an appropriately sized borehole pump lowered through the casing string. The pump must have sufficient head to pump the water vertically upwards from the lowest point below ground level of the system, and it must be narrow enough to fit down the casing string past other installed equipment. There are numerous borehole pumps available that will achieve these requirements. There is however a minimum depth of water required for such pumps to operate, typically around 1m and so at the end of pumping *c*. 1m water depth will remain inside the GTL.

Some of the remaining water can be removed by applying pressure to the containment and pushing it out through a tube. The tube must be fitted with a non-return valve at the end, lowered to the bottom of the water, and a pressure of *c*. 8-10bar applied. If well executed this should reduce the remaining water to just a few tens of litres at which point the tube would be lifted out of the tank.

The final removal of water will be through circulation of gas, if the gas is dry and warm it will evaporate the water allowing it to be returned to surface where it can be condensed (allowing the gas to be recirculated) or vented. Under default atmospheric conditions evaporation will be slow but by heating the water to 40$^{o}$C and the gas to 50$^{o}$C, and circulating the gas at 20m/s the rate can be improved by at least an order of magnitude and it will take only a couple of days to dry the tank according to the design requirements.

All water will be disposed of according to permits and regulations.

## 2.10 Site Demobilisation

Any remaining equipment brought to site for the construction phase can be removed at this point leaving only that which is required for the testing phase. Site demobilisation will be an ongoing process from the completion of the GTL installation (2.5). Any temporary platforms constructed for the installation will be removed and additional restoration of the site in line with site owner and/or planning requirements undertaken.

## 3.0 Construction Schedule

Table 2 provides an overview of the planned construction schedule which is expected to be completed within 12 months. This allows for a pause of 33 days towards the end of the schedule to complete pressurised hydrotesting of the system.

There is overall *c*. 20% time contingency to allow for unforeseen delays due to e.g. technical challenges, weather etc.

Scheduling appropriate to the dimensions and construction methodology of this shaft is well-understood from historical discussions with experienced contractors. Challenging and unforeseen ground conditions can lead to delays with any large subsurface infrastructure project. Current knowledge for the Aberdeen ETZ suggests that ground conditions are relatively favourable, but nonetheless the schedule allows for contingency.

Grout pumping time requirements have previously been provided by specialists and these have been extrapolated to estimate for concrete pumping and overburden installation.

Site preparation activities are generally routine and relatively quick to execute with lower risk of delays.

The liner and overburden installation are somewhat bespoke although all of the comprising activities and techniques planned are borrowed from other industries. Detailed assessment of the schedule from potential contractors involved in completing these steps has yet to be undertaken, and therefore time estimates are currently applied that allow for appropriate contingency. Whilst the Structural Liner installation is technically less challenging than the GTL installation, it is forecast to take the same amount of time as learnings from the former will help to expedite the latter.

Some of the construction activities such as shaft sinking, grout and concrete pours and on-site welding will be more easily conducted outside the coldest temperatures of the winter and efforts will be made to manage the schedule, or mitigate through temporary shelters and heating to avoid this and reduce risk of overruns.

*Table 2: Construction schedule*

| Stage | Detail | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 | M10 | M11 | M12 | Wks (est) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site Preparation | Security / safety | | | | | | | | | | | | | 1 |
| | Electrical connection | | | | | | | | | | | | | 1 |
| | Offices / welfare | | | | | | | | | | | | | 1.5 |
| | Site setup | | | | | | | | | | | | | 2 |
| Shaft sinking | Pre-grouting | | | | | | | | | | | | | n/a |
| | Pre-sink / collar | | | | | | | | | | | | | 2 |
| | Shaft sinking | | | | | | | | | | | | | 6 |
| Liner Install | Temporary Works | | | | | | | | | | | | | 4 |
| | Structural Liner | | | | | | | | | | | | | 6 |
| | Grout Pumping | | | | | | | | | | | | | 2 |
| | GTL | | | | | | | | | | | | | 6 |
| | Concrete Pumping | | | | | | | | | | | | | 2 |
| Finishing works | Overburden | | | | | | | | | | | | | 6 |
| | Process Equipment | | | | | | | | | | | | | 6 |
| | Hydrotesting | | | | | | | | | | | | | 4 |
| | Dewatering | | | | | | | | | | | | | 1.5 |
| | Site demob | | | | | | | | | | | | | 2 |

## 4.0 Procurement and Fabrication

### 4.1 Procurement Strategy

Longitude Engineering intends to act as the EPC for this project and procurement will be completed according to Longitude Engineering Standard Operating Procedures. A competitive tender process will be undertaken for all significant third party fabrication and construction works with a minimum of three proposals sought for evaluation. A minimum three proposals is important for benchmarking price. Note, that this strategy will also be in place for third party design contract work too. Some aspects of this technology demonstration are quite

bespoke and it is acknowledged that it may not be possible to find three companies with the required capability who wish to tender. If it is not possible to conduct a fully competitive tender process then the suitable company(s) identified will be subject to rigorous checks for experience and capability and counterfactuals for pricing will be sought to ensure value for money.

Competitive tenders will be marked against criteria related to capability, availability, experience, quality, risk, and price (value for money). A weighted matrix scoring system will be developed to assist quantitatively comparing and assessing tenders. As this is novel technology demonstration, lowest price may not necessarily be selected as it is crucial that the selected contractors are able to provide the necessary technical competency to deliver, nonetheless as this is a publicly funded project value-for-money will be sought as a priority.

### 4.1.1 Preferred Suppliers

Preferred suppliers have already been identified for some key areas of the demonstration construction. These are outlined below with reasoning for current choice. Note that although they are already identified as preferred suppliers they will still be expected to go through competitive tendering before final award of contracts.

Langfields – liner fabrication. Langfields have been working on the LRS concept for some time already helping to define welding techniques and materials. They have extensive experience of delivering complex and highly technical projects, particularly within the nuclear sector, and have experience of welding and fabrication for the hydrogen environment. They have suitable facilities within reasonable distance of the demonstration site which will reduce transport times and costs.

Joseph Gallagher Limited (JGL) – civils contractor. JGL are the preferred civils contractor as they worked on the design and construction planning with Gravitricity for a previous shaft with similar dimensions and methodology. They are one of the most experienced UK contractors for shaft sinking and have reputational excellence for quality and safety. The civils contractor would be responsible for the shaft sinking, overburden installation, temporary and permanent concrete pads and potentially will be involved in the temporary works for, and installation of, the steel liners.

Swerim – materials testing. Swerim are a non-profit organisation owned by the Swedish government. They have already been extensively involved with desktop materials studies and preparing a lab testing programme of parent and weld materials. They have previously worked on materials testing for Lined Rock Caverns and other hydrogen technology.

Outokumpu – materials supplier. Currently the preferred material for the GTL is single-source supplier (Outokumpu), and they can also supply material for the Structural Liner. Detailed discussions have been held with Outokumpu to understand pricing, steel plate dimensions, and lead times. Outokumpu have kindly offered to supply steel for the materials testing programme for free.

FoundOcean – specialist grouting. FoundOcean have been engaged with the project for some time already optimising material and construction methodology. They have extensive experience particularly with large offshore infrastructure projects and have a range of in-house designed products.

Y-Mattec – specialist concrete. Y-Mattec produce high-performance concrete primarily for the onshore and offshore wind industries. They have been assessing the technology requirements to optimise the concrete used and trialling bespoke mixes specifically for LRS technology.

A2AM – bespoke monitoring solutions. The unique nature of the technology and the monitoring required for the demonstration has proven quite challenging for some contractors to fulfil. A2AM have extensive experience in analogous fields developing in-house bespoke solutions and have access to world-leading researchers. Thus far they have been the only contractor found who are able to fully meet the project requirements.

AXIOM – ECA/NDT. AXIOM have worked extensively with Langfields in the past providing NDT, ECA, and other weld qualification services. They have experience with Hydrogen containment and process engineering. Initial discussions have been held to understand their availability, capability, and costs for both factory and on-site weld qualifications.

## 4.2 Schedule

Table 3 shows an indicative materials procurement and fabrication schedule. Most of these details are based on discussions with, and proposals received from, preferred suppliers. Note that many of these activities can be undertaken concurrently with the latter stages of detailed design and/or earlier stages of construction.

Grid connection (electricity) procurement can potentially take up to nine months, however a new substation is planned for the site and discussions with the ETZ indicate that there will be sufficient spare capacity for both the construction and operational phases of the project.

The critical path for procurement and fabrication is the GTL. There is a four-month lead-time for supply of the steel plate and the current favoured specification is available only from Outokumpu. Factory fabrication of the GTL is estimated at three months by Langfields. Therefore the materials testing programme and fabrication drawings for the GTL must be progressed sufficiently to place the order for the steel to ensure delivery of the GTL cans to site and maintain schedule.

*Table 3: Procurement and Fabrication schedule*

| Stage | Detail | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 | Wks (est) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Office /welfare | | | | | | | | | | | 1 |
| *Grid Connection (elec)* | | | | | | | | | | | *8* |
| Shaft sinking | | | | | | | | | | | 12 |
| Structural Liner | Materials | | | | | | | | | | 8 |
| | Fabrication | | | | | | | | | | 8 |
| Grout | Equipment / materials | | | | | | | | | | 9 |
| Gas-tight Liner | Materials | | | | | | | | | | 16 |
| | Fabrication | | | | | | | | | | 13 |
| Concrete | Equipment / materials | | | | | | | | | | 8 |
| Overburden | Anchors etc | | | | | | | | | | 8 |
| | Concrete | | | | | | | | | | 8 |
| Process Equipment | | | | | | | | | | | 12 |
| EC & I | Electrical Equipment | | | | | | | | | | 12 |
| | Control Equipment | | | | | | | | | | 12 |
| | Leak Management | | | | | | | | | | 12 |
| | Monitoring Equipment | | | | | | | | | | 12 |

Table 4 shows the fabrication and procurement schedules combined with construction schedule. This illustrates the lead-in time required in procurement to ensure the construction phase is not delayed. This in turn affects when detailed design (not shown here) must be completed by in the overall project schedule. Further to the lead-time for the GTL discussed above other key procurement activities to maintain the project schedule include equipment and materials for the site preparation and for the shaft sinking and associated groundworks. This will be completed through the preferred civils contractor.

*Table 4: Combined procurement, fabrication, and construction schedules*

| Stage | Detail | M-2 | M-1 | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 | M10 | M11 | M12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site Preparation | Security / safety | | | | | | | | | | | | | | |
| | Electrical connection | | | | | | | | | | | | | | |
| | Offices / welfare | | | | | | | | | | | | | | |
| | Site setup | | | | | | | | | | | | | | |
| Shaft sinking | Pre-grouting | | | | | | | | | | | | | | |
| | Pre-sink / collar | | | | | | | | | | | | | | |
| | Shaft sinking | | | | | | | | | | | | | | |
| Liner Install | Temporary Works | | | | | | | | | | | | | | |
| | Structural Liner | | | | | | | | | | | | | | |
| | Grout Pumping | | | | | | | | | | | | | | |
| | GTL | | | | | | | | | | | | | | |
| | Concrete Pumping | | | | | | | | | | | | | | |
| Finishing works | Overburden | | | | | | | | | | | | | | |
| | Process Equipment | | | | | | | | | | | | | | |
| | Hydrotesting | | | | | | | | | | | | | | |
| | Dewatering | | | | | | | | | | | | | | |
| | Site demob | | | | | | | | | | | | | | |

# Appendix A : Supplied Documents

LGG-L057401-R06-Rev00 Construction Storyboard – Provided as a separate document

REPORT.

LONGITUDE
An ABL Group Company

# Ofgem SIF B-Linepack+

# Sub-Surface Process Design Note

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## 1.0 Summary

This document provides a comprehensive design overview of the sub-surface process sub-system for the Lined Rock Shaft (LRS) technology demonstrator, developed as part of the Ofgem SIF B-Linepack+ storage demonstration project. The scope of the sub-system encompasses all process equipment below the interface with the wellhead, the process monitoring within the shaft, and the sub-surface leak management equipment.

The LRS system is designed to store gaseous hydrogen with a total capacity of 0.53 tonnes, comprising 0.09 tonnes of cushion gas and 0.44 tonnes of working gas, with a maximum operating pressure of 200 Barg and a cushion gas pressure of 30 Barg. The internal storage volume will be 35 $m^3$, with a standard operating temperature range of 10-70°C and an absolute range of 0-80°C. Ancillary storage, intended to facilitate hydrogen cycling, will have the same storage capacity as the LRS but will operate at a lower maximum pressure of 30 Barg.

The key components of the sub-system include the casing string, containment monitoring, and the leak management system. The casing string consists of tubing for fluid injection and withdrawal with safety valves for each. Containment monitoring is provided by temperature and pressure sensors distributed throughout the casing and containment. The leak management system will have leak venting pipes, perforated piping for gas capture and a gas-impermeable membrane to direct leaked gas. Dosing pipes will be used for system testing.

The LRS will operate in three primary modes: injection, withdrawal, and standby. During injection, hydrogen will be compressed from the ancillary storage into the LRS, with flow controlled by a flow control valve (FCV). A recirculation cooling loop will regulate temperature increases in the LRS. During withdrawal, hydrogen will flow from the LRS back into the ancillary storage, controlled by a FCV and a pressure control valve (PCV), with a recirculation heating loop regulating temperature decreases in the LRS. In standby mode, no hydrogen flow will occur and the LRS temperature will tend towards the surrounding rock temperature (~10°C).

The design will adhere to relevant legislation and codes where applicable. Due to the novel design, some aspects of the casing string and leak management lack directly applicable codes/legislation. The Offshore Installations and Wells Regulations may be voluntarily applied for the general casing string design, and ASME codes will be used for tubing design. The leak management system will follow best practices from regulations like the Dangerous Substances and Explosive Atmospheres Regulations 2002.

The casing string includes an injection tube with a tubing retrievable safety valve (TRSV), and a production tube with an annular safety valve (ASV). The injection tube is designed to facilitate injection within 12 hours and to fit a borehole pump for dewatering, while the production tube is designed to facilitate withdrawal within 6 hours.

Temperature regulation will be achieved using the recirculation heating and cooling loops. To prevent temperature stratification within the containment, active mixing may be evaluated.

Containment monitoring will be comprised of temperature and pressure sensors mounted on the injection tube exterior/interior. It is expected that standard process industry equipment will be used, positioned at regular intervals to provide a comprehensive dataset.

The leak management system will ensure that in the unlikely event of a leak from the containment, all gas is captured, vented and flared in a safe manner. The design will adopt similar methods used for Lined Rock Caverns (LRC).

Dewatering of the containment will be achieved by first using a borehole pump that can be lowered down through the injection tube. Thereafter, the remaining water left in the containment will be removed by pressurising the containment and pushing the water through a tube, then finally via the recirculation of warm dry gas.

## 2.0 Introduction

The purpose of this document is to provide design information for the sub-surface process sub-system for the technology demonstrator LRS as part of the Ofgem SIF B-Linepack+ storage demonstration project.

The scope of the sub-surface process sub-system of an LRS encompasses everything below the interface with the wellhead, the process monitoring within the shaft, and the sub-surface leak management equipment. For more information regarding the interfaces see the interface register PRZ0025-REG-0000-00002. For more information regarding the design of the sub-surface LRS system, see the general arrangement drawing LGG-L057401-D01. A Process Flow Diagram (PFD) showing the full process system is shown in Figure 1. It includes all the main equipment. All top-side process equipment (including gas compression, let down, thermal management and all additional ancillary equipment) is the scope of Premtech and shall not be detailed in this report.

For more information regarding the technology demonstrator aims and requirements, see the document LGG-L057401-R04 Basis of Design (Sub-Surface Containment) and PRZ0025-REG-0000-00001.

Requirements for the sub-surface process system can be found in the requirements register LGG-L057401-R01.

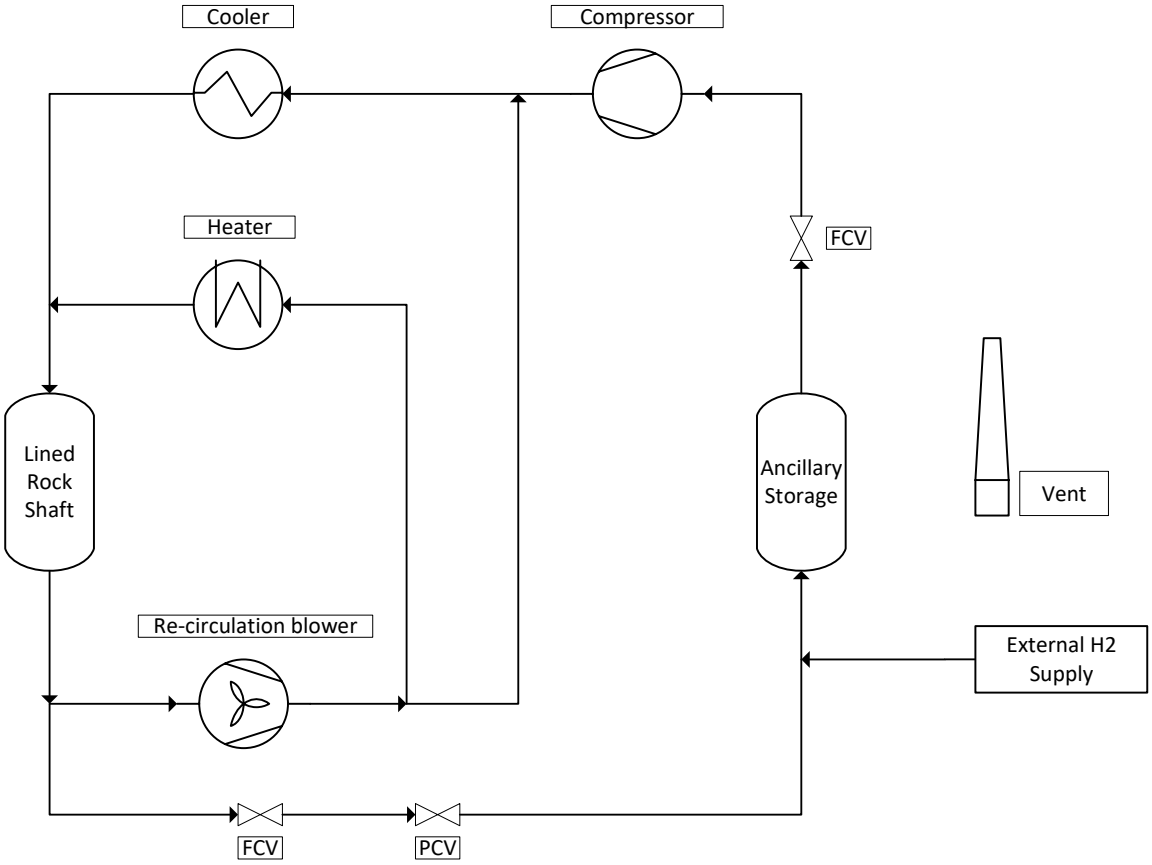


*Figure 1: Technology Demonstrator LRS PFD*

## 2.1 Abbreviations

Abbreviations used in this report are outlined in *Table 1*.

*Table 1: Abbreviations*

| | |
|---|---|
| ***LRS*** | *Lined Rock Shaft* |
| ***PFD*** | *Process Flow Diagram* |
| ***FCV*** | *Flow Control Valve* |
| ***PCV*** | *Pressure Control Valve* |
| ***MOP*** | *Maximum Operating Pressure* |
| ***CGP*** | *Cushion Gas Pressure* |
| ***TRSV*** | *Tubing Retrievable Safety Valve* |
| ***ASV*** | *Annular Safey Valve* |
| ***ALARP*** | *As Low As Reasonably Practicable* |
| ***NGT*** | *National Gas Transmissions* |
| ***P&ID*** | *Process and Instrumentation Diagram* |
| ***AGI*** | *Above Ground Installations* |
| ***U/G*** | *Underground* |
| ***SS*** | *Slam shut* |
| ***GTL*** | *Gas Tight Liner* |
| ***HPU*** | *Hydraulic Power Unit* |
| ***LRC*** | *Lined Rock Cavern* |
| ***FO*** | *Fiber Optic* |

## 3.0 System Overview

The high-level LRS properties are given in Table 2. It includes information that is relevant for the design of the sub-surface process sub-system. The high-level ancillary storage properties are given in Table 3. The purpose of the ancillary storage is to facilitate hydrogen gas cycling of the LRS, and therefore it will have the same storage capacity. It will likely be a standard storage technology, such as high-pressure canisters/pressure vessels. It will not have cushion gas, therefore only one storage capacity is given.

*Table 2: High-level LRS properties*

| Property | Value | Notes |
|---|---|---|
| **Storage capacity** | 0.53 t | Total hydrogen gas storage capacity assuming average storage temperature of 20 degrees Celsius. |
| **Cushion gas** | 0.09 t | The amount of gas which is permanently stored in the sub-surface containment. It prevents unwanted loading on the liner and shaft walls when the working gas has been removed. |
| **Working gas** | 0.44 t | Available gas for injection and withdrawal. |
| **Maximum Operating Pressure (MOP)** | 200 Barg | N/A |
| **Cushion Gas Pressure (CGP)** | 30 Barg | N/A |
| **Internal storage volume** | 35 $m^3$ | Internal volume of the gas-tight liner |
| **Standard operating temperature range** | 10-70 degrees C | N/A |
| **Absolute operating temperature range** | 0-80 degrees C | N/A |

*Table 3: High-level ancillary storage properties*

| Property | Value | Notes |
|---|---|---|
| **Storage capacity** | 0.53 t | Total hydrogen gas storage capacity assuming average storage temperature of 20 degrees Celsius. |
| **MOP** | 30 Barg | N/A |
| **Internal storage volume** | 210 $m^3$ | N/A |

## 3.1 Key Components

The sub-surface process sub-system, as previously noted, encompasses all process equipment below the interface with the wellhead, the process monitoring within the shaft, and the sub-surface leak management equipment. This includes the following key components:

**Casing String**

The casing string is comprised of the tubing between the wellhead and the LRS that facilitates the injection and withdrawal of hydrogen. This includes the injection tube, production tube, and safety valves for both.

**Containment monitoring**

The containment monitoring will include temperature and pressure sensing throughout the casing string and the containment.

**Leak Management**

The sub-surface leak management equipment is comprised of the leak venting equipment which will be perforated piping that provides a low resistance path for hydrogen to flow in the event of a leak. There will be a gas-impermeable membrane to direct the gas in the event of a leak. It also includes dosing pipes that facilitate dosing to allow regular testing that the leak management system is operating safely and as expected.

## 3.2 Thermodynamic Modelling

To determine the system behaviour in the different operating modes, thermodynamic modelling was performed as part of the Discovery project phase as detailed in the document 1103-001-01 Thermodynamic Modelling. Further modelling was performed prior to the Alpha phase, adding detail to the model and increasing confidence in the results. The modelling was performed in MATLAB using Simulink and Simscape. The results show the need for re-circulation heating and cooling as described in Section 3.3, with the LRS containment temperature exceeding the absolute operating temperature ranges without. The model was also used to determine the minimum injection and production tube pipe sizes to facilitate the required hydrogen injection/withdrawal flow-rates, as detailed later in Sections 4.3 and 4.4.

## 3.3 System Operating modes

The LRS system has three primary operational modes which are injection, withdrawal, and standby. The other operating modes - commissioning, maintenance and emergency shutdown - are not detailed in this report, see LGG-L057401-R02 EC&I Design Note. The three primary system modes and how the process equipment is operated is detailed in the following sub-sections.

### 3.3.1 Injection

The LRS system will be in the injection mode when hydrogen is compressed from the ancillary storage to the LRS. This is shown in Figure 2. Flow from the ancillary storage to the LRS is shown by highlighting the flow path green. The re-circulation cooling loop is shown by highlighting the flow path blue.

For all operating modes, it is assumed that no recirculation heating or cooling is required for the ancillary storage. This is because the expected temperature changes throughout operation should not exceed its standard operating temperature limits.

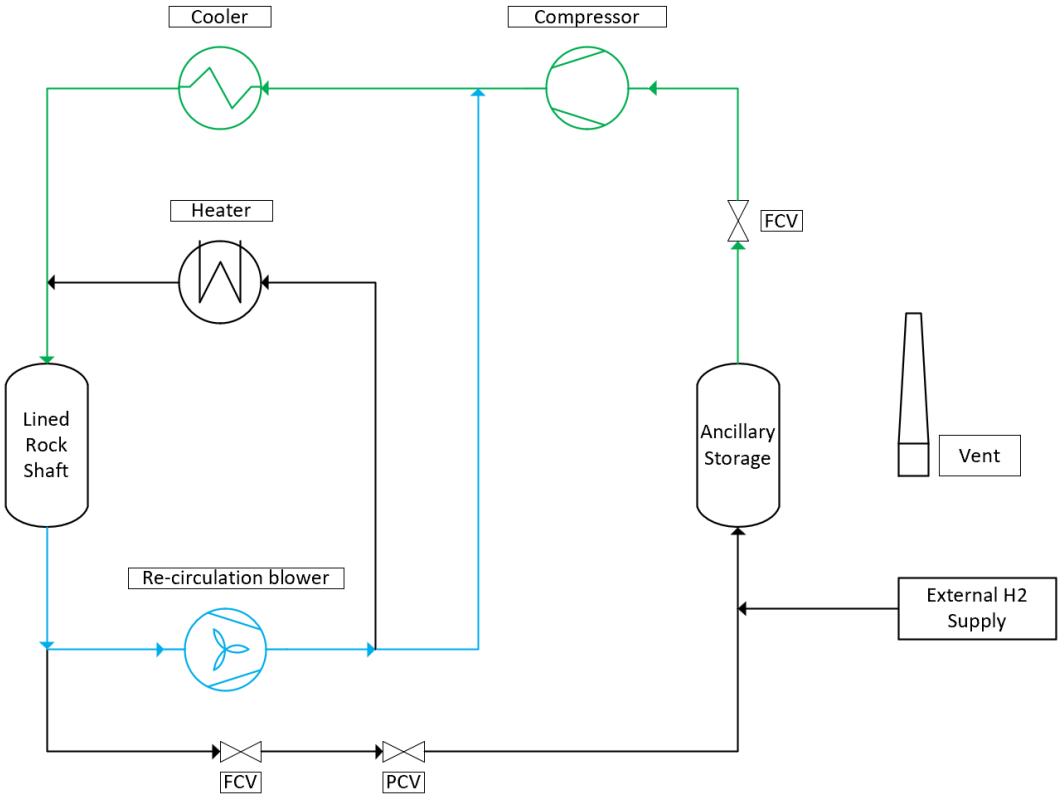


*Figure 2: Injection mode PFD*

### 3.3.2 Withdrawal

The LRS system will be in the withdrawal mode when hydrogen flows from the LRS to the ancillary storage. This is shown in Figure 3. Flow from the LRS to the ancillary storage is shown by highlighting the flow path green. The re-circulation heating loop is shown by highlighting the flow path red.

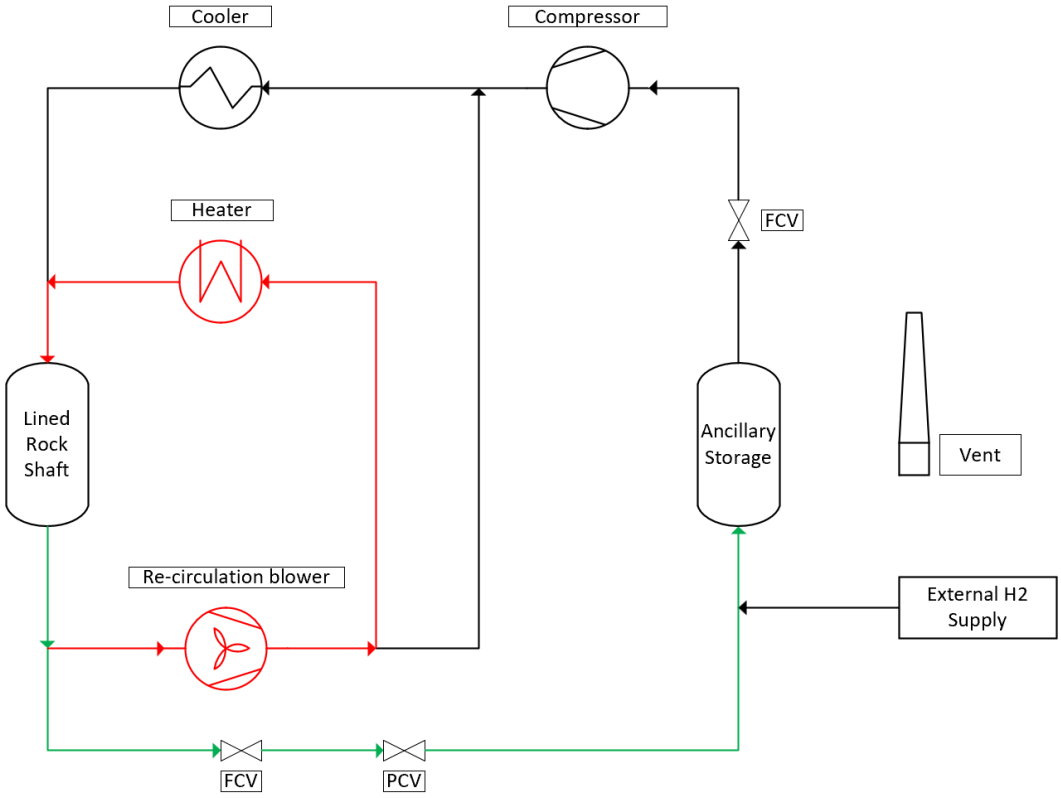


*Figure 3: Withdrawal mode PFD*

### 3.3.3 Standby

The LRS system will be in the standby mode when no hydrogen is flowing between the LRS and the ancillary storage. In this mode, the temperature of the LRS will tend towards the surrounding rock mass temperature. The rock mass temperature is expected to be approximately 10 degrees Celsius, which is the lower limit of the standard operating temperature range. This therefore means that it is unlikely that recirculation cooling will be required, but recirculation heating may be needed. For completeness, both recirculation loops are shown in Figure 4. Flow to and from the recirculation loops is shown by highlighting the flow path green. The heating loop is shown by highlighting the flow path red, and the cooling loop is shown by highlighting the flow path blue. Hydrogen will flow around the recirculation loops by the actuation of the recirculation blower.

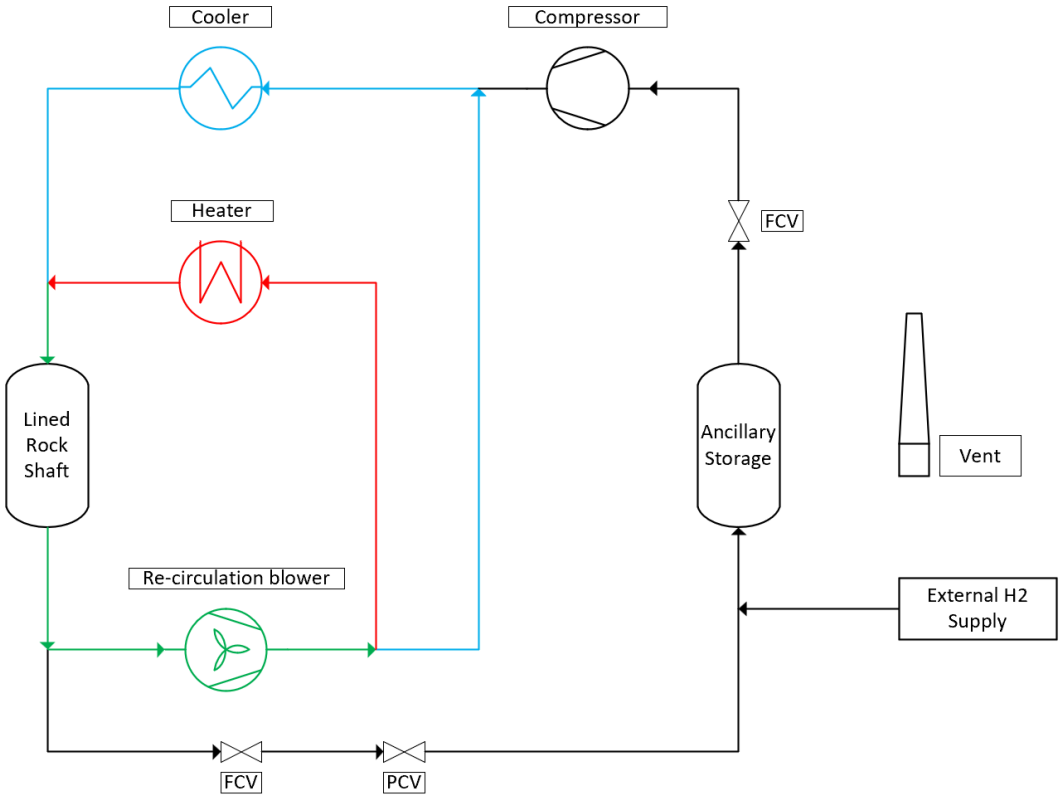


*Figure 4: Standby mode PFD*

## 3.4 Legislation

The sub-surface process sub-system will be designed according to legislation and design codes where possible. High-level legislation requirements have been detailed in the requirements register LGG-L057401-R01. Specifications are also provided in the high-level Basis of Design Document PRZ0025-REP-0000-0001. The LRS technology demonstration project is in collaboration with National Gas Transmissions (NGT) therefore best practice from the existing National Gas pipeline design standards and specifications will be reviewed. Future work is required to determine the specific sections and clauses applicable to the LRS and the therefore the detailed legislation requirements.

Due to the novel nature of the LRS design, there are aspects of the system for which directly applicable design codes and legislation don't exist. For the sub-surface process sub-system, this applies for aspects of the casing string, and the leak management design.

To ensure that risks are managed to be as low as reasonably practicable (ALARP), The Offshore Installations and Wells Regulations may be voluntarily adopted for the casing string, consistent with the approached adopted by salt caverns and geothermal installations. This means that the design would lean on existing good industry practice in terms of design, well completions and equipment. For the design of the tubing, the ASME B31.12-2023 Hydrogen Piping and Pipelines - ASME Code for Pressure Piping will be used.

For the leak management system, best practice for high-pressure process systems exists in documents such as the Dangerous Substances and Explosive Atmospheres Regulations 2002. These shall be applied meaning that again, the design would lean on existing good industry practice in terms of design and operation.

# 4.0 Casing String Design

The casing string is comprised of an injection tube, a production tube, an ASV in the production tube, a TRSV in the injection tube, and the interface to the top-side process equipment. In the following sub-sections, the design for each is presented.

## 4.1 Injection Tube Safety Valve

The injection tube safety valve will be a tubing retrievable safety valve (TRSV) that is located in-line, part way down the injection tube, connected at either end with a threaded or welded connection. For the LRS demonstrator, an off-the-shelf safety valve that is suitably certified for the operating conditions is preferred. The safety valve must meet the relevant requirements specified in the requirements register, with the primary factors influencing selection being:

- Shall facilitate injection from CGP to MOP in 12 hours
- Shall facilitate a borehole pump to pass through for de-watering
- Shall be suitably sized to interface with the injection tube
- Shall be suitable for hydrogen service conditions at the expected operating and test pressures/temperatures

A selection of reputable safety valve vendors within the oil and gas industry with previous experience in hydrogen application projects were approached for suitable products. An example safety valve that should be suitable for the LRS application is shown below in Figure 5. It is a tubing mounted, hydraulically actuated flapper safety valve rated for pressures up to 34 MPa, temperature between 4-149 degC, and for oil and gas applications certified according to API Spec 14A.

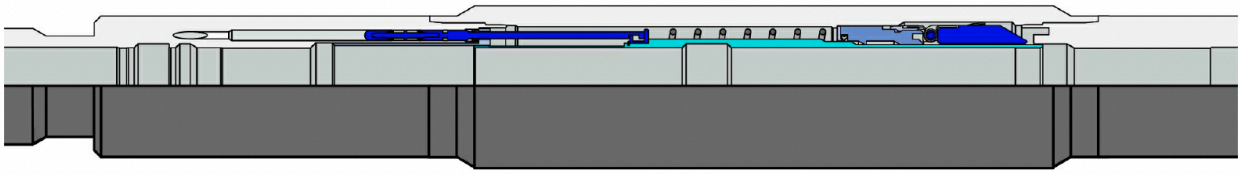

*Figure 5: Example TRSV for the injection tube*

The TRSV is controlled via a hydraulic line to surface. Hydraulic pressure will be provided by a hydraulic power unit (HPU). This will either be an HPU that provides pressure to the wider topside process equipment, or a standalone unit if required. It will be connected to the control system such that a loss of pressure signal would be fed back to set off an emergency shutdown. When pressure is maintained in the control line, the safety valve is kept open such that flow can pass through it. In the event of a loss of pressure in the control line (failure event) the safety valve would close preventing any flow across it. The hydraulic control line will pass to surface through the annulus between the injection and production tubes and then interface with the top-side process equipment. The design would ensure that the safety valve would actuate for all foreseeable and relevant failure events.

## 4.2 Production Tube Safety Valve

The safety valve for the production tube must be located in the annulus between the injection tube and production tube due to the tube in tube design. This means that an annular safety valve (ASV) is required. The ASV will be connected and installed as part of the injection tube. This will either be a threaded or welded connection. For the LRS demonstrator, an off-the-shelf safety valve that is suitably certified for the operating conditions is preferred. The safety valve must meet the relevant requirements specified in the requirements register, with the primary factors influencing selection being:

- Shall facilitate withdrawal from MOP to CGP in 6 hours
- Shall be suitably sized to interface with the injection and production tubes
- Shall be suitable for hydrogen service conditions at the expected operating and test pressures/temperatures

A selection of reputable safety valve vendors within the oil and gas industry with previous experience in hydrogen application projects were approached for suitable products. An example safety valve that should be suitable for the LRS application is shown below in Figure 6. It is a tubing mounted, hydraulically actuated safety valve rated for pressures up to 45 MPa, temperatures up to 149 degC, and for oil and gas applications certified according to API Spec 14A.

*Figure 6: Example ASV for the injection tube*

Similar to the TRSV, the ASV is controlled via a hydraulic line to surface. When pressure is maintained in the control line, the safety valve is kept open such that flow can pass through it. In the event of a loss of pressure in the control line (failure event) the safety valve would close preventing any flow across it. The hydraulic control line will pass to surface through the annulus between the injection and production tube and then interface with the top-side process equipment. The ASV also has the capacity for control lines from other equipment to pass through it. This shall be used for the TRSV control line which will be placed deeper than the ASV.

### 4.3 Injection Tube

The injection tube is the inner of the two tubes that make up the casing string. It will run from the interface with the wellhead at the surface, down to the base of the containment. It will be hung from surface, with no direct interface between the rest of the sub-surface containment other than for minor ancillary equipment such as control lines and monitoring. It will therefore only be fixed at one end with a flanged connection at the wellhead/hanger. At the base of the containment, it will be at a height from the bottom end cap of the gas-tight liner (GTL) that is most suitable to promote gas mixing on injection.

The injection tube must meet the relevant requirements specified in the requirements register, with the primary factors influencing the design being:

- Shall connect to the TRSV
- Shall connect to the ASV
- Shall facilitate injection from CGP to MOP in 12 hours
- Shall facilitate a borehole pump to pass through for de-watering
- Shall be suitable for hydrogen service conditions at the expected operating pressures/temperatures

### 4.4 Production Tube

The production tube is the outer of the two tubes that make up the casing string. It will be connected to the topside process equipment at surface, then connected to the top of the GTL. It will therefore be fixed at both ends. The interface between the production tube and the GTL is covered within the Geomechanical and Structural sub-system as detailed in LGG-L057401-R09. It must meet the relevant requirements specified in the requirements register, with the primary factors influencing the design being:

- Shall seal to the ASV
- Shall facilitate the passthrough of the ASV and TRSV control lines
- Shall facilitate withdrawal from MOP to CGP in 6 hours
- Shall pass through and be cemented within the overburden
- Shall be suitable for hydrogen service conditions at the expected operating pressures/temperatures

It is assumed that all dewatering, inspection and monitoring equipment shall be passed through the injection tube rather than the production tube, therefore there is currently no requirement for space between the production and injection tube for this.

To pass through the overburden, the tube will need to resist the external pressure of the concrete and any hydrostatic pressure. The internal gas pressure is expected to be far higher than the external pressures and therefore this external pressure should not impose difficulty in the design. The material used must be suitable for exposure to the concrete used for the overburden and any chemicals that may be present in the groundwater.

### 4.5 Temperature Mixing

To maintain the LRS containment within its operating temperature limits, recirculation heating and cooling will be required. Without this, the temperature limits as specified in Table 2 will be exceeded. For either the heating or cooling scenario, gas will be entering the containment at a different temperature to the gas already present in the containment. To ensure that the operating temperature limits aren't exceeded, these different temperature gases need to mix.

When hot gas is injected into the containment, due to the injection tube running to the base, gas convection will occur due to hotter gas at the base, and colder gas at the top. This may be sufficient to cause mixing to maintain a suitable overall temperature. However, it may be that due to relatively small temperature gradients, it isn't sufficient.

When cold gas is injected into the containment, convection mixing will not occur, because there will be hot gas at the top of the containment, and cold gas at the base. In this scenario, there is a greater risk that the re-circulation cooling may not effectively maintain the containment temperature, and that either colder gas has to be recirculated, increasing the energy used to cool the gas, or that higher recirculation rates are required, again increasing the energy used.

To help promote gas mixing to ensure the most efficient recirculation heating and cooling, more active mixing is proposed. To fully understand the risk of temperature stratification due to insufficient mixing, computation fluid dynamics modelling will be required.

# 5.0 Containment Monitoring

The containment monitoring will be comprised of temperature and pressure sensing using standard process industry equipment. The monitoring will be performed down the sides of the casing string, with sensors at intervals, and fibre optic (FO) cables running its full length. The comprehensive placement of sensors is to ensure that the temperature mixing within the containment is sufficient and that stratification does not occur.

The primary purpose of the containment monitoring is to provide data to the control system to ensure the safe operation of the LRS. See the document LGG-L057401-R02 EC&I Design Note for more information on the electrical, control, and instrumentation design of the LRS. The data will also provide thermodynamic behaviour and performance characteristics of the LRS, which will be used to validate thermodynamic models.

Due to the short lifespan of the technology demonstrator, the sensors are expected to operate for the life of the LRS without need for replacement or inspection. The number of sensors will ensure redundancy should any of them fail. The sensors will be calibrated on installation to ensure correct readings. The sensors will have sufficient sensitivity and reliability to provide high quality data to ensure safe operation at all times.

## 5.1 Pressure and temperature sensing

For the pressure and temperature sensors, a combined option will be used, as shown in Figure 7. A single hardware unit will provide continuous measurements. The example shown is designed for service in wells and oil and gas applications. Multiple sensors (up to 16 pressure and temperature sensors) can be deployed on a single power/communication cable, meaning that only one line would need to pass through the ASV for all required sensors. They are suitable for pressures up to 69MPa, with very low measurement drift, and high measurement accuracy. They are designed for exposure to hydrogen sulphide according to NACE MR0175 - *Petroleum and natural gas industries - Materials for use in H2S-containing Environments in oil and gas production*, therefore they are expected to be suitable for hydrogen service conditions.

Figure 7 shows how the sensor can be fitted to a tubing section, with the lower image showing the sensor connected at either end to the cable. It is expected that a similar method may be used to attach the sensor and cable to the injection tube.

*Figure 7: Pressure and temperature sensor for containment monitoring*

### 5.1.1 Fibre-optic sensing

For temperature sensing, a fibre optic (FO) cable will be used to compliment and provide redundancy to the sensors described in the section above. Longitude have identified suitable examples rated to 138 MPa and 300 degC. The cable will run the full length of the injection tube, providing a complete data array for the full depth of the containment, giving measurements at approximately every 0.5 m intervals. The FO cables will likely be chosen to match those used elsewhere on the LRS for structural monitoring, so that the same analyser can be used. This will be defined as the design develops.

# 6.0 Leak Management

## 6.1 Requirements

The gas-tight liner (GTL) is designed to be impermeable, so leaks are not expected. The likelihood of a leak will be made ALARP through system design.

The requirements that drive the need for a leak management system are 01-031, 32, 33 (see LGG-L057401-R01). These are:

- The system shall not allow for explosive atmospheres to form
- The system shall not allow for excessive pressure to build up out-with the GTL
- The system shall collect, contain, remove or render safe any release of hazardous gas or dangerous substance that may cause risk

For an explosive atmosphere to form, oxygen would need to be present with the hydrogen. Due to the sub-surface nature of the LRS, the likelihood of the presence of gaseous oxygen is greatly reduced. It must be ensured that all process systems, including the leak management systems, are operated in the absence of oxygen when hydrogen is being stored/handled. Inert gas (nitrogen and helium) should be used when an alternative gas to hydrogen is required.

To prevent excessive pressure building up external to the GTL, there must be means for venting pressurised gas/fluid with minimal resistance. Given that the containment is set in cementitious material surrounded by rock mass, this itself does not present any suitable pathways. It is expected that the concrete layer surrounding the GTL will be cracked, but this alone is not expected to be sufficient to provide a pathway for pressure relief. A specific pressure relief path is therefore required.

To collect, contain, remove or render safe any release of hazardous gas or dangerous substance that may cause risk, a leak management system must be implemented. The proposed design is expected to satisfy all the above detailed requirements.

## 6.2 Design proposal

The proposed design aims to provide contingency for a leak in the GTL. No leak management system is proposed for leaks from the casing string. This is because the risk of a leak from the casing string is expected to be much less than for the GTL. The tubing will be designed to design codes specifically for hydrogen service and operated within standard conditions.

The proposed system is very similar to the leak management system used and tested successfully for LRCs, for both natural gas and hydrogen storage (Jan Johansson, 2003). To test that the leak management system is operating safely as expected, a dosing system shall be installed. It will facilitate the injection of helium, nitrogen, or a helium-nitrogen gas mixture to simulate hydrogen leaking from the GTL. Further work is required to define the inert gas used for testing. The dosing system will also be able to test the sensitivity and latency of the leak management system.

To detect whether a hydrogen leak has occurred, multiple sensing methods shall be used. These include:

- Hydrogen gas detectors
- Pressure sensors
- Gas flow rate sensors

When the system is being tested, hydrogen won't be used, therefore only the pressure sensors and gas flow rate sensors will be effective. The hydrogen gas detectors will be tested for functionality separately.

## 7.0 Dewatering

For the installation procedure and for hydrotesting, the containment will be filled with water. To enable operation with gas during the containment commissioning test stage, the containment must be dewatered. The high-level dewatering procedure has been detailed in LGG-L057401-R07 Construction Sequence. The first step is to pump out the bulk of the water using a submersible borehole pump. It is intended that the borehole pump should be lowered into the containment through the injection tube such that no modification to the casing string is required. A dimensioned example shown in Figure 8. The high-level specification of this pump in given in Table 4.

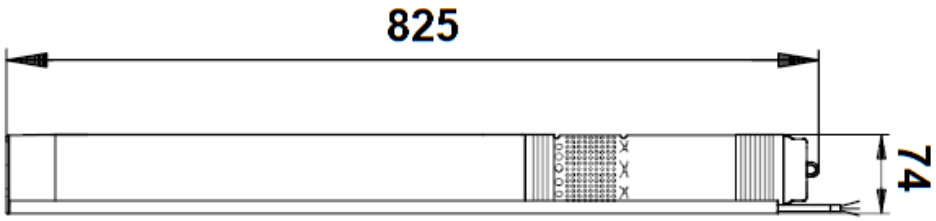


*Figure 8: 3-inch borehole pump for containment dewatering (upper end of the pump to the right)*

*Table 4: Borehole pump specification*

| Dimension | Value |
|---|---|
| Rated flow | 3 $m^3/h$ |
| Rated head | 125 m |
| Material | Stainless steel EN 1.4301 |
| Maximum operating pressure | 15 bar |

The proposed pump would result in a de-watering time of approx. 12 hours, considering that the technology demonstrator LRS has an internal containment volume of 35 $m^3$. It may be that a faster de-watering time could be achieved because the pump would be used with a maximum head of approx. 46 m, much less than the rated head of 125 m. The pump is suitable for ground water intake, therefore will be suitable for the clean water within the GTL.

As shown in Figure 8, the water inlet is part the way up the pump, denoted by the holes/dashes. This means that following de-watering using the pump, some water will remain in the containment. As described in the construction sequence, some water can be removed by applying pressure to the containment and pushing it out through a tube. Then the final remaining water will be removed through evaporation via the circulation of warm dry gas which is then dried and recirculated. A heater may be lowered into the containment to raise the water temperature to accelerate evaporation. Any equipment (such as tubing or heater) that is lowered into the containment is expected to be no greater in diameter than the borehole pump.

## 8.0 References

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# Ofgem SIF B-Linepack+

## Geomechanical & Structural Design Note

| REPORT DETAILS | | | |
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## 1.0 Summary

This document provides a comprehensive design overview of the geomechanical and structural sub-system for the Lined Rock Shaft (LRS) technology demonstrator, developed as part of the Ofgem SIF B-Linepack+ storage demonstration project. The scope of the sub-system encompasses the containment of stored gas, and the transfer of the internal pressure into the surrounding rock mass and the overburden. Specifically, this includes the lining layers which are the gas-tight liner (GTL), concrete liner (CL), structural liner (SL) and grout liner (GL). The LRS will be installed in a shaft with a diameter of 2.5m and a height of 47m.

The design will adhere to relevant legislation and design codes where applicable. Due to the novel design, all components of the geomechanical and structural sub-system lack directly applicable codes/legislation. The LRS containment does not straightforwardly comply with pressure vessel design codes because it uses the rock mass to help store the internal gas pressure. Despite this, design codes will be used as a guide for design and best practice where relevant, and risks shall be designed to be as low as reasonably practicable (ALARP).

The multi-layer liner is designed to strain under internal pressure, transferring the load from the internal gas pressure to the rock. Therefore, the steel liner thickness can be reduced relative to unsupported pressure vessels and cost savings are made. The LRS technology is designed for a wide range of geological conditions. In very hard/strong rock, there may be very little deformation of the lining. In poor/soft rock, a greater amount of deformation may be expected. The behaviour of the metallic liners, cementitious liners, and the rock mass is detailed, with comparisons made to analogous technologies that have successfully demonstrated similar behaviours for over 100 years. Further geomechanical modelling has been performed since the Discovery phase of the project, building confidence of the lining response whilst de-risking key aspects of the design.

The GTL, comprised of cylindrical sections and hemispherical end caps, will be made from a stainless steel. This is due to the materials resistance to hydrogen embrittlement (HE), high ductility, high strength, suitability for fabrication and reasonable cost. HE is a key risk for the GTL given the LRS service conditions, therefore selecting a suitable material is of critical importance. High quality welding is required for the GTL. Most welding will be performed in a workshop, with some welding required on site. An engineering critical assessment (ECA) will be performed for the GTL to determine the allowable defect size given the system cycle life. This will allow the non-destructive testing (NDT) methodology to be defined. To perform the ECA, the critical weld must be determined, which requires further design work. No published data for the material properties of the GTL material used in the LRS service conditions exists, therefore materials testing is required to determine the properties required to perform the ECA.

Similar to the GTL, the SL will be comprised of cylindrical sections with a hemispherical end cap at the base only. It will be made from a carbon structural steel, which has high ductility, strength, is suitable for fabrication, and is a reasonable cost option. It will not be used to contain high-pressure hydrogen therefore does not need to be as resistant to HE as the GTL does. The SL will be fabricated using industry standard methods, with most welding performed in a workshop, and some welding required on site. An ECA will be performed, and an NDT methodology defined. Unlike the GTL, the material properties required to perform the ECA analysis are well understood, and no material testing is required.

The CL, poured into the annulus between the GTL and SL will be a high strength mix. This will provide suitable strength for load transfer during service. Additives will be used to meet the requirements for installation, such as high flow, low shrinkage, low heat of hydration etc. Similar additives will be used for the GL which will have very similar installation requirements. It will also be a high strength mix which will be poured into the annulus between the excavated shaft wall and the SL.

As part of the LRS technology development, and prior to the deployment of a demonstrator, materials testing and lab scale testing are required. This is to collect design data for the GTL in hydrogen service conditions, and verify and correlate the multi-layer liner behaviour under pressure. The materials test programme will first the GTL parent material and weld filler materials, before performing fatigue and fracture mechanics testing to provide suitable data to enable the ECA to be performed. The multi-layer lab testing will be a ring of the lining system subject to internal pressure with artificial rock mass to recreate the LRS behaviour. This will demonstrate and correlate behaviour that cannot be shown via modelling, and de-risk aspects of the design before the demonstrator deployment.

## 2.0 Introduction

This document sets out the geomechanical and structural design for the technology demonstrator LRS as part of the Ofgem SIF B-Linepack+ storage demonstration project. The technology demonstrator aims to replicate the design of a full-scale system where possible. The geomechanical and structural sub-system encompasses the containment of stored gas, and the transfer of the internal pressure into the surrounding rock mass and the overburden. Specifically, this includes the lining layers which are the GTL, CL, SL and GL. A section view through the shaft showing the different lining layers is shown in Figure 1. This document is supported by the LGG-L057401-D01 General Arrangement.

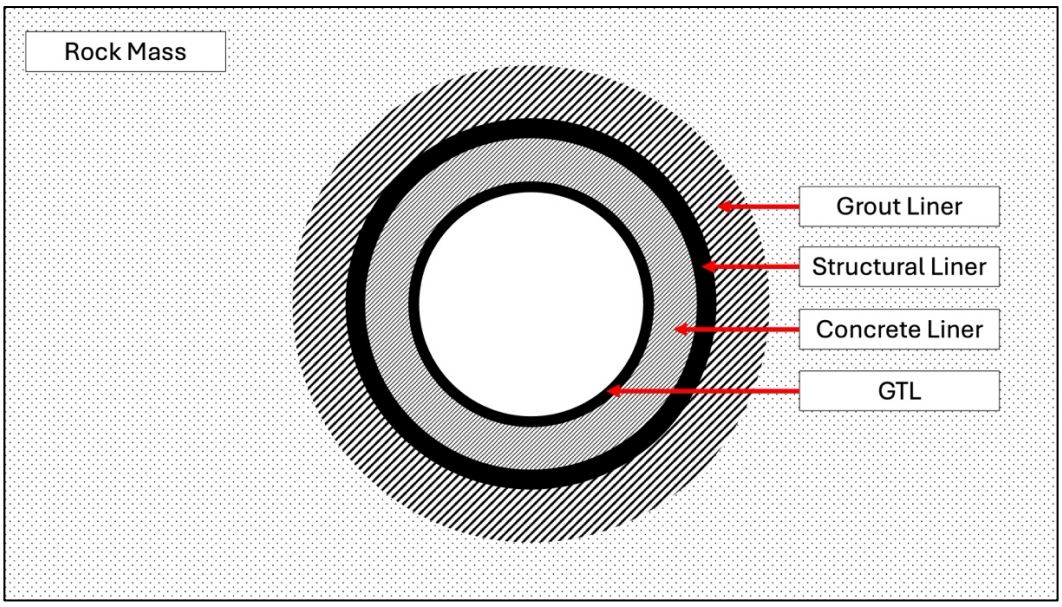


*Figure 1: LRS cross-section showing lining layers*

## 2.1 Abbreviations

Abbreviations used in this report are outlined in Table 1.

*Table 1: Abbreviations*

| | |
|---|---|
| ***LRS*** | *Lined Rock Shaft* |
| ***GTL*** | *Gas-Tight Liner* |
| ***CL*** | *Concrete Liner* |
| ***SL*** | *Structural Liner* |
| ***GL*** | *Grout Liner* |
| ***ALARP*** | *As Low As Reasonably Practicable* |
| ***WRA*** | *Well-Reasoned Argument* |
| ***ETZ*** | *Energy Transition Zone* |
| ***MOP*** | *Maximum Operating Pressure* |
| ***CGP*** | *Cushion Gas Pressure* |
| ***LRC*** | *Lined Rock Cavern* |
| ***UTS*** | *Ultimate Tensile Strength/Strain* |
| ***HE*** | *Hydrogen Embrittlement* |
| ***HEE*** | *Hydrogen Environmental Embrittlement* |
| ***IHE*** | *Internal Hydrogen Embrittlement* |
| ***HAZ*** | *Heat affected Zone* |
| ***TIG*** | *Tungsten Inert Gas* |
| ***TIP*** | *Technology Ingenieur Plasch* |
| ***NDT*** | *Non-destructive testing* |
| ***ECA*** | *Engineering Critical Assessment* |
| ***MLT*** | *Multi-Layer Testing* |

## 3.0 System Overview

The primary structure of an LRS is the containment. The multi-layered liner acts as one structure to provide gas-tight storage for the life of the system whilst transferring the load imposed by the high-pressure gas to the rock mass. The overburden, which is located above the containment, provides uplift resistance to the gas pressure acting vertically upwards. The overburden is within the scope of the civils sub-system. When considering the load transfer from the internal gas pressure to the surrounding support, both the rock mass and overburden must be considered. A casing string shall pass through the overburden which facilitates the injection and withdrawal of the stored gas.

The containment structure is shown in the general arrangement drawing. The dimensions of the LRS are provided in Table 2. The overall LRS shaft dimensions are based on the current understanding of the ground conditions at the Aberdeen Energy Transition Zone (ETZ) site. These may change once a ground investigation has been performed. The containment height assumes a cementitious material plug at the base of the shaft, then the containment, then the remainder of the shaft as the overburden. The thickness of the lining layers are the same as will be used for a full-scale LRS. The high-level material selections have been provided in Table 3. Further detail regarding materials is provided in the lining specific sections later in the report.

The cycle life of the technology demonstrator will be 5,000 full pressure cycles, (from cushion gas pressure (CGP) to maximum operating pressure (MOP) then back to CGP). This will be performed over a duration of approximately 22 months. The initial first c. 100 cycles will be performed with water, inert gas, and hydrogen as part of the commissioning and operational testing. The remaining cycles will be performed using water to complete the accelerated life testing. See document LGG-L057401-R03 Test Plan for more details.

*Table 2: LRS dimensions*

| Dimension | Value |
|---|---|
| Shaft Diameter (m) | 2.5 |
| Shaft Height (m) | 47 |

*Table 3: Containment materials*

| Layer | Material |
|---|---|
| GTL | Stainless Steel |
| CL | Structural Concrete |
| SL | Carbon Steel |
| GL | High strength Grout |

## 3.1 Key components

As previously noted, the key components of the sub-system are the GTL, SL, CL and GL. The primary functions of the different lining layers are given below. Further detail will be provided in later report sections.

**Gas tight liner:**

- Provide gas tightness
- Deform/expand under pressure without failure

**Concrete liner:**

- Load transfer to the rock mass, distributing deformation uniformly
- Resist ground and hydrostatic pressure loading
- Deform/expand under pressure without failure

**Structural liner:**

- Load transfer to the rock mass, distributing deformation uniformly
- Resist ground and hydrostatic pressure loading
- Limit concrete/grout cracking (concrete/grout reinforcement)
- Act as physical barrier to divide concrete and grout pours
- Impermeable barrier to groundwater ingress

**Grout liner:**

- Bond rock mass to lining system
- Level uneven rock mass surface (create smooth surface for SL to interface with)
- Load transfer to rock mass
- Limit water ingress
- Fill geological gaps and cracks around shaft

## 3.2 Legislation

The geomechanical and structural sub-system will be designed according to legislation where possible. High-level legislation requirements have been detailed in the requirements register LGG-L057401-R01. Further work is required to determine the specific sections and clauses applicable to the LRS.

Due to the novel nature of the LRS design, there are aspects of the system for which directly applicable design codes and legislation don't exist. For the geomechanical and structural sub-system, this applies to all components. The LRS containment does not straightforwardly comply with pressure vessel design codes because it uses the rock mass to help store the internal gas pressure. Despite this, PD5500 – Specification for Unfired Pressure Vessels, will be used as the primary guide for design and best practice where relevant.

Where the system cannot comply with any legislation/design codes, risks shall be designed to be ALARP with well-reasoned arguments (WRA) made presenting sufficient evidence/data for key design decisions. This was the method used to design Lined Rock Caverns (LRC) that have since been in commercial operation for underground gas storage for over 20 years (Johansson, 2003).

# 4.0 Lining behaviour

The multi-layer liner is designed to strain under internal pressure, transferring the load from the internal gas pressure to the rock. Therefore, the steel liner thickness can be reduced relative to unsupported pressure vessels and cost savings can be made. The LRS technology is designed for a wide range of geological conditions. In very hard/strong rock, there may be very little deformation of the lining. In poor/soft rock, a greater amount of deformation may be expected.

The first pressurisation of the LRS will be greater than MOP - when the system is hydrotested for containment commissioning (as detailed in LGG-L057401-R03 Test Plan). It is expected that there will be deformation of the lining and the rock mass. This deformation is expected to cause permanent deformation of the metallic liners (GTL & SL), and cracking of the cementitious liners (CL & GL). This is seen as part of the installation process of the LRS, rather than standard operation.

Following the initial pressurisation, the LRS will operate between its standard operating pressures. This will be from CGP of 30barg up to a MOP of 200barg. The CGP and MOP are subject to change following detailed geomechanical modelling using the data from a site ground investigation at the ETZ site.

## 4.1 Metallic liners

Following initial pressurisation, the deformation of the lining system is expected to be primarily elastic straining. It is expected that over the life of the system, the rock mass surrounding the LRS will consolidate.

The expected deformation behaviour of the metallic liners has been successfully demonstrated by analogous technology for over 100 years. This includes:

- **Lined Rock Caverns** – LRC technology has been in commercial operation for over 20 years for natural gas storage in Skallen, Sweden (Johansson, 2003). A pilot LRC has also been successfully demonstrated in recent years for the storage of gaseous hydrogen (Hybrit, 2025). LRC technology uses a large underground cavern lined with a multi-layer lining system similar to LRS design, to store gas at pressures up to 250barg, transferring the load of the gas pressure into the surrounding rock mass. It is constrained to operation in hard/strong rock conditions due to the excavation method used. The lining system has a thin metallic GTL which like the expected LRS GTL behaviour, sees plastic deformation on initial pressurization, with elastic straining thereafter.

- **Hydroelectric industry pressure shafts** – Pressure shafts are used to transport water from reservoirs to hydroelectric power plants to generate electricity. The shafts typically have a steel liner that is backfilled with a cementitious material. The internal pressures can reach 150bar, with dynamic pressures beyond 200bar, with fatigue loading from dynamic conditions often seen twice daily (Brekke, 1987). When rock conditions allow, the steel liner is designed to transfer some, or all the load from the water pressure to the surrounding rock. This results in the stress in the metal liner approaching 100-130% yield strength in some cases.

- **Cold stretched pressure vessels** – These are widely used in the process industry, typically for liquefied gases and cryogenic applications. A vessel is fabricated then over-pressurised to achieve significant plastic straining. The vessels are then used in the strained state, with the wall thickness of the vessel having been reduced by up to 30-50% compared to standard pressure vessels (Lu, 2021). Codes and standards exist for the design of such vessels including AS 1210 Supplement 2 (1999), EN 13458-2 (2002), ISO 20421-1 (2019), ISO 21009-1 (2022), and ASME Boiler & Pressure Vessel Code (BPVC) VIII-1 Appendix (2023). Such vessels have been used for low-cycle fatigue conditions (Miao, 2012), similar to the conditions which the LRS GTL will experience.

The metallic liners will have two primary failure modes – ultimate tensile strength (UTS) failure, or fatigue failure. UTS failure could occur from initial pressurisation, isolated rock failure or accumulated plastic straining. This will be addressed by the UTS of the selected materials.

Fatigue failure could be caused by the repeated pressure cycling of the LRS. Fatigue failure will be the most likely cause of failure of the metallic liners and therefore this will be of primary importance for the design of both liners. The mechanical properties of metallic materials can be negatively impacted by the presence of gaseous hydrogen. This will be addressed in later report sections specific to the two liners.

## 4.2 Cementitious liners and rock mass

The cementitious layers (CL and GL) and the rock mass will undergo a different deformation response due to their more brittle material properties. Under tension, they will crack at a lower stress condition. This will result in cracks forming. This has been shown in Figure 2. The upper sub-figure shows the lining system cross-section as seen in Figure 1, with CGP. The lower sub-figure shows the same lining cross section but with MOP. In this state, it shows cracks that have formed radially outwards within the CL, GL, and rock mass. These cracks will open and close as the internal pressure cycles between CGP and MOP.

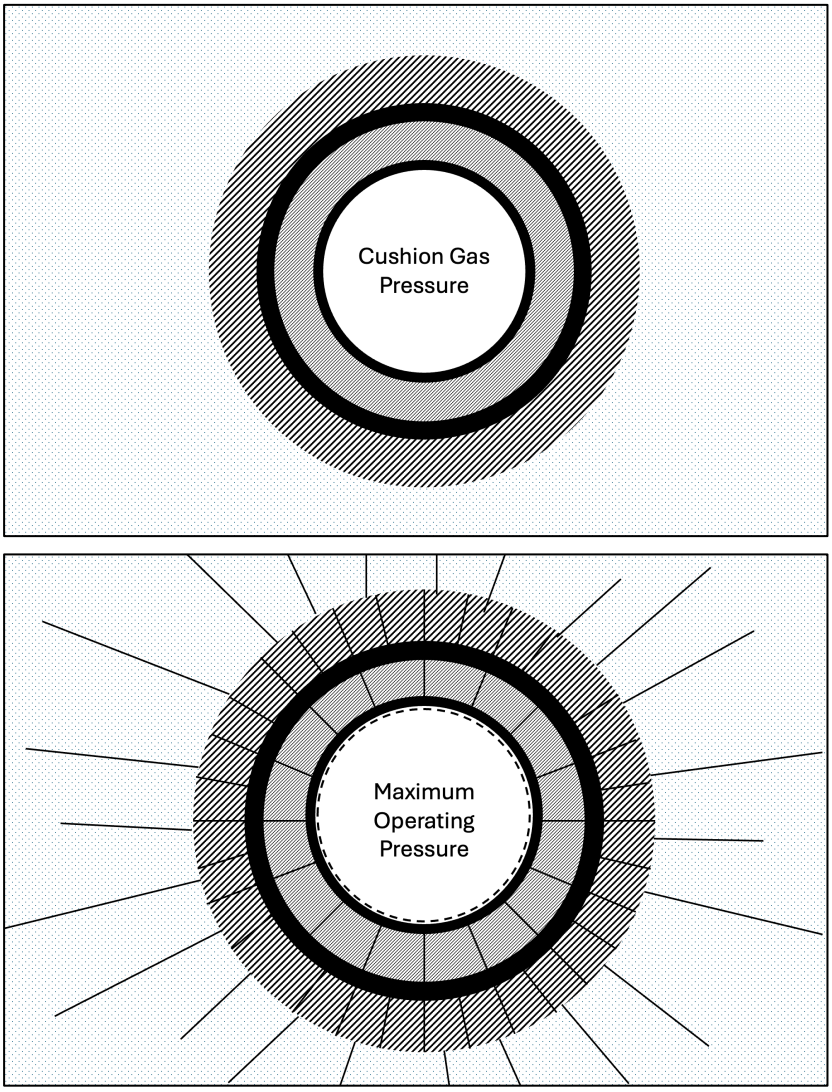


*Figure 2: Lining response to internal gas pressure of CGP (upper) to MOP (lower)*

The behaviour of the cementitious layers and rock mass is analogous to the behaviour of the concrete, shotcrete and rock mass as seen in LRC technology and is therefore deemed to be acceptable for the LRS technology. The specific material properties of the CL and GL will be addressed in the later report sections.

## 4.3 Geomechanical modelling

To determine the lining behaviour as described above and de-risk key aspects of the design, geomechanical modelling has been performed as part of the design development of the LRS technology. Following the Discovery phase of the Ofgem SIF project and prior to the beginning of the Alpha phase, further modelling has been performed. This included:

- **Scalability analysis** - This included modelling the LRS at varying excavated diameters to understand how the diameter of the lining system would impact the stress/strain response. This helped to inform the proposed diameter of the technical demonstrator system compared to a full-scale LRS. This increased the confidence of the expected lining behaviour and stress/strain that the lining might experience at the ETZ site.

- **Construction tolerances** - This included modelling the LRS with varying ovality of the GTL and varying concentricity of the GTL. This was performed to understand how sensitive the lining system is to changes in the thickness of the CL. It is highly likely that when the LRS is installed, there will be both some ovality and concentricity offset of the GTL. The modelling showed that the lining system is tolerant to some deviation and helped to inform the expected stress/strain response of the lining layers.

The modelling performed has helped to build upon the database of modelling results, therefore increasing the confidence of the response of the system to varying ground conditions and design/operation parameters.

The ground conditions at the ETZ site are expected to be favourable, a reason for its selection as the site for the technology demonstrator deployment. Once a desktop site investigation has been completed, more detailed modelling will be performed. Further modelling will also be performed once the data from the site ground investigation is available.

# 5.0 Gas-Tight Liner

The GTL is the primary containment liner for the LRS. Its purpose is to provide gas tightness and deform/expand under pressure without failure. For the technology demonstrator, gas tightness must be provided for the containment of water, inert gas and gaseous hydrogen.

To allow for the internal pressure to be transferred to the rock mass, the GTL liner is a thin wall structure, with significantly thinner wall section than would be specified for a pressure vessel with no additional pressure support. The liner sections will be made from welded steel plates.

## 5.1 Material

The primary considerations that drive material selection for the GTL are as follows:

- Resistance to HE
- High ductility
- Not prohibitively difficult to shape, form, and weld
- Not cost prohibitive

The nominated material for the GTL is stainless steel grade. Stainless steel is widely used in wet-corrosion environments, given its stable structure and pitting. It has high ductility, high strength, and is typically used for hydrogen applications.

Stainless steel has been used for the GTL of the LRC that has been successfully demonstrated for hydrogen service as previously referenced (Hybrit, 2025). Geomechanical modelling results show that the mechanical properties of stainless steel should be suitable for the expected operating conditions and site ground conditions.

Stainless steels can have excellent ductility, with high typical elongation at break values. This will ensure that even if greater deformation than expected is experienced, the material will still have a significant margin before UTS failure.

The stainless steel grade is expected to be suitably gas-tight and impermeable to hydrogen, with published literature showing very low permeation rates of hydrogen through stainless steel.

Alternative lower cost options for the GTL material were considered, but stainless steel was deemed most appropriate given the requirements.

### 5.1.1 Hydrogen Embrittlement

The entry of atomic hydrogen into metallic material can affect its mechanical properties, such as ductility, fracture toughness and tensile strength. This is commonly known as hydrogen embrittlement (HE), and can occur during different industrial processes such as welding, acid pickling, and electroplating. For the LRS technology, this may occur due to the GTL being exposed to highly pressurised gaseous hydrogen.

This is of high importance for the GTL, because the ductility and fracture toughness of the material will have a direct impact on the fatigue life, the primary failure mode of the LRS.

A degradation of the mechanical properties due to exposure to gaseous hydrogen whilst under an applied stress is typically referred to as hydrogen environmental embrittlement (HEE). This is most likely to occur at a notch or defect that results in crack initiation and accelerated crack propagation. A degradation of the mechanical properties due to diffusible hydrogen located within the metal that then moves to a highly stressed location in the metal is typically referred to as internal hydrogen embrittlement (IHE). This may also result in accelerated crack propagation.

Both HEE and IHE are a risk to the GTL. HEE because the GTL will be exposed to hydrogen during standard operating conditions, and IHE because of hydrogen already within the material, or that permeates into the material over the life of the system. The GTL will have notches, flaws, and defects present despite a quality manufacturing, fabrication, and NDT process; therefore locations of higher stress will occur that could result in crack initiation and propagation.

Different metals have different susceptibility to HE, therefore the selection of steel grade for the GTL is of critical importance to ensure safe operation throughout the system life. The primary factors that influence the susceptibility to HE are:

- **Diffusivity** – the speed that hydrogen can move through the metal. Higher diffusivity will make the metal more susceptible to HE because the hydrogen can move faster to a high-stress location, potentially accelerating crack propagation.
- **Solubility** – the concentration of hydrogen that can be within the metal lattice. A lower solubility will make the metal more susceptible to HE because it means it will become more easily saturated.
- **Permeability** – the rate at which hydrogen can enter the metal. A higher permeability will make the metal more susceptible to HE because the hydrogen can enter the metal faster.

Other factors that influence the effects of HE include:

- **Hydrogen gas pressure** – higher pressure will increase susceptibility to HEE
- **Material strain** – straining of the material can result in a phase transformation, resulting in a material more sensitive to HE. This is affected by the strain rate and the time held in a strained condition.
- **Temperature** – higher temperature will increase the solubility of hydrogen; however, it will also typically increase the diffusivity of metal

Stainless steel grades have been widely used in hydrogen gas applications and are presented as the highest rated steel type for resistance to HE in published literature. Within the stainless steel group, there are various grades with differing chemical compositions and therefore mechanical properties and susceptibility to HE. To down select the exact grade, a testing program is required, detailed later in the report.

## 5.2 Fabrication

The GTL will be fabricated from hot rolled plate. The welds will exhibit different characteristics to the parent material, and it is anticipated that the performance and fatigue life of the welds and the heat-affected zone will be most onerous to achieve. Due to the sub-surface nature of the LRS, there are minimal inspection and maintenance options for inside the GTL once it has been installed. This limitation means that ensuring the mechanical integrity of the lining system on installation is of critical importance, and therefore the welds must be of sufficiently high quality. Therefore, in defining the fabrication of the GTL, good quality welds and comprehensive NDT is prioritised.

### 5.2.1 GTL Geometry

For the cylindrical cans, the plate will be rolled to the required radius. Due to the diameter of the GTL, it is expected that plates will be rolled, with a single longitudinal weld to create a cylinder. Multiples of these cylinders will then be joined with circumferential welds performed to form the three GTL sections, as described earlier.

It is expected that both GTL end caps will be hemispherical in profile to provide maximum stress distribution, avoiding stress concentrations at the connection to the cylindrical sections. It is also expected that the fabrication of the end caps will be sub-contracted to a specialist manufacturer by the primary fabrication contractor. It is preferred that the manufacturer for the end caps for the technology demonstrator will also have the capability to produce the end caps for full-scale systems. Manufacturers who have the capability to produce end caps at sufficiently large diameters are not found in the UK, therefore it is expected that the production will be performed at one of the identified suppliers in Europe. Due to the specific high-quality welding required for the GTL, it is proposed that welders from the primary fabricator complete the welding for the dished ends.

### 5.2.2 Welding location

Workshop welding is preferred for all welds, however due to the size of the GTL and road transport limits, some welds must be completed on site. All welds of the individual GTL sections shall be performed in the workshop,

including the bottom end cap to the lower most cylindrical section, and the top end cap to the upper most cylindrical section. The welds between the cylindrical liner sections and the top cap to the production tube will be performed on site. The methodology for these site welds and the temporary works required has been described in LGG-L057401-R07 Construction Sequence.

For full-scale systems, it may be that full cylindrical sections of the GTL won't be road transportable due to their larger diameter, therefore longitudinal and circumferential welds to create the cylindrical sections will be required on site. In this case, tents and temporary structures (not over the shaft) will be required to create environmentally controlled conditions suitable for high quality welding.

#### 5.2.3 Weld filler material

A major stainless-steel manufacturer was approached for recommendations for weld filler materials. Two primary options were proposed, one free of ferrite, and one with a low ferrite number of 2. The option free of ferrite is expected to give the best weld performance in the LRS service conditions considering hydrogen service, however it has a higher risk of solidification cracking. To determine which weld filler material will be used, further testing is required, as discussed later in the report.

#### 5.2.4 Critical welds

The welded joints of the GTL are identified as the critical failure point, both for fatigue and HE. This is for the following reasons:

- The weld may have stress concentrations that act as crack initiation sites
- The weld may have imperfections such as cracks, pores, inclusions etc. that act as crack initiation sites
- The weld and the heat-affected zone will have different properties to the parent material which may have lower fatigue strength or be more susceptible to HE
- The weld may result in residual stress that will add to fatigue loading

The weld toe, root, any start/stop positions, or weld cross-over points on the inside of the GTL are the most likely sites for crack initiation if it is assumed the welds are free of internal defects.

Using fatigue quality levels, the Eurocode for fatigue calculations, and estimations for the loading at each of the welds, the number of cycles to failure can be calculated. After both the site desktop study and ground investigation are performed, geomechanical modelling will be performed to add confidence to the loading at each of the welds. It is important that the critical weld for the structure is determined because this will be the used to inform the materials testing program as discussed later in the report.

### 5.3 Engineering Critical Assessment and Non-destructive Testing

As mentioned in the previous section, due to the sub-surface nature of the LRS, there are minimal inspection and maintenance options for inside the GTL once it has been installed. This limitation means that ensuring the mechanical integrity of the lining system on installation is of critical importance, and therefore the welds must be of sufficiently high quality. To ensure the welds are of sufficient quality, a comprehensive NDT strategy is required.

To determine the NDT requirements, first an ECA must be performed. This is used to determine the cycle life of the structure given the expected defect size, loading scenarios, and the material properties. The ECA analysis uses a fracture mechanics approach, and will be performed according to BS 7910 – Guide to methods for assessing the acceptability of flaws in metallic structures.

Once the cycle life has been determined, the results will be used to determine an acceptable defect size which meets the system requirements and which can be detected using available NDT methods. Following fabrication of the liner, the NDT method can be used to demonstrate that any given defects in the structure will not cause failure within the system cycle life.

The ECA analysis has not yet been completed, and therefore the NDT procedure has not yet been specified. It is expected that very sensitive methods of NDT will be required due to the high strain experienced by the GTL. There will be 100% weld length inspection for all welds.

To perform the ECA analysis, material properties are required, including the fracture toughness. As previously detailed, HE can affect the fracture toughness of metals, increasing the vulnerability of the liner to crack initiation and propagation from defects. Currently no guidance exists in published design/fitness for service codes

regarding the impact of HE on fracture toughness. In addition, there is no published data for material properties of the proposed GTL materials for the LRS service conditions.

To provide preliminary results, the ECA will be performed using material property estimates according to guidance in published literature. Meanwhile, materials testing will be performed, including fracture mechanics testing of welded samples to determine the fracture toughness of the GTL. This can then be used to perform a robust ECA analysis, and thereafter the NDT procedure finalised.

## 5.4 Installation Considerations

To facilitate the transport and installation of the GTL, braces and guides may be temporarily installed internally to ensure it maintains its desired geometry. Fitment checks will be performed in the workshop before transporting to site. It is critical that the sections line up well on-site and that overlap/offset of the different sections is avoided prior to welding. Temporary lifting points will be added to the GTL prior to transport/install, which will be removed before the concrete annulus pour is begun.

## 5.5 Production Tube Interface

At the top of the GTL, the end cap will interface with the bottom end of the production tube. As described in the report 1103-002-01 Casing String Design as part of the Discovery phase, it is expected that a complex geometry will be required to ensure sufficient load transfer to the rock through the transition whilst avoiding stress concentrations.

Fabrication experts were engaged to determine possible interface designs, with supporting finite element analysis (FEA) modelling performed to understand suitability. Further work is required to down select the most suitable design. Thereafter, geomechanical modelling will be performed incorporating the proposed design to support the FEA modelling and ensure suitability for the technology demonstrator ground conditions.

# 6.0 Structural Liner

The SL is the secondary metallic liner for the LRS. Its primary structural purpose is to help transfer the load from the internal gas pressure to the rock mass, distributing the deformation uniformly, whilst deforming/expanding under pressure without failure. To distribute the deformation uniformly, it limits concrete/grout cracking by providing crack reinforcement from the adhesion/frictional interface between the steel and the concrete/grout. When the rock mass is loaded and deforms, it is likely that cracks will open, resulting in a non-uniform deformation. These cracks will likely result in a similar crack distribution at the interface with the grout. With the presence of the SL, these cracks should become more evenly distributed, such that the cracking in the concrete is evenly distributed, reducing the amount of uneven loading in the GTL. This desired behaviour is the same principle for the inclusion of a steel reinforcement mesh in the liner of a LRC (Johansson, 2003).

The SL provides additional structural purposes. During the installation procedure, it acts to resist ground and hydrostatic pressure loading from the surrounding rock mass whilst the remainder of the LRS is being installed. The SL will be most effective in resisting this external pressure once the GL has been installed. When installed, the SL continues to provide structural support from external loading when the internal gas pressure is low, or when the containment is empty.

The SL acts as a physical barrier during the installation procedure to divide the grout and concrete pours. It also acts as impermeable barrier to help limit groundwater ingress towards the GTL.

To allow for load to be transferred to the rock mass, the SL liner is a thin wall structure, but thicker than the GTL. The liner sections will be made from welded steel plates.

## 6.1 Material

The primary considerations that drive material selection for the SL are as follows:

- High ductility
- Not prohibitively difficult to shape, form, and weld
- Not cost prohibitive

The nominated material for the SL is a low carbon structural steel. They are widely used for structural applications and is suitable for use in sub-surface conditions. Similar grades of steel have been used for the internal liner for LRCs. Furthermore, low carbon steels with similar thickness to the LRS SL are often used as a shaft liner for standard lined shafts for the mining industry. Geomechanical modelling results show that mechanical properties of low carbon steel are suitable for the expected operating conditions and site ground conditions.

The only scenario that the SL would be exposed to high pressure gaseous hydrogen is in the event of a leak from the GTL. The low permeability of the GTL liner means that the SL will not be exposed to gaseous hydrogen during standard operation of the LRS. Therefore, the need for the SL to be resistant to HE is significantly less than the GTL, allowing a lower cost carbon steel to be used.

Alternative lower cost options for the structural liner material were considered, but low carbon steel was deemed most appropriate given the requirements.

## 6.2 Fabrication

The SL will be fabricated from rolled plate. Similar to the constraints detailed earlier for the GTL, the SL will be sub-surface, set within the CL and GL for the life of the system. This means that once installed, no inspection or repairs will be possible for the SL. This limitation means that ensuring the mechanical integrity of the lining system on installation is of critical importance, and therefore the welds must be of sufficiently high quality. However, as detailed previously, the SL will not be exposed to high pressure gaseous hydrogen during normal service and therefore the need for high-quality welding is less than for the GTL, but still important. A comprehensive NDT program will still be required.

### 6.2.1 SL Geometry

Similar to the GTL, the cylindrical cans will be formed from plate rolled to the required radius. Both longitudinal and circumferential welds will be performed. Only one end cap is required for SL. The end cap is expected to be hemispherical in profile to provide maximum stress distribution, avoiding a stress concentration at the connection to the cylindrical section.

### 6.2.2 Welding location

Similar to the GTL, workshop welding is preferred for all welds, however due to the size of the SL and road transport limits, some welds must be completed on site. All welds of the individual SL sections shall be performed in the workshop, including the bottom end cap to the lower most cylindrical section. The welds between the cylindrical liner sections will be performed on site. The methodology for these site welds and the temporary works required has been described in LGG-L057401-R07 Construction Sequence.

For full-scale systems, it may be that full cylindrical sections of the SL won't be road transportable due to their larger diameter, therefore longitudinal and circumferential welds to create the cylindrical sections will be required on site. In this case, tents and temporary structures (not over the shaft) will be required to create environmentally controlled conditions suitable for high quality welding.

### 6.2.3 Welding Methodology

The welding methodology for the SL has not yet been defined, as it is expected that industry standard methods can be adopted. Welding requirements for the SL will be less onerous than the GTL and do not require a material test programme.

The welding methodology shall be defined on further engagement with fabrication experts at a later stage of the design.

### 6.2.4 Weld filler material

A standard weld filler material will be suitable for the fabrication of the SL, and therefore it will be specified on further engagement with fabrication specialists.

### 6.2.5 Critical weld

The loading on the SL will be less than the GTL, and it won't be providing gas-tightness for hydrogen containment. There is no requirement for testing of the SL parent material or welded samples, therefore there is no need to determine the critical weld.

## 6.3 Engineering Critical Assessment and Non-destructive Testing

As detailed earlier, the mechanical integrity of the lining system on installation is of critical importance, and therefore the welds must be of sufficiently high quality. To ensure the welds are of sufficient quality, a comprehensive NDT strategy is required.

Similar to the GTL, to determine the NDT requirements, first an ECA must be performed. The allowable defect size for the SL will be determined, then NDT methods can be chosen that will sufficiently characterise these defects. Once Fabrication has been completed, it will be possible to assure that all defects in the SL shall not give rise to failure within its cycle life.

The ECA analysis has not yet been completed, and therefore the NDT procedure has not yet been specified. It is expected that sensitive methods of NDT will be required due to the high strain experienced by the SL. There will be 100% weld length inspection for all welds.

Unlike the GTL, the material properties required to perform the ECA analysis are well understood. At a later design maturity, the ECA shall be performed and the NDT procedure specified.

### 6.4 Installation considerations

To facilitate the transport and installation of the SL, braces and guides may be temporarily installed within to ensure it maintains its desired geometry. Fitment checks will be performed in the workshop before transporting to site. It is critical that the sections line up well on-site and that overlap/offset is avoided prior to welding. Temporary lifting points will be added to the SL prior to transport/installation, which will be removed before the grout annulus pour is begun.

# 7.0 Concrete Liner

The CL works in unison with the SL to provide structural support to the LRS, with its primary purpose to transfer load to the surrounding rock mass. In addition, the CL shall distribute deformation under load uniformly, resist ground and hydrostatic pressure loading whilst deforming/expanding under pressure without failure.

The use of concrete for structural purposes is commonplace, however, the expectation and need for concrete to crack in service is uncommon. The concrete cracking behaviour, explained earlier, will occur when the lining expands. This is the same behaviour that is expected and observed in LRC operation (Johansson, 2003).

The CL will be created by filling the annulus between the GTL and SL as described in the construction sequence (LGG-L057401-R07).

## 7.1 Material

The primary considerations that drive material selection for the CL are as follows:

- Resist the loading experienced during the life of the system
- Suitable for installation for the technology demonstrator and full-scale systems
- Suitable for sub-surface conditions for the life of the system

### 7.1.1 Mechanical

The nominated material is a standard high strength concrete mix. Geomechanical modelling has been performed using a high strength mix, with results showing acceptable behaviour.

As stated above, the concrete is expected to crack during service. There is also a requirement of a fatigue life of at least 5,000 cycles. Concrete experts have informed that there are mixes that should be suitable for the application. Other applications such as wind-turbine foundations require a fatigue life >1 million, and although cracks will form in the CL, they are expected to be very small in size therefore having limited impact on the fatigue life.

### 7.1.2 Installation

The more strenuous requirements imposed on selecting a concrete mix is from the installation. The same mix should be used for the technical demonstrator as for full-scale systems, and therefore it needs to be suitable for installation up to depths of 300m, with even greater pump depths. Considerations for installation include:

- High flow to reach the required depths
- Avoid segregation
- Low shrinkage to avoid voids forming
- Low hydration heat to avoid overheating
- No washout due to pouring in submerged conditions
- Appropriate cure time

The concrete mix requirements were discussed with various concrete experts. Specific additives will be used in the mix to help in achieving the behaviours required. The delivery depth was seen as no issue, with similar flow requirements seen in other applications, including the pumping distance. The flowability of the concrete would be tested prior to the pour onsite, and flow could be monitored at intervals during the delivery to ensure it was flowing as expected.

A standard aggregate size may be used, with segregation to be considered, but not seen as a prohibitive issue. Freefall of the concrete will be minimised in the delivery pipes to help avoid segregation.

A non-shrink concrete mix will be used, however some shrinkage will still occur. Drying shrinkage will be minimised due to the submerged conditions when curing, but chemical shrinkage will still occur. Once a mix has been defined, the amount of shrinkage expected will need to be considered in the design.

To minimise heat build-up during curing, a low heat of hydration is required. Where possible, this will be targeted with additives. Pouring the concrete submerged under water will also help to reduce heat build-up.

To minimise wash-out, when the concrete is delivered to the base of the shaft, freefall through water will be avoided.

The cure time for the concrete needs to be long enough so that it can be mixed and delivered to depth, but ideally quick enough such that it can begin to set at full depth, whilst it is still being poured at a shallower depth. Separate pours will be avoided where possible, to avoid cold faces, that could result in a weaker CL. The cure time is proposed to be *c*. 2-6hrs, but this may change following further engagement with concrete experts.

# 8.0 Grout Liner

The GL acts to bond the SL to the rock mass. When the shaft is excavated, the shaft wall will likely be rough and uneven (depending on the ground conditions and the construction methodology). Once the SL is installed, grout will fill the annulus between the SL and the rock mass. With a much smaller aggregate size than the CL, the grout will flow into the cracks and voids in the rock, creating a robust and strong connection. Pre-grouting will have been performed prior to shaft excavation filling any extensive fracture networks and voids in the rock mass. Grout is commonly used in the annulus between an excavated shaft and a steel liner for other applications such as the mining industry, and more generally for structural applications when a bond is required with an uneven surface.

Similar to the SL and CL, the GL acts to transfer the load from the gas pressure into the surrounding rock mass. The GL is also expected to crack when the lining expands, similar to the concrete in LRC operation (Johansson, 2003). Despite cracks forming, the GL is expected to provide some prevention of water ingress from the rock mass, especially when the internal gas pressure is low, and the cracks have closed.

The GL will be created by filling the annulus between the SL and the excavated shaft as described in the construction sequence (LGG-L057401-R07).

## 8.1 Material

The primary considerations that drive material selection for the GL are as follows:

- Resist the loading experienced during the life of the system
- Suitable for installation for the technology demonstrator and full-scale systems
- Suitable for sub-surface conditions for the life of the system

### 8.1.1 Mechanical

The nominated material is a high strength grout mix. Geomechanical modelling has been performed using a high strength mix, with results showing acceptable behaviour. It is also expected that the fatigue life of 500 cycles should be feasible.

### 8.1.2 Installation

Similar to the CL, the more strenuous requirements imposed on selecting a grout mix is from the installation. The same mix should be used for the technical demonstrator as for full-scale systems, and therefore it needs to be suitable for installation up to depths of 300m, with even greater pump cepths. Considerations for installation include:

- High flow to reach the required depths
- Avoid segregation
- Low shrinkage to avoid voids forming
- Low hydration heat to avoid overheating
- No washout due to pouring in submerged conditions
- Sufficient cure time

The grout mix requirements were discussed with various grout experts. Specific additives will be used in the mix to help in achieving the behaviours required. Similar to the CL, the requirements are deemed as achievable, with many of the same methods/mitigations used.

A small aggregate size is proposed, with segregation to be considered but not seen as a prohibitive issue. Freefall of the grout will be minimised in the delivery pipes to help avoid segregation. A non-shrink grout mix will be used, however some shrinkage will still occur. Hydration heat is not seen as in issue, aided by delivering in submerged conditions, with a slow delivery rate. Freefall through water will be minimised where possible, with grout delivered below the surface of already poured grout where possible. Again, the cure time for the grout has similar requirements to the concrete, with a cure time of 2-6hrs proposed.

## 9.0 Pre-demonstration test program

The LRS technology requires a robust development program. As detailed in the Basis of Design (LGG-L057401-R04), this includes three major stages which are:

- Determination of design data for GTL
- Verification and correlation of multi-layer behaviour under pressure
- Verification and correlation of rock mass behaviour.

The first will be achieved by performing a GTL materials test program, and the second by performing multi-layer liner testing. These are both described in more detail in the following sections. The last stage is achieved with the technology demonstrator.

### 9.1 Materials Test Program

The aim of the materials test program is to first determine the most suitable parent and weld filler material for the GTL, then determine the design data.

As discussed earlier, different materials are affected differently by exposure to gaseous hydrogen. Their susceptibility to HE is very dependent on the operating conditions, and therefore they must be tested in the expected conditions of the LRS. No test data exists for the materials of interest in the expected conditions, therefore the testing must be performed. The following parameters are some of the conditions that must be controlled:

- Gas purity
- Gas pressure and cyclic profile
- Temperature profile
- Strain levels, amplitude, cycle time, number of cycles etc.
- Strain direction
- Steel grade and condition
- Rolling direction
- Steel thickness
- Weld methodology and condition
- Weld geometry and quality
- Residual stresses
- Service time

All these parameters must be as close as possible to the expected operating conditions to ensure that any test data is relevant for LRS service conditions.

To test the material's sensitivity to HE, mechanical testing must be performed with exposure to hydrogen. There are different methods for exposing samples to hydrogen during testing.

The first method is to pre-charge test samples with hydrogen, then perform mechanical testing thereafter. The pre-charging introduces atomic hydrogen within the metallic structure, which tests the sensitivity to IHE. The second method is to perform mechanical testing in a hydrogen environment. This tests the sensitivity to HEE. Testing in a hydrogen environment is similar to the operating conditions at the start of service life, but won't have allowed hydrogen to permeate into the material over time, as would happen in service. Pre-charging is often used to saturate the material with internal hydrogen to simulate it having been in a hydrogen environment for a prolonged period. A combination of both methods is often used, and shall be the approach used for the GTL materials test program.

To achieve pre-charging, test samples will be exposed to high-pressure gaseous hydrogen at elevated temperature. The elevated temperature results in faster up-take than at lower temperatures.

To perform testing in a hydrogen environment, two methods exist, both of which shall be used for the test program. The first is to test in an autoclave – a high-pressure chamber that can be filled with hydrogen, with a traditional mechanical test method performed, with the sample within the pressure chamber. This is considered the most accurate method and typically used for testing where design data is required. It is usually more expensive however, and there are fewer test facilities with the capability to perform this method.

The second method is to perform a traditional mechanical test but using a hollow sample, with high-pressure hydrogen within the sample. This would be performed according to ISO 7039:2024 Metallic materials — Tensile testing — Method for evaluating the susceptibility of materials to the effects of high-pressure gas within hollow test pieces. This is usually a cheaper method that can make use of less complex equipment. However, it is considered to be less accurate and therefore it is typically only used for screening testing.

### 9.1.1 Material Screening

To screen the parent material and the welded samples, slow strain rate testing (SSRT), fatigue testing, and hydrogen uptake testing shall be performed. The parent material screening will be used to determine the specific grade within the stainless steel group to use. The welded sample screening will be used to determine which of the two proposed weld filler materials to use. All tests will be using the hollow sample method for hydrogen exposure. Although the hollow sample method is less representative of service conditions, it is suitable, and a common method for screening. This is because the results will only be used to compare between options, rather than as design data. Figure 3 shows a section view of a hollow sample test specimen. It is similar to a standard tensile test specimen but with a hollow centre that will be filled with hydrogen during the testing.

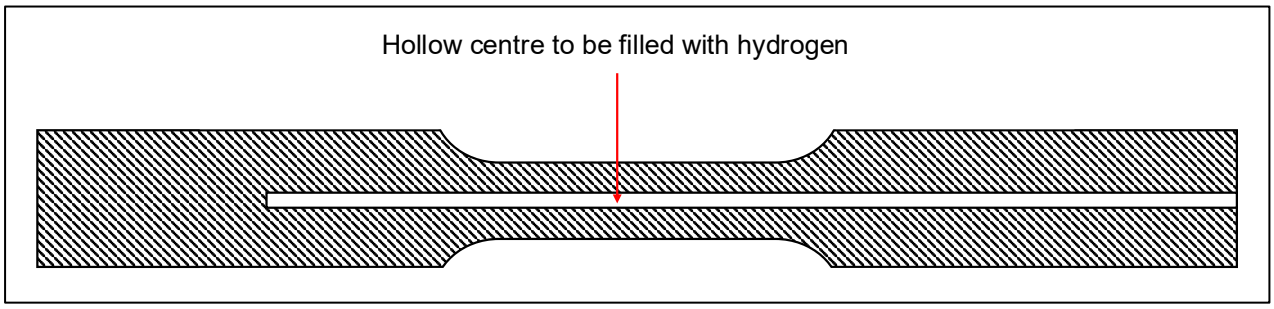


*Figure 3: Hollow sample test specimen section view*

#### 9.1.1.1 Parent Material Screening

First, the parent material shall be screened, with two candidates being compared. The aim of the tests will be to understand both materials sensitivity to HEE, IHE, and the impact of temperature for the expected LRS operating conditions.

#### 9.1.1.2 Weld Screening

The weld screening will be performed using fatigue testing and uptake testing of hollow samples. Testing will be performed for both of the parent material options, both with two weld filler material options. This will give four potential weld options. The test methodology for each will be determined once relevant results have been obtained from the parent material testing, such as whether to test pre-charged or not.

The results of both the parent material screening and weld screening will highlight the most suitable parent material and weld material combination for the LRS service conditions. It will also show the sensitivity of the combination to hydrogen up-take, and give an indicative cycle count to failure. Given that the weld is expected to be the critical failure point for the GTL, it is expected that the welded sample test will have the lower cycle count to failure. With a selected parent material and weld, more detailed testing will be performed to obtain design data.

Following the screening testing, a final weld procedure will be developed, considering the chosen weld filler material. It is anticipated that this activity will align with the results of the site ground investigation. This will allow more detailed geomechanical modelling to be performed and the critical weld of the GTL determined. Ground investigation results will allow modelling to be refined to provide final strain conditions for the GTL and therefore inform the test conditions required for deriving design data.

### 9.1.2 Fatigue and Fracture Mechanics testing

The design data that is required shall be obtained by performing fatigue and fracture mechanics testing. This will be performed using traditional mechanical testing specimens in an autoclave. Given that the weld is the critical failure location for the GTL, all testing shall be performed with welded specimens.

As detailed earlier, the results from the fatigue and fracture mechanics testing are required to complete the ECA analysis. This will determine the allowable defect size in the GTL to ensure sufficient fatigue performance. Using this information, the NDT procedures can be defined, to provide validation that the manufacture and fabrication of the GTL is to specification.

## 9.2 Multi-layer Liner Testing

The aim of the multi-layer liner testing (MLT) is to verify and correlate the LRS liner behaviour under pressure to the design calculations and geomechanical modelling. As detailed earlier, geomechanical modelling is critical in determining the behaviour of the LRS in the ground conditions at the ETZ site. It is however a computational method modelling a system with complex material behaviour for which there is no specific data to verify against. To ensure that the system will behave as modelled in the real world prior to the deployment of the technical demonstrator, the MLT will be performed.

The specific behaviours that the MLT aims to test are:

- Effect of cyclic loading on the liner
- Cracking behaviour of the GL and CL
- Impact of cracking on the SL and GTL
- Impact of leak management equipment and instrumentation

The test will be used to demonstrate the suitability of the monitoring equipment within the lining, but also to collect data for the lining response. This will check that the instrumentation planned for the technical demonstrator will provide the data required. Additional monitoring will be used during the testing to check that the equipment installed within the lining is giving the correct results.

To understand the CL and GL cracking behaviour, visual examination will be used for the upper and lower end, then additional inspection or NDT methods may also be employed.

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ENERGY REFORM
MODELLING THE ENERGY TRANSITION

# B-Linepack+ Alpha

## Deliverable 8 – Energy System Modelling

**30/01/2025**

# Executive Summary

This report presents the results of energy system modelling undertaken for Deliverable 8 of the B-linepack+ Alpha project. The analysis evaluates the potential system-level value of distributed short-duration hydrogen storage (B-linepack+) within a future, highly renewable, co-optimised electricity and hydrogen system in Great Britain. In hydrogen transmission networks, pipeline linepack is substantially lower than in today's natural gas system due to hydrogen's lower volumetric energy density, reducing an important source of operational flexibility at the same time as system variability increases.

The study uses the open-source Spine modelling framework to represent co-optimised operation of the electricity and hydrogen systems, including a pressure-driven gas network formulation that captures pipeline linepack, nodal pressure constraints, and short-term system balancing requirements. A 2040 GB energy system is modelled based on ENTSO-E's TYNDP 2024 National Trends scenario, reflecting high renewable penetration, widespread electrification, and moderate hydrogen demand. A Base case with no additional short-term hydrogen storage is compared against scenarios with B-linepack+ deployment and two counterfactual storage options: Liquid Organic Hydrogen Carriers (LOHC) and additional large-scale salt cavern storage.

Results show that in a hydrogen system with significantly reduced linepack capacity relative to natural gas, pipeline linepack continues to play a critical role in providing short-term flexibility. In the absence of additional storage, the system relies heavily on linepack to balance intraday and short-term variations in hydrogen supply and demand, leading to relatively high average and peak daily pressure-driven linepack swings.

Introducing distributed B-linepack+ storage materially alters system operation. Despite representing a modest increase in total hydrogen storage capacity (approximately 30.5 GWh, or less than 1% of total system storage), B-linepack+ consistently reduces both average and maximum daily linepack swings. This reduction in pressure cycling implies lower compressor utilisation, reduced mechanical stress on the transmission system, and associated reductions in transport-related costs. In contrast, the counterfactual storage technologies examined are substantially less effective at managing short-term system flexibility: LOHC storage is constrained by lower round-trip efficiency, while additional salt cavern capacity primarily supports longer-term balancing and import/export optimisation.

Deployment of B-linepack+ delivers meaningful system-wide cost savings relative to the Base case, driven by a combination of reduced reliance on hydrogen imports, increased utilisation of low-cost renewable electricity through electrolysers, and reduced dependence on transmission linepack and associated compression. B-linepack+ is the only storage option considered that simultaneously delivers cost reductions, renewable curtailment reductions, and a material decrease in linepack utilisation.

While results are system-specific and sensitive to modelling assumptions, the analysis demonstrates that geographically distributed, efficient, and fast-response hydrogen storage can play a valuable role in replacing flexibility historically provided by natural gas linepack. The findings indicate that relatively

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# 1. Introduction

This report summarises the modelling and analysis completed for Deliverable 8 (Energy System Modelling) of the B-linepack+ Alpha project. In hydrogen transmission networks, linepack energy—i.e. energy content of the gas stored in high-pressure pipelines— is expected to be substantially lower than in today's natural gas system. Linepack provides valuable operational flexibility, which becomes increasingly important in high-renewable energy systems due to greater variability in net demand (the demand to be met after accounting for production from variable renewables such as wind and solar) and, where hydrogen is produced via electrolysers, variability in hydrogen supply driven by renewable generation and electricity prices.

The report is organised as follows. Section 2 describes the objectives of Deliverable 8 and provides an overview of the Spine toolchain (Spine Toolbox and SpineOpt), including the pressure-driven gas transfer formulation implemented. The focus of the modelling work in the Alpha phase is also described. Section 3 describes the GB model implemented in SpineOpt, including the electricity network, the gas network, the scenario and portfolio assumptions, and the dispatch modelling approach. Section 4 describes the storage representations implemented to complete the analysis. Section 5 summarises results, comparing system costs with and without additional storage. Section 6 provides discussion and conclusions.

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# 2. D 8 High Level Objectives

The objective of this deliverable is to evaluate the potential energy system benefits of deploying B-linepack+ at scale within the GB energy system. In a high-renewables, hydrogen-based future, electricity and hydrogen networks become increasingly integrated. Weather conditions drive variability in both energy demand and renewable generation, which in turn affects electricity prices and the optimal scheduling of electrolysers for hydrogen production. Managing this intra-day and seasonal variability requires increased system flexibility, including storage, to maintain efficient operation of both the electricity and hydrogen systems. While the need for system flexibility increases due to this increased variability, on the other hand, the linepack in a hydrogen-based network is reduced, due primarily to the lower energy density of hydrogen compared to natural gas. B Linepack+ supplements this flexibility by providing additional localised hydrogen storage. The objective is thus to quantify the value across the GB system of this increased flexibility.

Co-optimising electricity and hydrogen operation can improve overall efficiency and reduce system costs, but it requires a modelling framework capable of representing both networks at sufficient detail. The modelling approach used in this deliverable is therefore designed to capture co-optimised operations and to quantify the system impacts of additional flexibility options, including B-linepack+, in terms of costs, renewable curtailment, and reliance on transmission linepack.

## 2.1. Spine

The Spine open-source energy system modelling framework was used to complete Deliverable 8. The Spine modelling framework[1] was initially developed as part of the Horizon 2020 project, “Spine”. The framework consists of two main components. Spine Toolbox (see Figure 1), is used to create projects and manage complex workflows, and SpineOpt[2] is the native energy system modelling component.

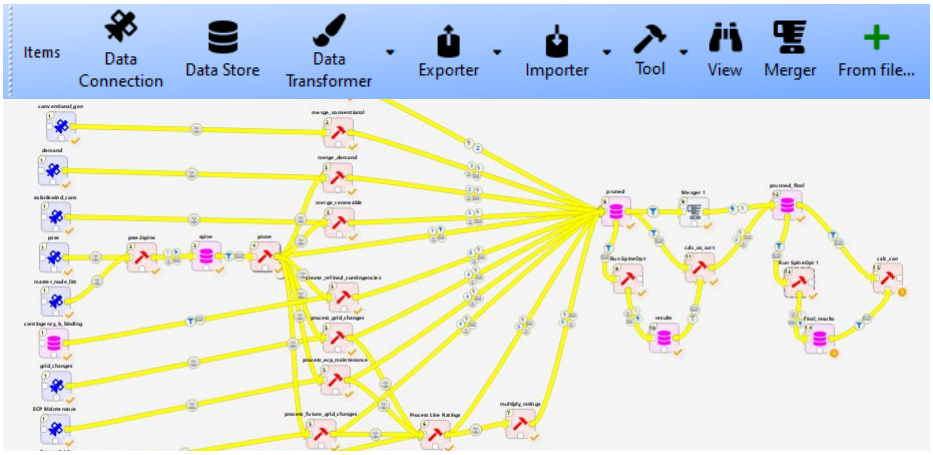


FIGURE 1 SPINEOPT WORKFLOW OF A NETWORK MODEL, INCLUDING DATA, TRANSFORMATIONS AND ANALYSIS

[1] https://github.com/spine-tools
[2] https://www.sciencedirect.com/science/article/pii/S2211467X22000955



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small amounts of strategically located distributed storage can significantly enhance operational robustness in future hydrogen networks, supporting a cost-effective and resilient transition to a hydrogen-based energy system in Great Britain.

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These were specifically developed to manage many of the key modelling challenges faced when analysing the energy transition.

SpineOpt's generic nature allows any energy carrier and energy transformation, indeed any combination of energy carriers and energy transformations to be modelled. The flexible structure and temporal resolution allows different energy carriers and different parts of a system to be modelled at variable levels of detail, giving modellers the ability to tune the models, focussing on the area of interest while managing the model size of these complex optimisations. This unique structure makes SpineOpt particularly well suited for modelling integrated energy systems. An arbitrary level of sector coupling becomes straightforward within the same framework, greatly expanding the scope of what is possible within a single model. Figure 2 below illustrates how many different conversions and processes can be implemented in SpineOpt using the basic fundamental elements of units, connections and nodes.

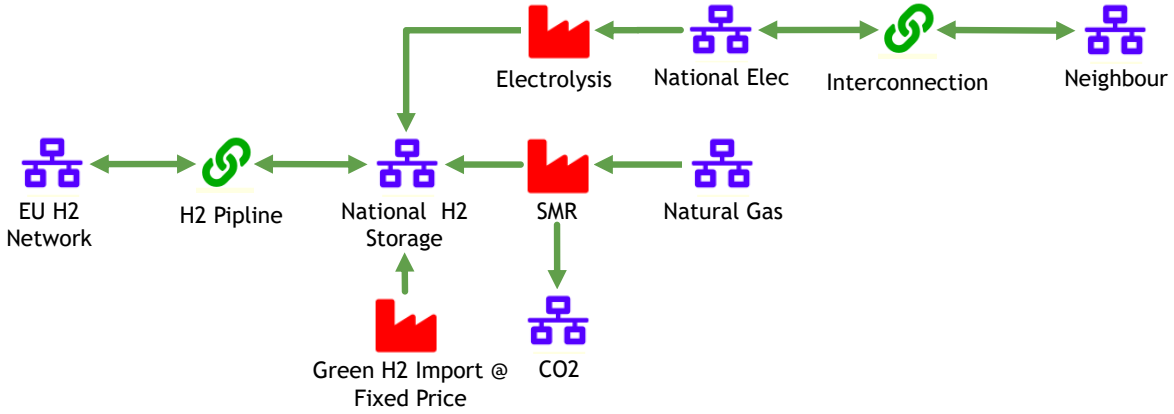


FIGURE 2 SECTOR COUPLING IN SPINEOPT

## 2.2. Pressure-driven Gas Transfer

Another key feature of SpineOpt is the ability to model pressure driven gas transfers. The Weymouth equation (see equation 1), which can be used to describe the gas flow between two points depending on the pressures at those points, is nonlinear.

$$q_{m,u,t} = K_{m,u}\sqrt{p_{m,t}^2 - p_{u,t}^2} \quad \forall\,(m,u) \in Z \;\forall\, t \in T \tag{1}$$

To be included in a larger energy system model, a suitable linear approximation to this constraint is required. In SpineOpt, bidirectional gas flows, accounting for linepack, are modelled using a tractable mixed-integer linear programming (MILP) formulation along with parameters for the supply and demand, the physical network and the gas properties, allowing pressures and gas flows across the network to be approximated.



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Where $q$ is the gas flow in pipeline $(m,u)$ in period $t$, $K_{m,u}$ is the Weymouth gas flow constant of the pipeline, and $p_{m,t}$ and $p_{u,t}$ are the pressures at nodes $m$ and $u$ in period $t$. $T$ represents the set of time periods and $Z$ represents the set of gas pipelines $(m,u)$.

Each equality constraint in the model is replaced by a set of linear inequalities, that approximate the Weymouth equation around fixed pressure points[3] (see equation 2).

$$q_{m,u,t} \approx K_{m,u}\left(\frac{P_{m,v}}{\sqrt{P_{m,v}^2 - P_{u,v}^2}} p_{m,t} - \frac{P_{u,v}}{\sqrt{P_{m,v}^2 - P_{u,v}^2}} p_{u,t}\right) \forall\,(m,u) \in Z, \forall\, v \in V,\ \forall\, t \in T \qquad (2)$$

Where $P_{m,v}$ and $P_{u,v}$ represent fixed pressure points for nodes $m$ and $u$. $V$ represents the set of fixed pressure points.

A binary variable, in combination with a big M constant (set to higher than the maximum possible flow in the pipeline) is used to ensure that gas flow only occurs in one direction for a given time period. For more details on the methodology, please refer to Schwele et al[3].

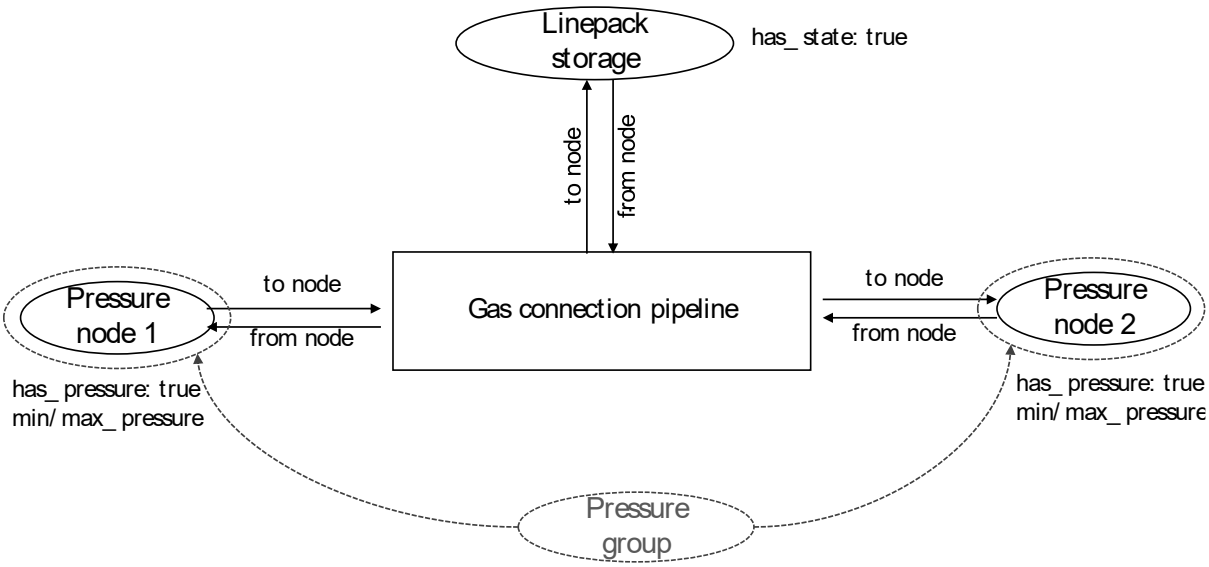


FIGURE 3 LINEPACK MODELLING IN SPINEOPT

To represent the gas network in SpineOpt, nodes at either end of each pipeline are specified and described with a maximum and minimum pressure. A third node is introduced to represent the linepack, internal pressure-linked storage associated with the pipeline. The pipeline is represented as a connection in SpineOpt, and fixed pressure constants, to facilitate the Weymouth approximation, are calculated for each connection and node pair. It is necessary to specify the number of fixed pressure points required and supply a Weymouth constant for each pipeline (depending on the

[3] https://ieeexplore.ieee.org/document/8810632



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physical properties of the pipeline and the gas being transported). A linepack constant describes the storage capacity of the pipeline per unit of pressure.

## 2.3. Alpha Phase

During the Discovery phase, the emphasis was on demonstrating the impact of reduced linepack in a large-scale, integrated electricity and hydrogen energy system compared to a natural gas system. This work examined the loss of system flexibility associated with reduced linepack and assessed the potential role of alternative storage solutions in replacing that flexibility. A combined gas and electricity test system previously studied in the literature was selected and implemented in SpineOpt to enable benchmarking. The benchmark system was converted from natural gas to hydrogen, the resulting reduction in flexibility was quantified, and alternative storage solutions, including B-linepack+, were introduced and compared. While the absolute value of storage is system-specific, the use of a benchmarked test system enabled robust comparison of alternative solutions and their relative ability to replace lost flexibility.

In the Alpha phase, this work is extended from a test system to a 2040 representation of the combined GB gas and electricity systems. The focus shifts to a fully co-optimised electricity and hydrogen system operating under a future high-renewables portfolio. A Base case (2040 portfolio with no additional short-term storage) is first modelled. A B-linepack+ solution with discrete deployments distributed across the network is then introduced and evaluated relative to the Base case using key system metrics. Two counterfactual storage solutions—liquid organic hydrogen carriers (LOHC) and additional salt cavern storage—are also modelled and compared against the B-linepack+ case.

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# 3. G.B. System Study

In the Alpha phase, the analysis moves from the benchmark test system used in the Discovery phase to a full model of the integrated electricity and hydrogen energy system in Great Britain in 2040. This transition enables the value of B-linepack+, previously demonstrated under controlled benchmarking conditions, to be assessed within a realistic, future GB system context.

## 3.1. Electricity Network

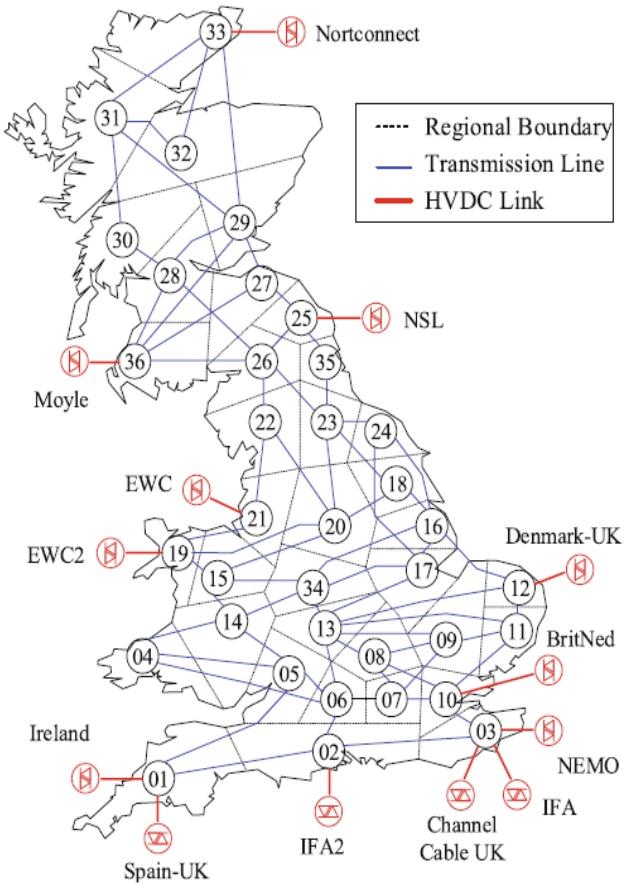


FIGURE 4 SIMPLIFIED GB ELECTRICITY TRANSMISSION NETWORK[4]

The electricity network is represented by a simplified 36-bus network. An updated network model in PSS/E format was provided by NESO, with an updated view regarding grid reinforcements in a 2040

[4] Azizipanah-Abarghooee, R., Malekpour, M., Karimi, M., Terzija, V., Development of the equivalent Great Britain 36-zone power system for frequency control studies, International Journal of Electrical Power & Energy Systems, Vol. 153, 2023.



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GB system. The network data was converted to Spine format. Using Network Prune[5], the final transmission model was presented as a 36-bus model with demand aggregated across the 36 nodes.

## 3.2. Gas/Hydrogen Network

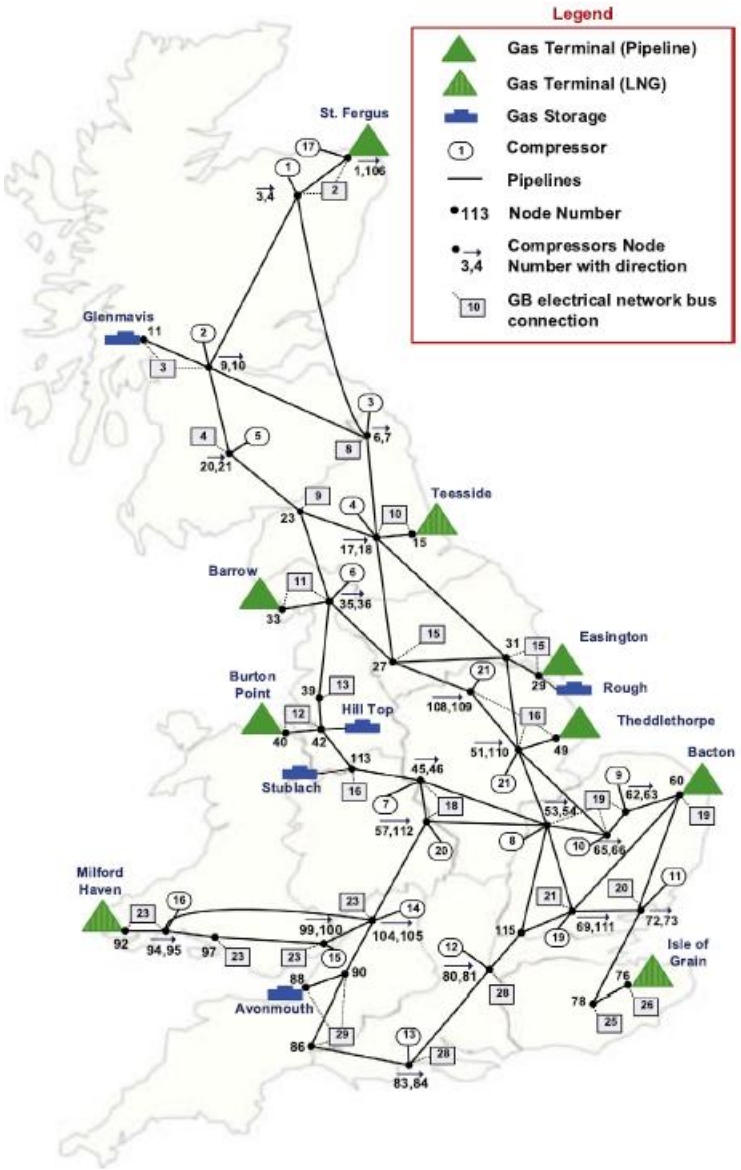


FIGURE 5 GB SIMPLIFIED GAS NETWORK[6]

[5] https://github.com/spine-tools/Network_Prune
[6] Ameli, H., Qadrdan, M., Strbac, M., Value of gas network infrastructure flexibility in supporting cost effective operation of power systems, Applied Energy, Vol. 202, 2017.



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A simplified GB gas network with 42 nodes and 54 pipelines, based on the work of Qadrdan from Cardiff University[7] was implemented in Spine. The simplified topology was reviewed and validated by National Gas engineers, with updates made where required, particularly in relation to the location of large-scale storage facilities.

Pipeline characteristics (including diameter and length), gas properties and node pressure limits are used to support pressure-driven gas transfer modelling. Based on these physical properties, a Weymouth constant and a linepack constant are estimated for each pipeline assuming hydrogen operation. Minimum and maximum operating pressures are specified for each node and form key model inputs for the pressure-driven formulation described in Section 2.2.

## 3.3. High Level Scenario

ENTSO-E's TYNDP[8] 2024 National Trends (NT) scenario was selected as the base scenario for this work due to the comprehensive, publicly available dataset. The TYNDP provides technology portfolios for electricity and hydrogen supply, demand projections, and weather-driven renewable and demand time series for multiple study years, including 2040.

The Ten-Year Network Development Plan (TYNDP) is ENTSO-E's long-term planning framework that assesses Europe's electricity system needs over a 10-year horizon using harmonised scenarios, identifying cross-border infrastructure investments required to ensure security of supply, market integration, and the cost-efficient achievement of EU climate and energy objectives. The National Trends Scenario is a bottom up scenario, built from TSO inputs that reflect each country's National Energy and Climate Plans (NECPs), national policy frameworks and long-term strategies, rather than a top-down optimisation of "least-cost Europe".

The National Trends Scenario assumes strong energy-efficiency and continuing electrification of transport and heating (EVs, heat pumps, hybrid heat pumps). The scenario includes large increases in wind and solar generation capacity; offshore wind in particular ramps up between 2030 and 2040. Hydrogen plays a moderate, rather than extreme role, with a focus on industry and heavy transport and an annual demand of 148 TWh.

[7] https://orca.cardiff.ac.uk/id/eprint/24178/1/2012QadrdanMPhD.pdf
[8] https://www.entsoe.eu/outlooks/tyndp/2024/

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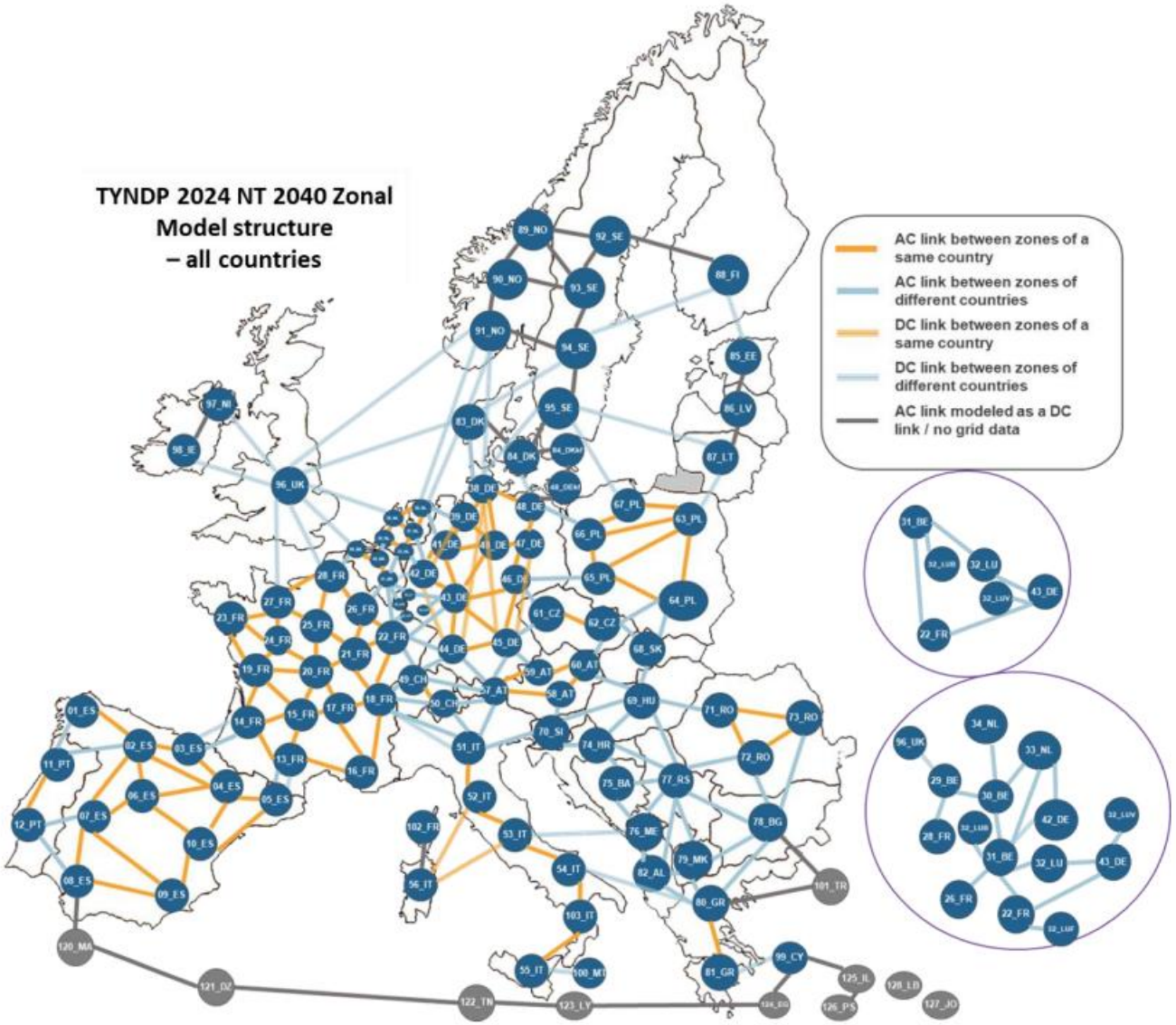


FIGURE 6 TYNDP 2024 NT 2040 ZONAL MODEL STRUCTURE[9]

## 3.4. Portfolio Overview

Generation portfolios for each country are published on the TYNDP website[10]. GB capacities of key technologies are summarised in the table below. GB electricity and hydrogen capacities in 2040 are dominated by large-scale renewable deployment. Total wind capacity is 137 GW, with offshore wind forming the largest share. Solar PV reaches over 59 GW, combining rooftop and utility-scale installations.

[9] TYNDP 2024 Identification of the System Needs Study Methodology
[10] https://2024.entsos-tyndp-scenarios.eu/download/



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Thermal capacity is significantly reduced, with 13 GW of nuclear and 11 GW of gas fired plant providing firm and dispatchable capacity. Hydrogen electrolysers reach 25 GW, while battery storage consists of 23 GW of power and 37 GWh of energy. Hydro capacity in GB remains broadly stable rather than expanding. Although modest in energy terms, hydro provides high-value flexibility alongside batteries and hydrogen electrolysers.

TABLE 1 NT SCENARIO GB CAPACITY SUMMARY

| Technology | Capacity |
|---|---|
| Offshore wind | 95 GW |
| Onshore wind | 42 GW |
| Solar PV (total) | 59 GW |
| Nuclear | 13 GW |
| Gas | 11.0 GW |
| Batteries | 23.3 GW |
| Hydro | 5.1 GW |
| Electrolysers | 25.2 GW |

Demand response in the National Trends Scenario is represented through a combination of explicit and implicit mechanisms.

- Explicit DSR (DSR unit): modelled as a Demand Side Response unit with an available capacity of ~22.9 GW in the GB 2040 portfolio. This resource is price activated in the dispatch model within energy and availability limits
- Implicit DSR (iDSR) / embedded flexibility: in addition to the explicit DSR unit, part of the assumed flexibility is captured implicitly via time-shifting demand technologies (iDSR) (notably shares of EVs and heat pumps) reflected in the shape of the underlying demand time series

Electricity interconnectors with neighbouring regions have a total capacity of 12.6 GW (see Section 3.6 for more details).

Modelled costs include fuel costs, carbon costs, start-up costs, VOM costs. TYNDP 2040 price assumptions used:

- Natural Gas: 18.06 £/MWh
- Nuclear: 5.39 £/MWh
- Carbon Price: 129.36 £/t$CO_2$

For any cost data in Euro, an exchange rate of 0.88 £/€ was used.

## 3.5. Hydrogen Summary

As mentioned in Section 3.3, hydrogen plays a moderate, rather than extreme role in the National Trends Scenario in GB, with a focus on industry and heavy transport as the main drivers of demand.

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Hydrogen demand is met by a combination of green hydrogen, blue hydrogen and imports from neighbouring regions.

25.2 GW of electrolysers provide valuable system flexibility in GB and operate preferentially during low-price hours (i.e combined system is co-optimised, minimising total system costs). 1.5 GW of steam methane reformers (combined with CCS) are also included and operated when required to meet hydrogen demand. 4 GW of import / export capacity is assumed between GB and Belgium, with the average price at the Belgium node being 82.74 €/MWh (72.81 £/MWh).

As the NT model sees imports via a single terminal, to ensure feasibility, additional back-up supply at 4 additional terminals at higher price point 176 £/MWh is included, representing potential higher cost options (e.g. hydrogen from ammonia). This set up ensures feasibility under constrained import topology, and is not intended to represent specific projects The hydrogen network is based on the existing gas network, including all large-scale storage. 8.25 TWh of large-scale hydrogen storage is included in the model[11]. Annual demand in 2040 is 148 TWh and the hourly time series is taken from the TYNDP NT dataset.

## 3.6. Disaggregation and Model Updates

The National Trends portfolio for GB within the ENTSO-E TYNDP model is represented as a single node. For this study the portfolio must be disaggregated across the Gas and Electricity nodes. Data provided by Guidehouse at regional level (NUTS1) used for a previous linepack report[12] was used along with publicly available FES data[13] to disaggregate the portfolio.

Imports / exports of both electricity and hydrogen are facilitated in the model, with all interconnectors modelled along with a simplified representation of the import/export region, where the marginal price at each node (an exogenous price signal based on published TYNDP results) is included. This facilitates price-based imports and exports, accounting for renewable availability at an hourly resolution.

As mentioned in Section 3.5, the National Trends Scenario assumes import / export of hydrogen at 1 terminal only (from Belgium). To ensure feasibility, a back up supply of higher cost hydrogen imports is allowed at 4 additional terminals.

The detailed modelling completed for this study considers a full year of operations in 2040. The rolling model has a 72-hour window at a resolution of 3 hours, which rolls every 24 hours, with each window overlapping. This means short-term system flexibility needs can be captured in detail, while still considering the medium-term system needs in future days (important for valuing the stored hydrogen). A two-stage model is applied, to optimise long-term storage. The first stage solves for the full year at daily resolution, where the large-scale storage is optimised. The storage state for the large-scale storage is fed into the rolling model, setting energy targets for the end of each day, with a penalty

[11] https://www.ofgem.gov.uk/sites/default/files/2025-01/gb_gas_storage_publication.pdf
[12] https://smarter.energynetworks.org/projects/nia_ngt0223/
[13] https://www.neso.energy/publications/future-energy-scenarios-fes

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applied when the targets are not met. The large-scale storage can still play a limited role providing intraday flexibility.

The initial implementation of pressure driven gas transfer in Spine (based on Schwele et al.) included compressors with a compressor ratio on relevant pipelines. Compressor costs were not captured. As outlined in the Guidehouse report[12], compressor costs are significant, particularly in a hydrogen-based system and should not be neglected. To capture compressor costs a small throughput-based cost is calibrated to Guidehouse's 2040 hydrogen compressor cost estimates (£466–546 million per annum) adjusted by 15% to account for additional pipeline transport and operational costs consistent with published hydrogen pipeline transport tariffs reported by the European Hydrogen Backbone[14].

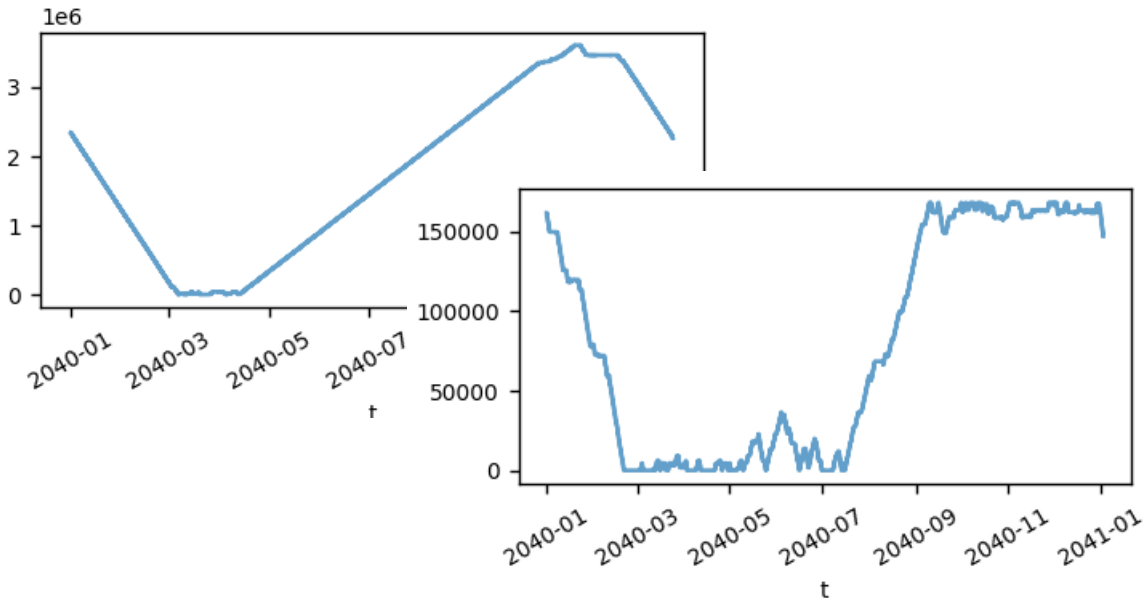


FIGURE 6 SAMPLE LARGE-SCALE STORAGE TRAJECTORIES

The entire workflow, including data handling, model building and model runs is shown in the following diagram.

[14] https://ehb.eu/files/downloads/EHB-2023-Implementation-Roadmap-Part-1.pdf



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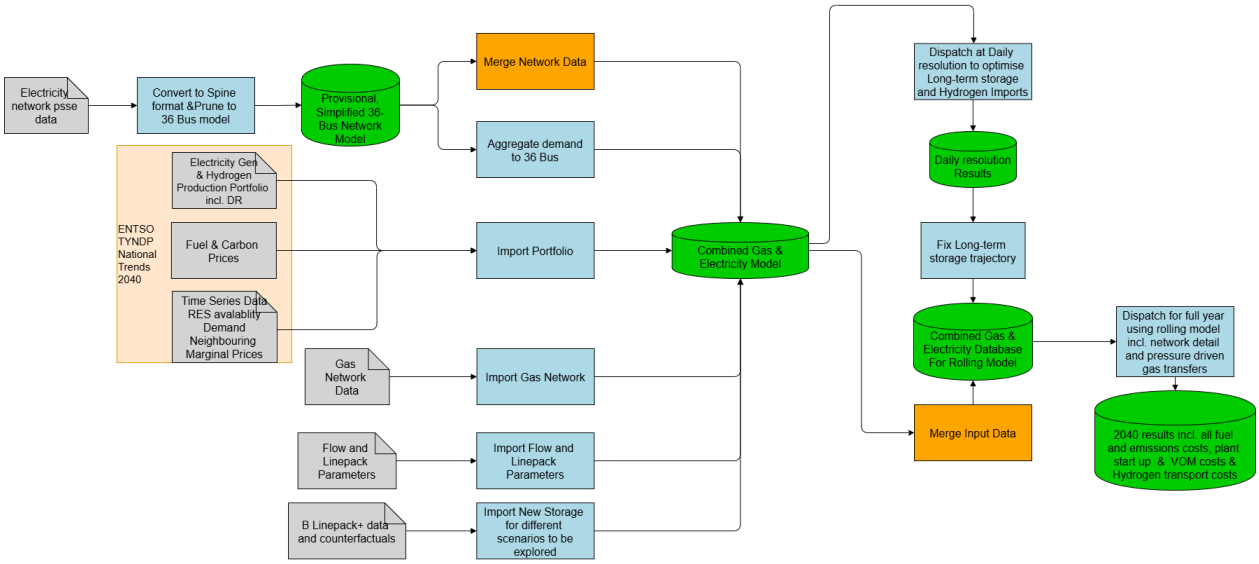


**FIGURE 7 MODELLING WORKFLOW**

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# 4. B-Linepack+ and Counterfactual Storage Modelling

B-linepack+ lined rock shafts are modelled in Spine, along with two counterfactual storage technologies, with key parameters including capacity (working gas), injection and withdrawal rates and round-trip efficiency. The hydrogen storage capacity included in each of the scenarios is shown in Table 2. Results are presented in this report for 4 scenarios, a base scenario with no additional storage and three additional scenarios with 30.5 GWh of additional hydrogen storage capacity provided by 3 different technologies.

TABLE 2 HYDROGEN STORAGE CAPACITIES EXCLUDING SYSTEM LINEPACK

| Scenario | Hydrogen Storage Capacity (GWh) (excluding system linepack) |
|---|---|
| Base | 8,250.0 |
| B-Linepack+ | 8,280.5 |
| LOHC | 8,280.5 |
| Salt Cavern/Large-Scale Storage | 8,280.5 |

## 4.1. B-Linepack+ SpineOpt Model

Figure 8 shows the key B-linepack+ parameters for inclusion in the Spine model.

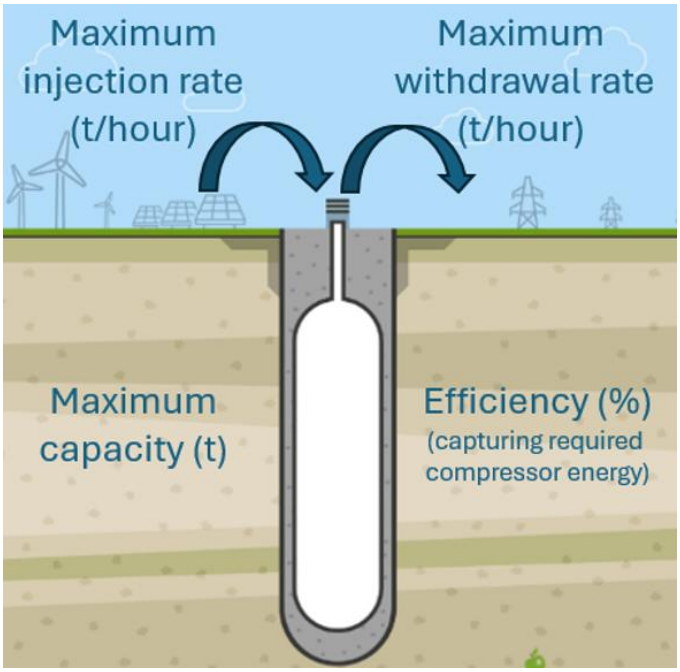


FIGURE 8 KEY B-LINEPACK+ PARAMETERS IN SPINE MODEL



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Assumptions for the B-linepack+ systems are the same as those used in the discovery phase and are shown in the table below. These assumptions are based on 2040 targets for a 65 t system – i.e. a total capacity of 65t of hydrogen, with a working gas capacity of 57t. In this study, 16 B-linepack+ systems are added to the energy system, corresponding to an additional 30.5 GWh of working hydrogen storage. While this represents a modest increase relative to existing large-scale storage, it provides a useful benchmark for comparison with alternative flexibility options with the advantage that it can be deployed virtually anywhere on the system.

TABLE 3 B-LINEPACK+ KEY PARAMETERS AS MODELLED IN SPINE

| Parameter | Value |
|---|---|
| Max. Injection | 4.5t / hour |
| Max. Withdrawal | 4.5t / hour |
| Capacity (total inventory) | 65t |
| Working Gas (usable capacity) | 57t |
| Round Trip Efficiency | 95% |

## 4.2. Liquid Organic Hydrogen Carrier SpineOpt Model

Figure 9 shows the modelled process for Liquid Organic Hydrogen Carriers (LOHCs). The storage hydrogen (in energy) is matched to the B-linepack+ system to facilitate side by side comparison.

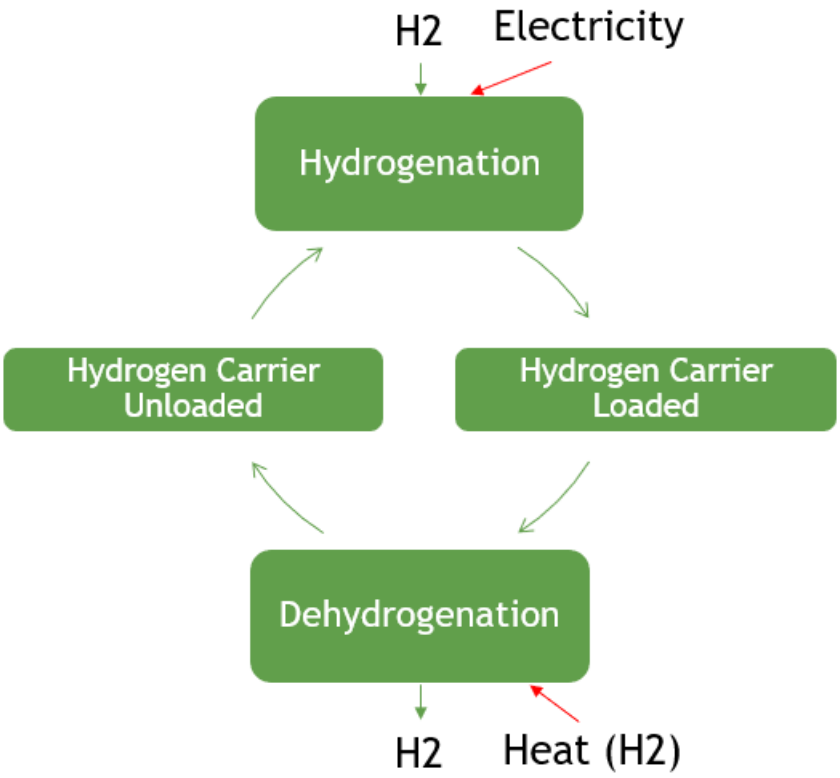


FIGURE 9 LIQUID ORGANIC HYDROGEN CARRIER



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A small electrical load is required (hydrogenation / dehydrogenation) which is mapped to the nearest electric node in the Spine model for a given system. Losses are also applied at the dehydrogenation step, assuming hydrogen is used to provide the required heat. Assumptions are based on the process described by the Clean Air Task Force[15]. LOHC is one of two modelled counterfactual storage technologies.

## 4.3. Salt Cavern / Large-Scale Storage SpineOpt Model

Rather than introducing a new storage facility, the equivalent storage capacity is added to an existing large-scale hydrogen storage asset in Cheshire as a counterfactual storage option. This counterfactual representation avoids introducing additional siting or network effects and isolates the impact of additional storage capacity. Large-scale storage is modelled with a round-trip efficiency of 95%.

As described in Section 3.6, large-scale storage operation is optimised using a two-stage approach. A daily-resolution optimisation determines long-term storage trajectories and end-of-day energy targets, which are then enforced in the rolling, higher-resolution operational model through penalty terms. This allows large-scale storage to contribute primarily to medium- and long-term balancing, while still providing limited intraday flexibility.

The modelled large-scale storage are shown in the table below. The table shows the assumed working gas capacity for both the Base scenario and the counterfactual storage scenario (increased capacity at facility 4). The injection and withdrawal rates assumed for a hydrogen system are also shown along with the nearest node on the simplified gas network.

**TABLE 4 LARGE-SCALE STORAGE MODEL PARAMETERS**

| Facility | H2 working gas (GWh) | Counterfactual H2 working gas (GWh) | Max. H2 withdrawal (MWh/h) | Max. H2 injection (MWh/h) | Nearest Node |
|---|---|---|---|---|---|
| 1 | 3600 | 3600 | 1787.5 | 1125 | 29 |
| 2 | 924 | 924 | 1950 | 375 | 31 |
| 3 | 846 | 846 | 4225 | 3250 | 31 |
| 4 | 726 | **757** | 3575 | 3250 | 42 |
| 5 | 177 | 177 | 2112.5 | 1625 | 42 |
| 6 | 609 | 609 | 1137.5 | 1000 | 83 |
| 7 | 168 | 168 | 325 | 250 | 108 |
| 8 | 1200 | 1200 | 4875 | 3750 | 113 |

[15] https://cdn.catf.us/wp-content/uploads/2023/05/23054736/catf-kbr-landed-cost-hydrogen-carriers.pdf

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# 5. Results

This section summarises the modelling results, starting with the results from the base model (no additional storage beyond the large-scale storage and the system linepack), followed by results with 16 B-linepack+ systems deployed. The counterfactual storage results are then presented.

## 5.1. Base Model Results

The base model consists of the National Trends GB model, disaggregated across the electricity and hydrogen network, with no additional hydrogen storage. This section summarises the results from the base scenario.

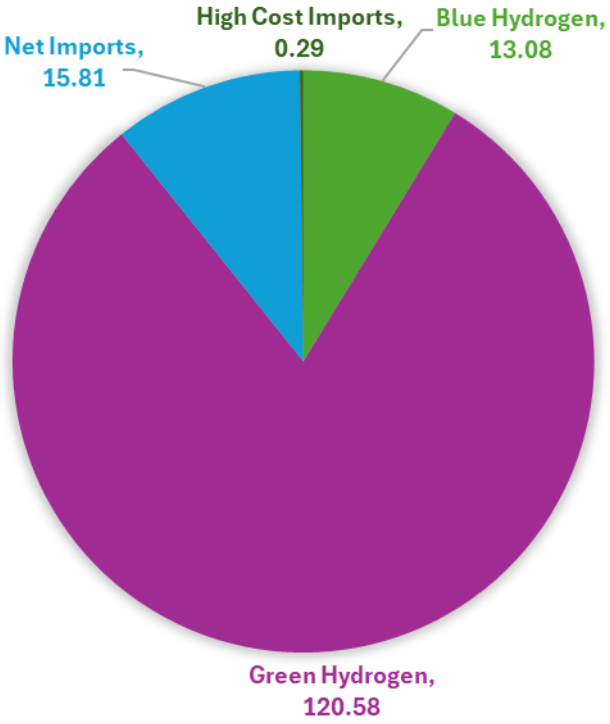


FIGURE 10 GB HYDROGEN SUPPLY (BASE MODEL)

The majority of hydrogen demand is met by production from the electrolysers - 120.6 TWh. Significant net imports make up the next largest category at 15.8 TWh. The relatively modest SMR fleet (with CCS) produces 13.1 TWh, with the balance met by high-cost imports (back-up supply at four additional terminals) totalling 0.29 TWh.

Figure 11 shows the renewable generation and curtailment for the base model. A total of 534.5 TWh of renewable energy is generated, with an additional 70.4 TWh of renewable energy curtailed. This represents 11.6% of the available renewable energy. Offshore wind dominates, with 369 TWh generated, followed by onshore wind at 107 TWh and solar at 59 TWh.

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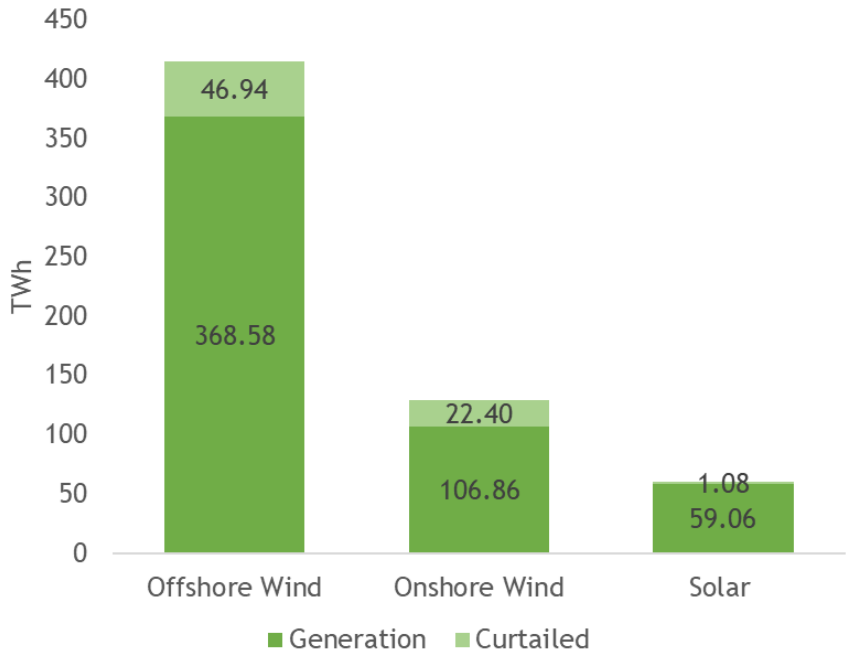


FIGURE 11 RENEWABLES GENERATION AND CURTAILMENT (BASE MODEL)

Considering the system linepack, up to 828 GWh of hydrogen is stored in the gas pipelines (aggregated over the 54 modelled pipelines). As expected, this is significantly below the energy stored in the natural gas network today due to the reduced linepack capacity for a hydrogen system. Linepack swing is defined here as the maximum absolute daily change in stored hydrogen energy within the transmission system. An average daily swing of 42.9 GWh is seen, with a maximum daily swing of 208.9 GWh. The system linepack provides valuable flexibility, with balancing provided across the day and across the week (see Figure 12). Since linepack is a function of pipeline dimensions and operating pressure, Figure 13 illustrates its distribution across individual pipelines.

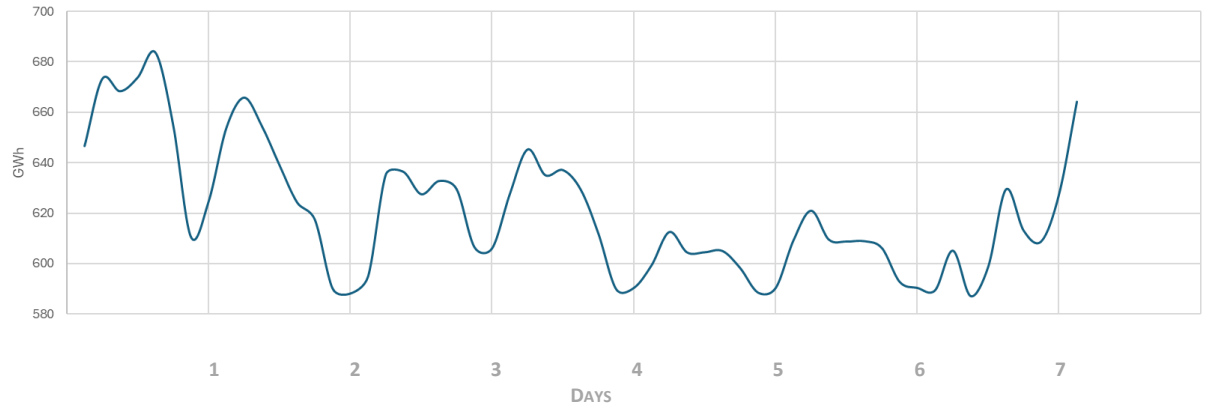


FIGURE 12 SYSTEM LINEPACK 12/12/2040 – 19/12/2040

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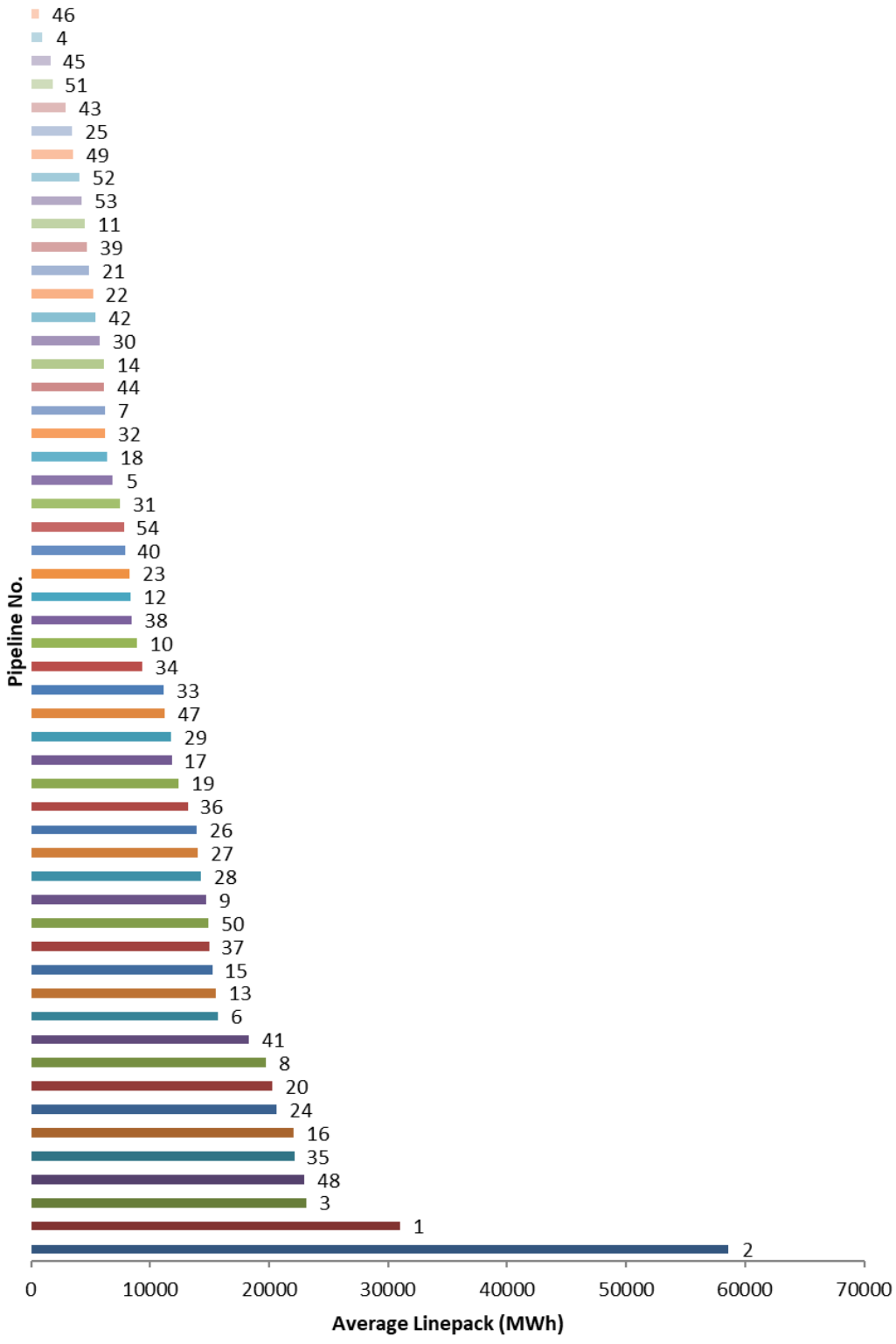


FIGURE 13 AVERAGE LINEPACK FOR THE 54 MODELLED PIPELINES

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## 5.2. B-Linepack+ Results

Before completing the B-linepack+ scenario, a screening run was first completed with B-linepack+ at each gas node to guide siting. As per discovery phase, the value of additional storage is sensitive to its location on the system. Annual throughput for each of the B-linepack+ stores was ranked to narrow down site selection and nodes with very low throughput were eliminated. With a target of 16 B-linepack+ systems, where possible 2 systems per node (resulting in reduced CAPEX), the 16 lined rock shafts were distributed across 11 gas nodes. Deliverable 5 “UK wide mapping of lined rock shaft deployability and system integration”, informed site selection, avoiding / minimising sites requiring a modified system. The siting of the B-linepack+ systems are shown in Figure 14. Nodes selected for B-linepack+ are marked with either a 1 or a 2 (the number of systems at the node). Note that for the counterfactual storage runs, LOHCs are placed at the same locations, while storage capacity for the large-scale storage is increased at a single site in Cheshire.

Note that the total capacity (working gas) for the 16 B-linepack+ systems is 30.5 GWh. This is in addition to the 8.25 TWh of large-scale storage capacity included in the base model, and the system linepack (~ 830 GWh). The 16 B-linepack+ systems represents an increase of 3.7% of short term storage (i.e. intraday to multi-day flexibility) and an increase of 0.34% of total system storage. While the additional capacity is small relative to peak daily linepack swing, the distributed nature of B-linepack+ enables it to reduce reliance on system linepack for intraday balancing.

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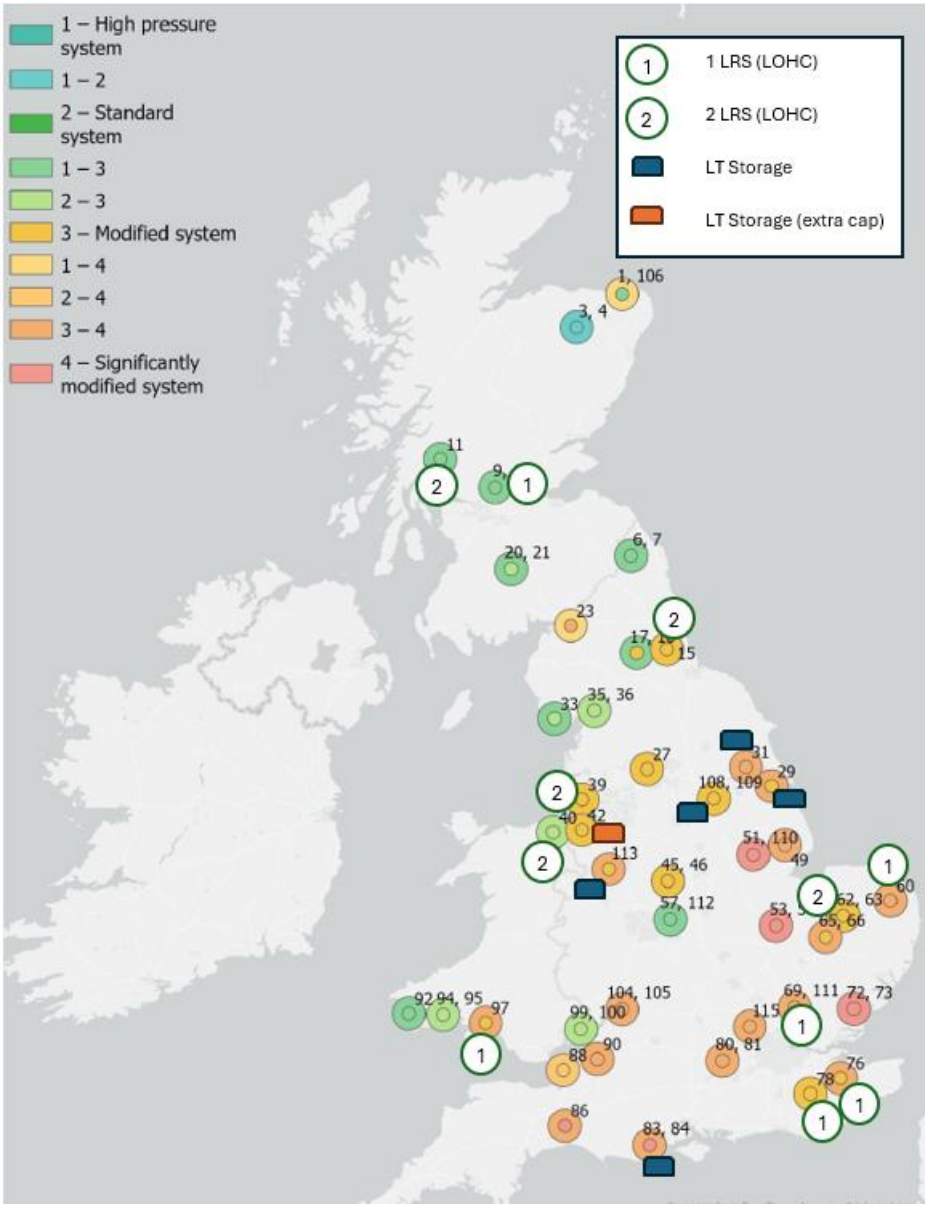


FIGURE 14 STORAGE SITING – LARGE-SCALE STORAGE, B-LINEPACK+ & COUNTERFACTUAL STORAGE

The B-linepack+ scenario was repeated with 16 B-linepack+ systems across 11 nodes. Significant cost savings are seen over the year - £26.53 million over 1 year of operation compared to the base model run (no additional storage). The cost savings result from:

- More efficient imports / exports with a small reduction of 93.5GWh of net imports from Belgium (0.6% reduction).
- Reduced fuel and carbon costs, with an additional 1.4TWh of renewable energy generated due to reduced curtailment (0.26% of available renewable energy)
- Reduced network compressor costs, with reduced reliance on system linepack



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The breakdown of the modelled cost savings are shown in Figure 15. Transport costs (based on the calibrated throughput cost described in Section 3.6) dominate, with significant additional system operating cost savings (fuel and carbon costs, more efficient imports / exports).

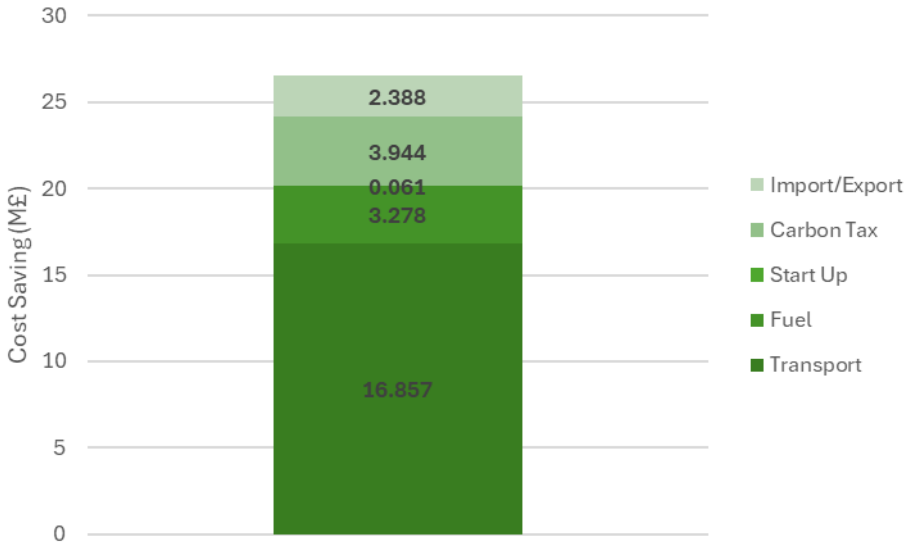


FIGURE 15 BREAKDOWN OF B-LINEPACK+ SYSTEM COST SAVINGS

While the B-linepack+ is dispatched to minimise total system costs (electricity & hydrogen), with cost savings spread across the system, maximum system linepack is reduced from 828 GWh to 818 GWh. The average daily swing reduces from 42.9 to 41.2 GWh with the maximum daily swing down to 196 GWh from 208.9 GWh. The average throughput of the B-Linepack+ systems is 136 GWh, a total of 2.18 TWh for the 16 systems.

## 5.3. Counterfactual Storage Results

B-linepack+ generated £26.53 million cost savings across the modelled year. Liquid Organic Hydrogen Carriers deployed at the same sites, with the same capacities generated lower cost savings of £9.53 million across the year, as the system has a significantly lower round trip efficiency.

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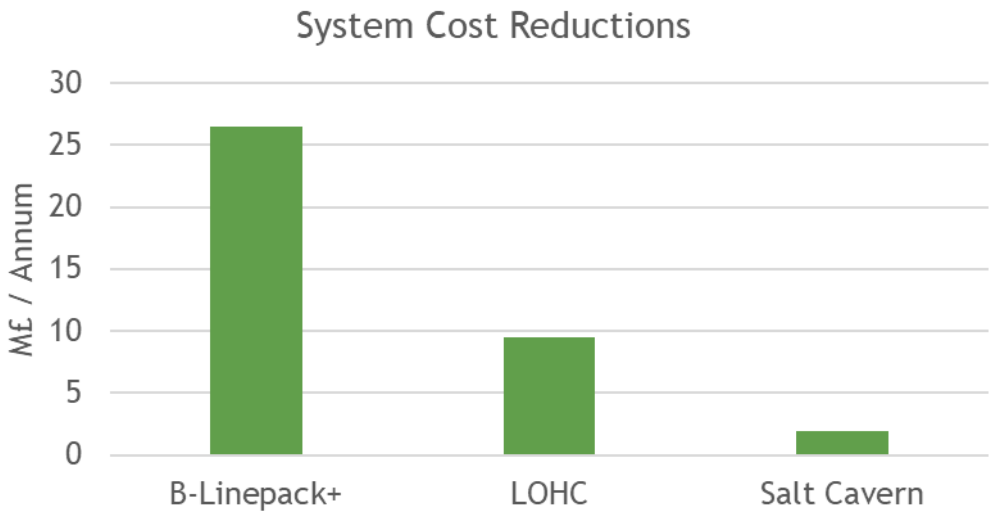


FIGURE 16 SYSTEM COST REDUCTIONS GENERATED BY THE ADDITION OF STORAGE TO THE BASE MODEL

The additional long-term storage capacity saw modest cost savings of £1.94 million, primarily driven by more efficient imports / exports of Hydrogen, with minimal impact of fuel costs and transport costs.

The B-linepack+ was also the most effective at reducing system level curtailment of wind and solar generation. While the B-linepack+ systems resulted in curtailment reductions of 1.4 TWh, the reductions achieved by the LOHC systems was 0.3 TWh. The large-scale storage saw negligible curtailment reductions, with the additional capacity used primarily to drive more efficient imports / exports.

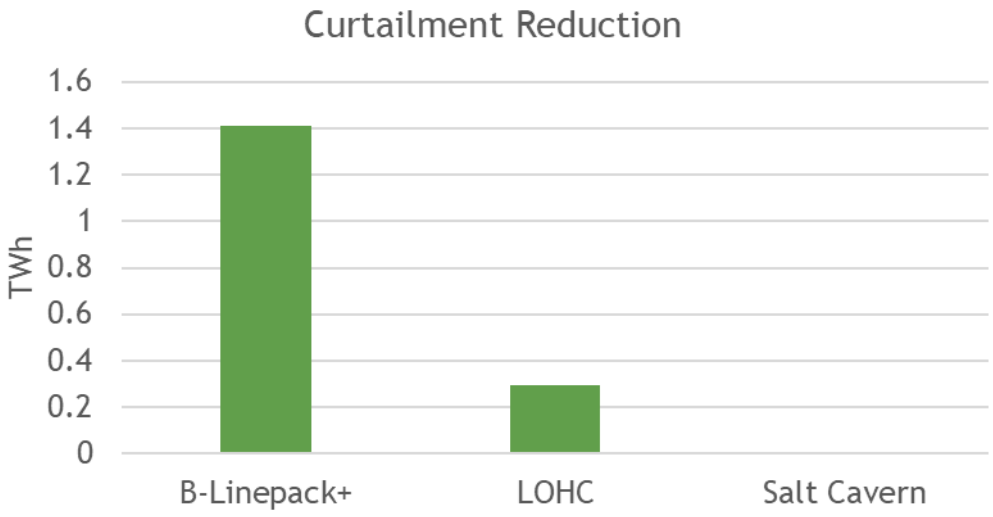


FIGURE 17 SYSTEM CURTAILMENT REDUCTIONS WITH THE ADDITION OF STORAGE TO THE BASE MODEL

The B-linepack+ systems were demonstrated to be effective at reducing maximum and average daily swing for the system linepack (see Section 5.2).

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The impact of B-linepack+ is driven by its utilisation profile and location rather than its contribution to total stored energy, as demonstrated by the results in terms of cost savings, curtailment reduction and its impact on system linepack compared to the counterfactual storage.

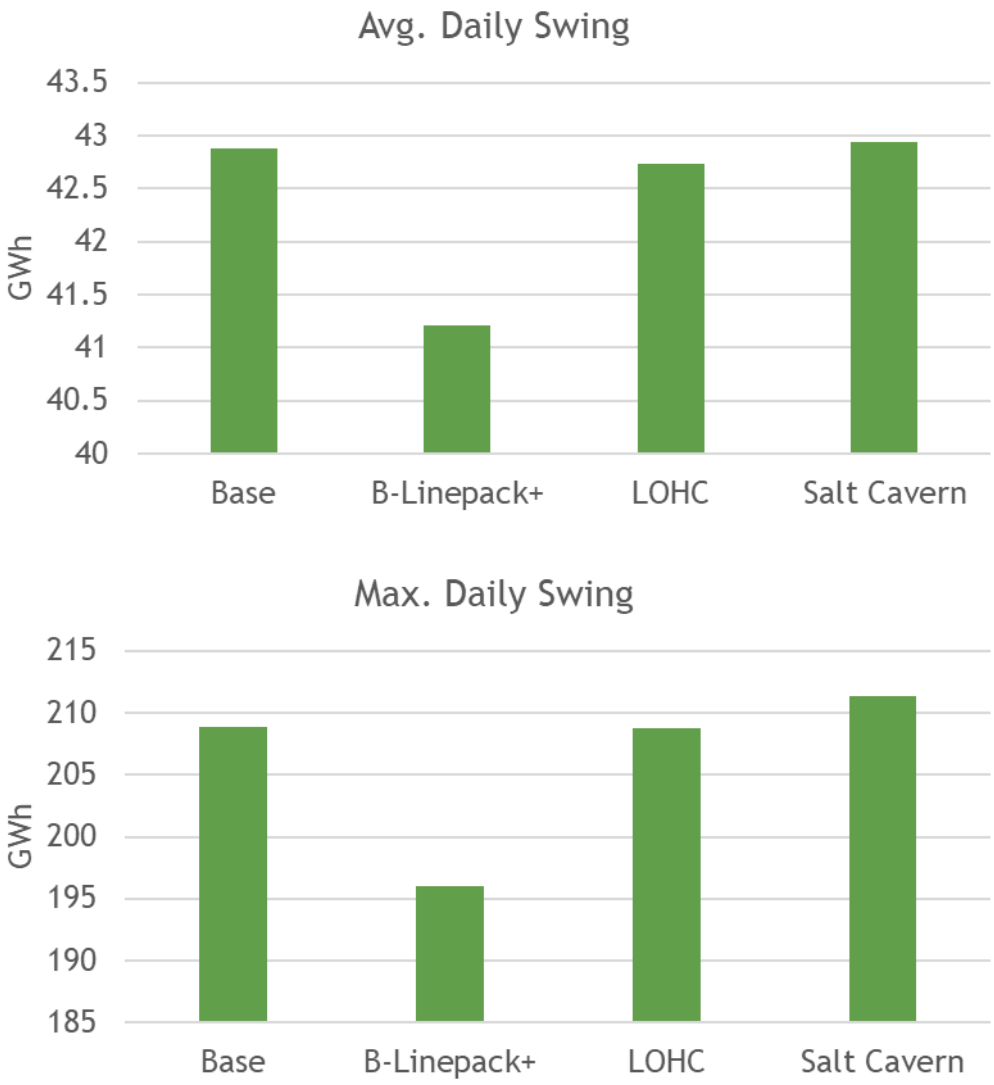


**FIGURE 18 AVERAGE AND MAXIMUM DAILY LINEPACK SWING FOR THE BASE MODEL, B-LINEPACK+ SYSTEMS AND THE COUNTERFACTUAL STORAGE**

Comparing these results to the counterfactual storage, the LOHC has a modest impact on system linepack (average daily swing 42.7, maximum. daily swing 208.8). The additional salt-cavern capacity results slightly higher values of daily linepack swing (average daily swing 42.9, maximum daily swing 211.4).

Of the three storage solutions studied, B-linepack+ is the only solution that has a significant impact on system linepack.

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# 6. Discussion & Conclusions

The modelling results provide clear evidence on the role of distributed hydrogen storage in supporting system flexibility and cost-effective operation, leading to the following conclusions:

- Distributed hydrogen storage can provide high system value in a future co-optimised electricity and hydrogen system, even when deployed at relatively modest scale.
- B-linepack+ is demonstrably more effective at managing short-term system flexibility and reducing reliance on transmission linepack than the counterfactual storage technologies examined.
- The benefits of B-linepack+ extend beyond cost savings to include reduced renewable curtailment and improved operational behaviour of the hydrogen network.
- Storage technologies that are geographically distributed, efficient, and capable of rapid response are particularly well suited to replacing flexibility historically provided by natural gas linepack.

This study demonstrates the value of distributed short-duration hydrogen storage within a future, highly renewable, co-optimised electricity and hydrogen system. Using a detailed pressure-driven gas network representation within SpineOpt, the analysis quantifies the role of system linepack, the increased need for flexibility when transitioning from natural gas to hydrogen, the reduced flexibility available from linepack and the extent to which alternative storage solutions can mitigate this loss.

The results presented are inherently system specific and sensitive to modelling assumptions, including the assumed 2040 generation and demand portfolios, network topology and storage characteristics. The hydrogen network implemented in this study is based on a simplified representation of the existing GB gas transmission system, reflecting the absence of a fully specified 2040 hydrogen network design. While this approach is appropriate for system-level assessment and comparative analysis, the absolute magnitudes of flows, costs, and storage utilisation should not be interpreted as forecasts.

Nevertheless, the modelling framework captures the key physical and operational characteristics required to assess the relative value of different storage technologies in a future hydrogen-based system.

The base model results confirm that, even in a hydrogen system with substantially reduced linepack capacity compared to natural gas, pipeline linepack continues to provide valuable short-term flexibility. In the absence of additional storage, the system relies heavily on linepack to balance intraday and short-term variations in hydrogen supply and demand, leading to relatively high average and peak daily linepack swings.

Introducing distributed B-Linepack+ storage materially alters this behaviour. Despite representing a relatively modest increase in total hydrogen storage capacity (approximately 30.5 GWh, or less than 1% of total system storage), B-Linepack+ consistently reduces both average and maximum daily linepack swing. The resulting reduction in pressure cycling implies lower compressor utilisation and reduced mechanical stress on the pipeline system, with associated reductions in transport-related

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costs, as shown in Section 5.2. This demonstrates that distributed, fast-response storage located close to demand and injection points can absorb short-term imbalances that would otherwise be managed through pressure variation in the transmission system.By contrast, the counterfactual storage solutions examined are significantly less effective at managing system linepack. Liquid Organic Hydrogen Carrier (LOHC) storage provides limited benefit due to its lower round-trip efficiency, while additional large-scale salt cavern capacity primarily supports longer-term balancing and import/export optimisation, with minimal impact on short-term system flexibility. These findings highlight that location, injection and withdrawal rates, and efficiency are as important as total storage capacity when valuing flexibility resources.

The deployment of B-linepack+ systems delivers meaningful system-wide cost savings relative to the base case. These savings arise from a combination of reduced reliance on hydrogen imports, increased utilisation of low-cost renewable electricity via electrolysers, and reduced dependence on system linepack and associated compression requirements.

**While cost savings are distributed across the electricity and hydrogen systems, B-linepack+ is the only storage option considered that simultaneously delivers cost reductions, curtailment reduction, and a material decrease in linepack utilisation.** This distinguishes it from both LOHC and large-scale cavern storage, which primarily influence longer-term energy balancing and trade flows rather than short-term system operation.

The reduction in average and peak daily linepack swing achieved through B-linepack+ deployment is particularly relevant when viewed in the context of external benchmarks. Previous studies have shown that aggressive reliance on linepack in future hydrogen systems may require operation well beyond historical natural gas experience, especially under high-stress conditions[16]. The results presented here indicate that relatively small amounts of strategically located distributed storage can significantly moderate this requirement, improving operational robustness without the need for extensive reinforcement of the transmission network.

Overall, the analysis demonstrates that B-linepack+ has the potential to play a valuable role in enabling a resilient and cost-effective transition to a hydrogen-based energy system in Great Britain, complementing both large-scale storage and cross-border trade.

Future work should focus on optimising the sizing of B-linepack+ systems and undertaking further sensitivity analysis. It is possible that a substantial proportion of the system benefits could be achieved with smaller capacities than those considered here (only 65 t systems were analysed in this study). Future work could also explore the key drivers of system cost reductions and assess how closely flexibility requirements are linked to the reduction in linepack associated with a transition from natural gas to hydrogen networks.

[16] https://smarter.energynetworks.org/projects/nia_ngt0223/

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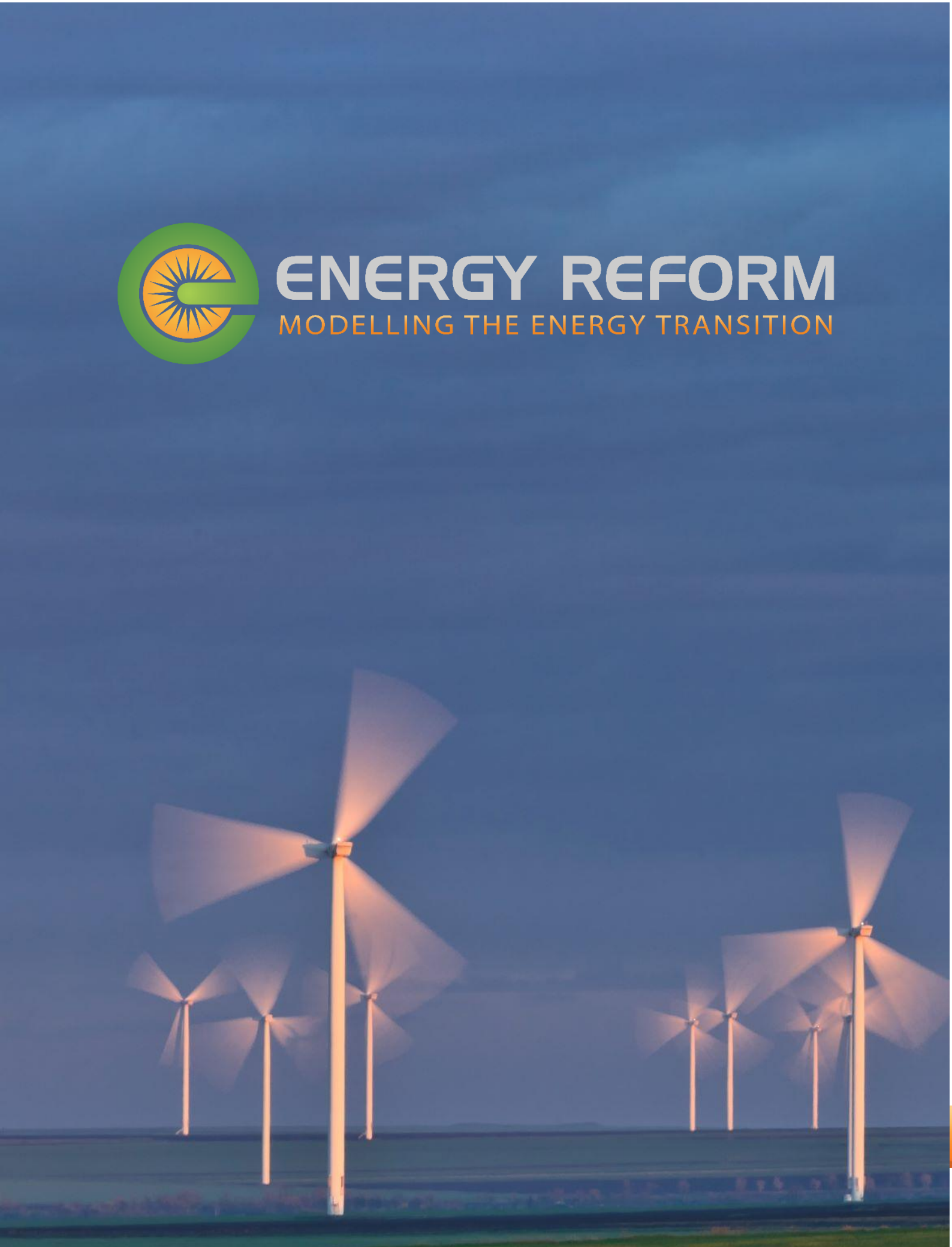
ENERGY REFORM
MODELLING THE ENERGY TRANSITION

national gas transmission

# B-Linepack+

# Alpha Phase

## Basis of Design Document

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| Issue | Description | Originator | Date | Checker | Date | Approver | Date |
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| | | | | | | | |
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| | | | | | | | |
| 00 | Initial Issue | A Bradshaw-Jones | 02/07/25 | N. Horan-Martin | 30/09/25 | N. Horan-Martin | 30/09/25 |

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# Revision Index

| Revision | Summary of Changes |
|---|---|
| 00 | Initial Issue |
| | |
| | |
| | |
| | |

# Hold Record

| Hold | Hold Details |
|---|---|
| [HOLD 1] | How the hydrogen is brought to the test facility is to be confirmed. |
| [HOLD 2] | The parameters of the provided hydrogen are to be confirmed. |
| [HOLD 3] | The SOL of the Lined Rock Shaft is dependent on the geology at the test site location. |
| [HOLD 4] | The outlet parameters for the hydrogen from the test facility are to be confirmed. |

# Abbreviations

| | |
|---|---|
| AGI | Above Ground Installation |
| COMAH | Control of Major Accident Hazards |
| DSEAR | Dangerous Substances and Explosive Atmospheres Regulations |
| ETZ | Energy Transition Zone |
| GSMR | Gas Safety (Management) Regulations |
| HAZOP | Hazards in Operability |
| HSWA | Health and Safety at Work etc Act 1974 |
| LOPA | Layer of Protection Analysis |
| LRS | Lined Rock Shaft |
| MOP | Maximum Operating Pressure |
| NGT | National Gas Transmission |
| NTS | National Transmission System |
| PSR | Pipeline Safety Regulations |
| PSSR | Pressure Systems Safety Regulations |
| PU:EC | Project Union : East Coast |
| SOL | Safe Operating Limit |

# Executive Summary

As the UK looks to move towards Net Zero, hydrogen storage solutions need to be developed to support proposed hydrogen networks due to the known reduction in energy content per kilometre of linepack for hydrogen.

As part of a Strategic Innovation Funded Alpha phase project, National Gas Transmission, alongside other project partners, are looking at developing a technical demonstrator for Lined Rock Shaft (LRS) systems. Gravitricity, the developers of the LRS technology and a project partner, are looking to use the technical demonstrator as a proof of concept for their LRS.

The objective of this document is to define at an appropriate level of detail the design parameters, design principles, and principal design standards for the technical demonstrator.

A separate technical interface document has been produced that describes and defines the overall technical interface philosophy and design requirements at each of the technical interfaces.

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# 1 Introduction

## 1.1 General

Linepack flexibility is key for National Gas Transmission (NGT) to provide system resilience by management of swings within operational limits. In a hydrogen world, it is known that the energy content per kilometre of linepack will decrease by up to 76%. Therefore, embedded resilience systems in the form of Lined Rock Shafts (LRS) are being investigated to supplement loss in linepack capability. It is envisaged that these systems, if implemented, for hydrogen transmission will act in a similar manner to how, now decommissioned, natural gas holders were utilised for operational flexibility, pressure regulation, supply/demand mismatch management, load balancing, emergency backup and production buffering.

This project follows on from the previous discovery phase. In discovery, the feasibility of using intermediate scale geological hydrogen embedded resilience solutions to supplement linepack in a hydrogen transmission system were investigated. Due to the lower volumetric energy density of hydrogen, the energy content of linepack is only 1/3 of that of natural gas. Lined rock shafts were identified to have favourable characteristics for "Linepack+" supplementation due to:

- Fast deployability (2-3 years)
- Competitive levelised cost of storage (£250-550/kg-$H_2$)
- Increased safety due to subsurface nature
- Low footprint and visibility
- Geographical flexibility
- High cycling flexibility, up to 2 cycles per week with low degradation
- High purity and no implications of impurities being introduced due to steel liner utilised

## 1.2 Project Objectives

This project focuses on innovation in hydrogen embedded resilience solutions in the subsurface to develop a technical demonstrator for lined rock shafts. It also includes an energy system modelling work package to develop an integrated GB energy system model for Power 2 Gas to identify network flexibility and optimisation opportunities.

## 1.3 Document Objectives

The objective of this document is to define at an appropriate level of detail the design parameters, design principles, and principal design standards for the Above Ground Installation (AGI) required for the technical demonstration for LRS. The design parameters for the LRS are the responsibility of others.

A separate technical interface document has been produced that describes and defines the overall technical interface philosophy and design requirements at each of the technical interfaces.

# 2 Design Requirements

## 2.1 Legislation

When considering hydrogen piping and AGIs, consideration shall be given to the following legislation, which contains specific references to hydrogen:

- The Planning (Hazardous Substances) Regulations 2015 [1]
- Control of Major Accident Hazards (COMAH) Regulations 2015 [2]
- Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002 [3]
- Gas Act 1986 (amended 1995) [4]

Other, non-hydrogen specific legislation is also relevant, and where not directly referencing hydrogen, the best practices outlined within the legislation have been appropriately applied. This legislation is detailed below:

- Health and Safety at Work etc Act 1974 (HSWA) [5]
- Town and Country Planning Act 1990 [6]
- Gas Safety (Management) Regulations (GSMR) 1996 [7]
- Pressure Systems Safety Regulations (PSSR) 2000 [8]
- Pipeline Safety Regulations (PSR) 1996 [9]

It should be noted that COMAH does not apply to hydrogen systems which are less than 5 tonnes in size. The size of the demonstrator is 1 tonne and therefore is under the lower tier threshold for COMAH to apply. However, it has still been considered in this project as best practice.

## 2.2 Specifications

### 2.2.1 Key Hydrogen Specific Standards, Specifications & Guidance Documents

- IGEM/TD/13 Edition 3 – Pressure regulating pipeline installations exceeding 7 bar [10][1]
- IGEM/TD/13 Edition 3 Supplement 1 – Pressure regulating installations for Hydrogen at pressures exceeding 7 bar [11][2]
- IGEM/SR/25 Edition 2 – Hazardous area classification of Natural Gas installations [12]
- IGEM/SR/25 Edition 2 Supplement 1 – Hazardous area classification of installations using Hydrogen or blends of up to and including 20% by volume Hydrogen in Natural Gas [13]
- ASME B31.12 – Hydrogen Piping and Pipelines [14]

### 2.2.2 National Gas Standards and Specifications

Whilst not specific to hydrogen as a fluid, cognisance should be taken of existing National Gas pipeline design standards and specifications.

- T/SP/TR/18 – Engineering of Pipelines and Installations Operating at Above 7Barg [15]

[1] It should be noted that IGEM/TD/13 Edition 3 Supplement 1 is only applicable for up to 100 barg. Therefore, although this system is outside of the scope of IGEM/TD/13, it has still been used as best practice. A technical query, PRZ0025-TQ-0000-0001 has been produced to confirm this.

- T/SP/TR/17 – Management Procedure for Isolation of Above 2 bar Plant and Equipment [16]
- T/SP/G/37 – Site Location and Layout Studies and Reviews [17]

# 3 Design Parameters

To aid with determining the requirements for the technical demonstrator, such as line and equipment sizing, the design parameters to be applied are detailed within the section below.

## 3.1 Pressure

As detailed within T/PM/PS/3 [18], the specification applies to National Gas Transmission's pressure systems containing relevant fluids as defined by the PSSR [8] regulations. This includes any fluid at a pressure of greater than 0.5 barg above atmospheric pressure. Therefore, the pressure relationships between MOP and SOL within T/PM/PS/3 [18] have been utilised within this project.

### 3.1.1 Pre-Compression Operating Pressures

As the aim of the project is a technical demonstration of the LRS to provide linepack flexibility, then the required pressures should, where possible, be aligned to proposed hydrogen network pressures. The minimum and maximum operating pressures prior to compression have been aligned to those pressures stated in the Project Union: East Coast (PU:EC) Basis of Design. This gives an operating pressure range of 30 to 50 barg.

### 3.1.2 Lined Rock Shaft

To provide the linepack flexibility, the LRS will store hydrogen at higher pressures than the proposed hydrogen network. For the technical demonstration, Gravitricity; the designer of the LRS, have stated a Safe Operating Limit (SOL) for the LRS of 200 barg.

## 3.2 Temperature

### 3.2.1 Recirculation Heating

Whilst the hydrogen is held under pressure within the LRS, there will be temperature decay of the stored hydrogen. Temperature loss will occur through the LRS shaft material due to the difference in gas and ground temperatures. To maintain the gas temperature within design and operational temperature limits of the LRS, recirculation heating is required as part of the technical demonstrator.

The heating system shall be sized to suit the required flow rate and temperature increase needed to maintain a suitable gas temperature.

### 3.2.2 Cooling

Compression is required within the technical demonstrator facility to ensure the hydrogen is stored at the required pressure of circa 200 barg. The compression results in work being done to the hydrogen, which increases the gas temperature.

Therefore, aftercooling is required downstream of the compressor to reduce the temperature within the hydrogen to circa 15°C. This ensures the gas temperature is within the design and operational limits of the demonstrator piping and LRS.

## 3.3 Flow Rates

For the technical demonstrator, the LRS will have an internal volume of 80m$^3$ and therefore holds 1 Tonne of hydrogen at maximum pressure.

The preferred withdrawal time is 12 hours, as this is for foreseen withdrawal time for the technology when deployed as part of a hydrogen network.

However, it has been agreed that a shorter withdrawal time, by up to a factor of 10, is acceptable for the technical demonstrator to provide flexibility on the requirements for the compression package.

## 3.4 Design Parameters Summary

The following table summarises the key design parameters for the technical demonstrator. However, these parameters may be subject to change and are subject to further investigation and design development.

Table 1: Summary of Design Parameters

| Parameter | Unit | Value | Comment |
|---|---|---|---|
| Line Rock Shaft Design Pressure | Barg | 200 | *As provided by others* |
| Maximum Operating Pressure (MOP) | Barg | 188.7 | *SOL = MOP * 1.06 as per T/PM/PS/3* [18] |
| Lined Rock Shaft Safe Operating Limit | Barg | 200[2] | *[HOLD 3]* |
| Maximum Entry Pressure into Compressor | Barg | 50 | *Project Union BoDD* |
| Minimum Entry Pressure into Compressor | Barg | 30 | *Project Union BoDD* |
| Minimum Flow Rate | scmh | 426 | *Based on 0.46te of hydrogen and a 12-hour cycle time* |
| Minimum Mass Flow Rate | kg/hr | 38 | *Based on 0.46te of hydrogen and a 12-hour cycle time* |
| Maximum Flow Rate | scmh | 945 | *Based upon 1.02te of hydrogen and a 12-hour cycle time* |
| Maximum Mass Flow Rate | kg/hr | 85 | *Based upon 1.02te of hydrogen and a 12-hour cycle time* |
| Maximum Allowable Velocity | m/s | 40 | *Filtered Hydrogen is required for the system* |
| Material Design Temperature | °C | -20 to 60 | |
| Expected Normal Operating Temperature | °C | 10 to 30 | |
| Lined Rock Shaft Operational Temperature | °C | 10 to 70 | |
| Lined Rock Shaft Absolute Temperature | °C | 0 to 80 | |

## 3.5 Composition Specification

The composition of hydrogen is assumed to at least 99.99% $H_2$ [HOLD 2]. This shall mean that the hydrogen should not require filtration as part of the trial and can be treated as filtered gas.

[2] It is noted that the SOL of the line rock shaft will be dependent on the ground geology at the selected location and may vary. This is to be confirmed once ground investigations have been undertaken at the selected location.

# 4 Operating Philosophy

This stage of the project is focussed on the proof of concept of the LRS and therefore shall be focused on the technical demonstrator for the Lined Rock Shaft.

It is assumed that the hydrogen shall be delivered and stored on the test facility within a high-pressure tube trailer [HOLD 1][HOLD 2].

Compression and pressure reduction are required, along with flow control to simulate a pipeline network and provide a cyclic duty for the LRS to demonstrate its application. Pressure protection devices shall be required to ensure that all risks associated with over pressurisation are suitably managed.

## 4.1 Pressure Protection

IGEM/TD/13 Edition 3 Supplement 1 [11] applies between 7 and 100 barg. As the 188.7 barg MOP of the LRS exceeds this limit, the technical demonstrator will, in part, operate outside of the scope of IGEM/TD/13 Edition 3 Supplement 1 [11]. However, as good practice, the design principles of IGEM/TD/13 Edition 3 [10] and IGEM/TD/13 Edition 3 Supplement 1 [11] have been adopted. In particular, the requirements regarding the number of safety devices and accuracy requirements for pressure regulators and slam-shut valve are to be used.

In accordance with IGEM/TD/13 Edition 3 [10], a decision algorithm is used to determine the number of safety devices. This algorithm is shown below:

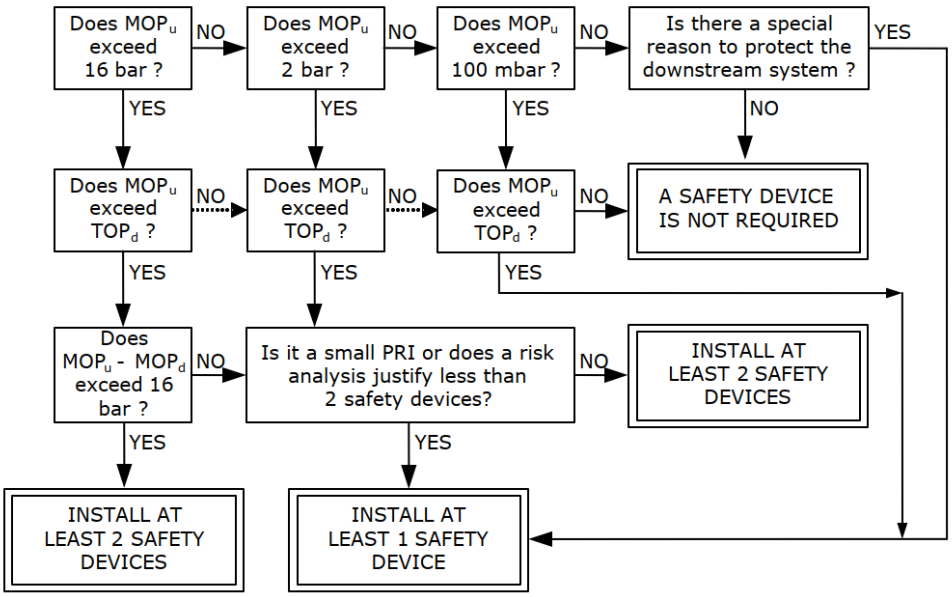


Figure 1: Decision algorithm for the minimum number of safety devices from IGEM/TD/13 Edition 3

As detailed within Table 1, there is an inlet MOP of 188.7 barg and an outlet MOP of 50 barg. As the difference between upstream and downstream MOP is greater than 16 barg, at least two safety devices are required to be installed. As the technical demonstrator is a closed loop system security of supply is not a concern [HOLD 4]. As such, it is proposed to use two

independent slam shut devices as safety devices for the pressure reduction system. This requirement will need to be confirmed in Beta phase through sufficient safety studies such as HAZOP and LOPA.

A technical query, PRZ0025-TQ-0000-0001, has been submitted to confirm this approach.

## 4.2 Actuation

It is proposed to used use a combination of electric and electro-hydraulic actuation for all the valves within the testing arrangement, depending on the valve function. Most valves shall be electrically actuated, whilst safety valves, such as slam-shuts shall be electro-hydraulic, so as they could operate in the scenario of a loss of electricity. These are considered preferable to pneumatic valves which require constant venting to operate, as well as using the hydrogen within the system to operate.

## 4.3 Venting and Flaring

Venting shall be minimised in the design of the technical demonstrator, to reduce the quantity of hydrogen released into the atmosphere. Therefore, the use of relief valves is to be avoided where possible, in preference on non-venting alternatives.

Flaring is generally used to ensure that large quantities of hydrogen are not released into the atmosphere. This causes a risk of explosion and over-pressurisation if delayed ignition occurs. Therefore. it is proposed to have a flare on site through the commissioning, demonstration and decommissioning.

## 4.4 Redundancy

As the technical demonstrator will have a short operational life (weeks / months), it is proposed to have no redundancy for any process equipment such as the compressor package or pressure and flow control stream.

Any faults or trips leading to the cessation of compression or activation of pressure protection devices will result in the suspension of the technical demonstration.

## 4.5 Leak and Flame Detection

As detailed within IGEM/TD/13 Edition 3 Supplement 1 [11], leak and flame detection is required to be installed at appropriate locations, as it is assumed that the hydrogen is unodorised and shall not have flame colourant added.

Consideration shall be given to linking the link and flame detection equipment to the safety system.

The final location of the leak and flame detection equipment shall be determined and specified within the Beta phase based on the selected equipment and the coverage required.

# 5 Design and Materials

## 5.1 Location

The proposed location of the test facility has been reviewed, with multiple sites being considered, including existing sites on the National Transmission System (NTS), including Towton, Burley Bank and ICI Billingham, as these are all proposed to be a part of the Project Union network.

A previously leased site, adjacent to ICI Billingham was also reviewed, Billingham Enron. However, as ICI Billingham has been descoped form the repurposing aspect of PU:EC and National Gas would need to renew the land lease, Billingham Enron has been considered unfavourable as a location for the technical demonstrator.

The only remaining viable option is Zone C of the Aberdeen Energy Transition Zone (ETZ), which is focussed on the development of hydrogen technologies aimed towards net-zero. The financial need case for this location would need to be proven; however, the project is progressing with the demonstrator facility being based within Zone C of the Aberdeen ETZ.

## 5.2 Maximum Design Factor

Zone C of the Aberdeen ETZ is located adjacent to the Aberdeen waste transfer and disposal station, which has a significant number of people present to work. Therefore, it is proposed to progress based on the site located within an S type area.

The design factor for the pipework to be used as part of the technical demonstrator will be based on the material grade, as detailed in section S7.9.2.5 of IGEM/TD/13 Edition 3 Supplement 1 [11] and in Figure 2 below.

| MATERIAL GRADE | DESIGN FACTOR f | MATERIAL PERFORMANCE FACTOR h |
|---|---|---|
| L360 / X52 and below | 0.5 | 1.0 |
| L415 / X60 | 0.43 | 0.87 |
| L450 / X65 | 0.4 | 0.8 |
| L485 / X70 | 0.37 | 0.74 |

Figure 2: IGEM/TD/13 Edition 3 Supplement 1 – Maximum Design Factor Extract

This shall be used to ensure the pipework on site will be qualified for use with hydrogen and compliant on a site within an S type area.

## 5.3 Maximum Velocity

It is proposed that the hydrogen used for the demonstrator shall be filtered and therefore, the maximum gas velocity shall not exceed 40ms$^{-1}$. High gas velocity can result in excessive sound pressure levels and induced vibration, as well as internal piping erosion.

## 5.4 Materials

### 5.4.1 Class Rating

It is proposed that the technical demonstrator consist of CL1500 materials, i.e., suitable for a pressure of 250 barg. Although the assets between the pressure reduction and compression would be suitable for CL600 materials due to the 30 to 50 barg operating pressure, it is preferred to maintain for consistency across the trial equipment.

### 5.4.2 Valves

When selecting valves to be used as part of the technical demonstrator, the specific requirements of IGEM/TD/13 Edition 3 Supplement 1 [19] clause S7.4.4 shall be included in the valve specification. These requirements shall be included to prevent leakage across the valve and to atmosphere.

Therefore, to minimise the potential for leaks the following or equivalent requirement shall be specified:

- Double Block and Bleed valve arrangement
- Each casting to be hydraulically leak tested
- Soft seats in a metal retainer for in-line automatic valves and automatic vents; specify bubble tight shut-off
- Metal to metal seat of soft seats in a retainer for in-line manual valves; these should be combined with a means of positive isolation if used to block the flow path before attempting invasive maintenance or inspection inside the installation
- Metallic seat with valve outlet blocked
- Minimise through bolting, body flanges or threaded connections in assembly of the body of the valve unless gaskets are suitable for hydrogen service.
- Non-metallic materials present in seals shall be qualified for hydrogen service.
- Cast or ductile iron shall not be used for the valve shell

### 5.4.3 Gaskets

Due to the flammability of hydrogen, where raised face flanges are used, the gasket shall be a Teflon or graphite spiral wound gasket. For ring type joint flanges, copper rings should be used.

### 5.4.4 Bolting, studs, nuts and washers

Where they may be exposed to hydrogen, bolting, studs, nuts and washers shall be suitable for use with hydrogen and compatible with the relevant fittings.

### 5.4.5 Pressure Regulators and Safety Systems

Pressure regulators and relief valves shall be designed with the inclusion of hardened seats and plugs. Relief Valves, if required, shall also be suitable for higher temperatures which shall be experienced where hydrogen is vented.

# 6 Bibliography

[1] The Planning (Hazardous Substances) regulations, 2015.

[2] COMAH, *Control of Major Accident Hazards (COMAH) Regulations,* legislation.gov.uk, 2015.

[3] DSEAR 2002, *Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002,* Legislation.gov.uk, 2002.

[4] Gas Act, UK Public General Acts, 1986.

[5] HSWA, *Health and Safety at Work etc Act 1974,* 1974: legislation.gov.uk.

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[7] GSMR, *Gas Safety Management Regulations,* HSE, 1996.

[8] PSSR 2000, *The Pressure System Safety Regulations 2000,* legislation.gov.uk, 2000.

[9] PSR, *Pipeline Safety Regulations (PSR) 1996,* legislation.gov.uk, 1996.

[10] IGEM/TD/13 Edition 3, *Pressure Regulating Pipeline Installations Exceeding 7 bar,* IGEM, 2023.

[11] IGEM/TD/13 Edition 3 Supplement 1, *Pressure Regulating Installations for Hydrogen at Pressures Exceeding 7 bar,* IGEM, 2024.

[12] IGEM/SR/25 Edition 2, *Hazardous Area Classification of Natural Gas Installations,* IGEM, 2013.

[13] IGEM/SR/25 Edition 2 Supplement 1, *Hazardous Area Classification of Installations Using Hydrogen or Blends up to and including 20% by Volume Hydrogen in Natural Gas,* IGEM, 2022.

[14] ASME B31.12, *Hydrogen Piping and Pipelines,* The American Society of Mechanical Engineers, 2023.

[15] T/SP/TR/18, *Specification for Engineering of Pipelines and Installations Operating at Above 7 barg,* National Grid, 2021.

[16] T/SP/TR/17, *Management Procedure for Isolation of Above 2 Bar Plant and Equipment,* National Grid, 2017.

[17] T/SP/G/37, *Site Location and Layout Studies and Reviews,* National Gas Transmission, 2025.

[18] T/PM/PS/3, *Management Procedure for Ensuring Compliance with the Pressure Systems Safety Regulations 2000 General Compliance Duties,* National Grid, 2015.

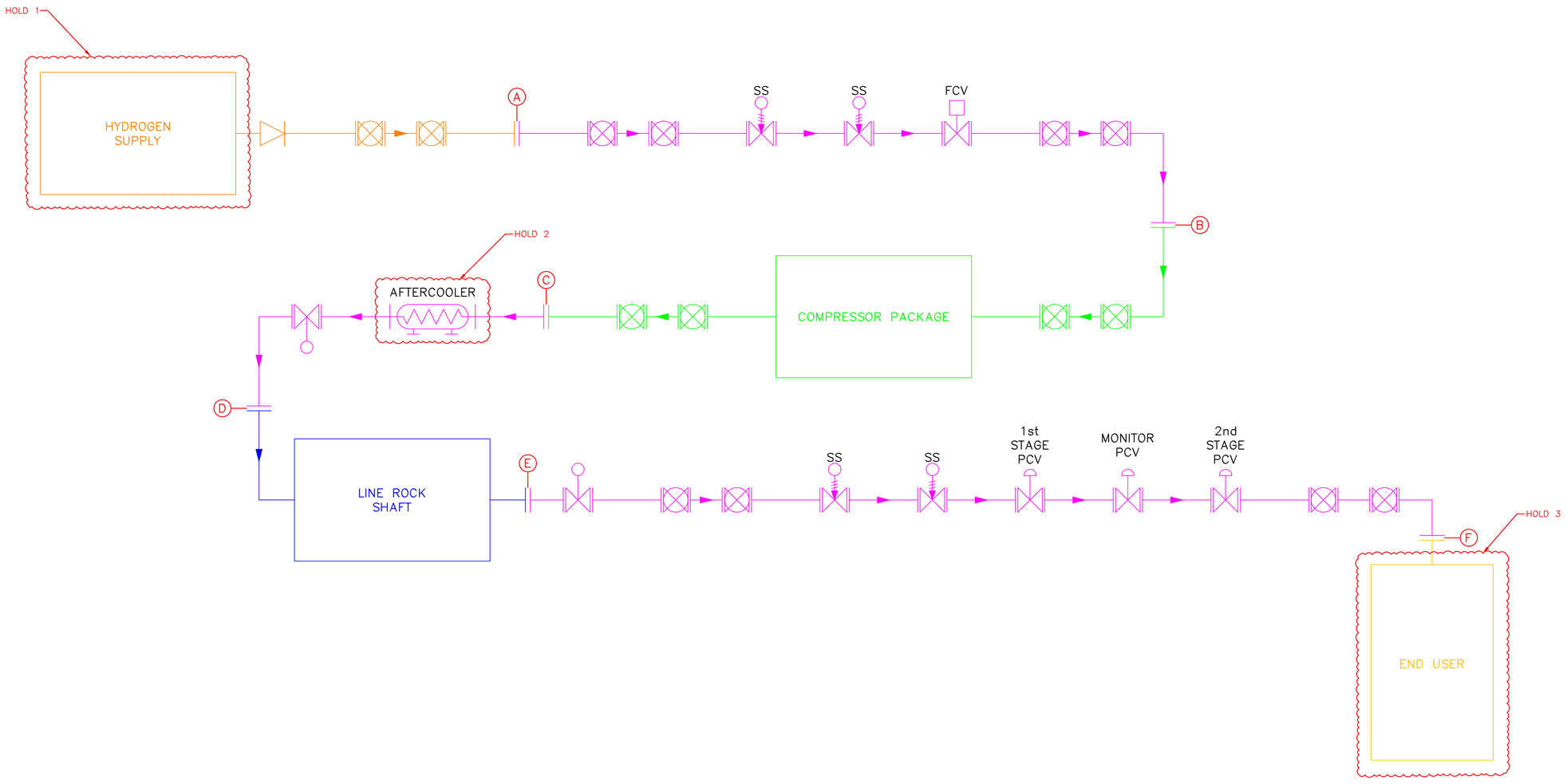
[19] IGEM/TD/13 Edition 3 Supplement 1, *Pressure Regulating Installations for Hydrogen Transmission at Pressures Exceeding 7 bar,* IGEM, 2024.

# Appendix A Premzero Drawings

| Document Title | Document Number | Included (Y/N) |
|---|---|---|
| Process Flow Diagram – Proposed Arrangement | PRZ0025-ELD-0000-0001 | Y |
| Engineering Line Diagram – Proposed Arrangement | PRZ0025-ELD-0000-0002 | Y |

DRG. No.
PRZ0025-ELD-0000-0001

| DESIGN PARAMETERS | | | | | | |
|---|---|---|---|---|---|---|
| LOCATION | SOL (Barg) | MOP (Barg) | MINIMUM PRESSURE (Barg) | MAX FLOW (scm/h) | MIN FLOW (scm/h) | TEMPERATURE |
| A | 50 (HOLD 1) | 45 (HOLD 1) | 30 | TBC (HOLD 4) | TBC (HOLD 4) | 5 |
| B | 50 | 45 | 30 | 945 | 426 | 5 |
| C | 200 | 188.7 | 180 | 945 | 426 | TBC (HOLD 5) |
| D | 200 | 188.7 | 180 | 945 | 426 | 5 |
| E | 200 | 188.7 | 180 | 945 | 426 | 5 |
| F | TBC (HOLD 3) | TBC (HOLD 3) | TBC (HOLD 3) | TBC (HOLD 3) | TBC (HOLD 3) | 5 |




## HOLD

1. PARAMETERS OF HYDROGEN SUPPLY TO BE CONFIRMED.
2. AFTERCOOLER REQUIREMENTS TO BE CONFIRMED.
3. THE END USER REQUIREMENTS TO BE CONFIRMED.
4. THE FLOW RATE PROVIDED FROM THE HYDROGEN SUPPLY IS TO BE CONFIRMED.
5. THE TEMPERATURE GAINED THROUGH COMPRESSION IS TO BE CONFIRMED.

## NOTES

1. SMALL BORE PIPEWORK OMITTED FROM DRAWING.
2. SAFETY DEVICE REQUIREMENTS ARE TO BE CONFIRMED.
3. ARRANGEMENT ASSUMES A LINEAR SYSTEM, RATHER THAN A CLOSED SYSTEM.

## KEY

- HYDROGEN SUPPLIER
- PREMTECH
- COMPRESSOR SUPPLIER
- GRAVITRICITY
- HYDROGEN END USER

FCV FLOW CONTROL VALVE
PCV PRESSURE CONTROL VALVE
SS SLAMSHUT

(XX) REFERENCE PARAMETER LOCATION

### PIPEWORK & FITTINGS

FLANGED CONNECTION; REDUCER; DOME END END CAP; VENTED PLUG; SOLID PLUG

### EQUIPMENT

FILTER; PIG TRAP; INSULATION JOINT; ISOLATING FLANGES; UNDER PRESSURE CONNECTIONS; FLOW METER; ORIFICE PLATE; TURBINE METER; VENTURI TUBE; METER WITH MOUNTED PLATE; ULTRASONIC METER

### VALVES

GENERIC; BALL VALVE; PLUG VALVE; NON RETURN VALVE; GATE VALVE; GLOBE VALVE; BUTTERFLY VALVE; DOUBLE BLOCK & BLEED VALVE

### VALVE OPERATION

GENERIC; MANUAL HANDWHEEL; MOTORISED; DIAPHRAGM; SOLENOID; SLAM SHUT

### HEATERS

WATERBATH HEATER; ELECTRIC WATERBATH HEATER; INLINE HEAT EXCHANGER; ELECTRIC HEATER

### INSTRUMENTATION

(X) FIELD; (X) REMOTE; (X) LOCAL CONTROL PANEL

| | | | |
|---|---|---|---|
| A | ALARM | U | MULTIVARIABLE |
| C | CONTROL | X | BURSTING DISC |
| D | DIFFERENTIAL | Y | EVENT, STATE |
| E | DENSITY | | PRESENCE |
| F | ELEMENT | Z | SHUT-DOWN |
| G | FLOW | N | GAS |
| H | POSITION | O | FIRE |
| I | HAND | E | DOOR |
| L | INDICATOR | GEN | GENERATOR |
| P | LEVEL | VP | VALVE POSITION |
| Q | PRESSURE | FT | FLOW TRANSMITTER |
| S | QUANTITY | SOV | SOLENOID VALVE |
| T | SWITCH | | |
| TI | TEMPERATURE/TRANSMITTER | | |
| | TEMP. INDICATOR | | |

| | DATE | DRAWN | CHECKED | APPROVED | AMENDMENT |
|---|---|---|---|---|---|
| F | | | | | |
| E | | | | | |
| D | | | | | |
| C | | | | | |
| B | | | | | |
| A | 04/08/2025 | JJS | | | INITIAL ISSUE FOR REVIEW AND COMMENT |

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PROJECT

B-LINEPACK+

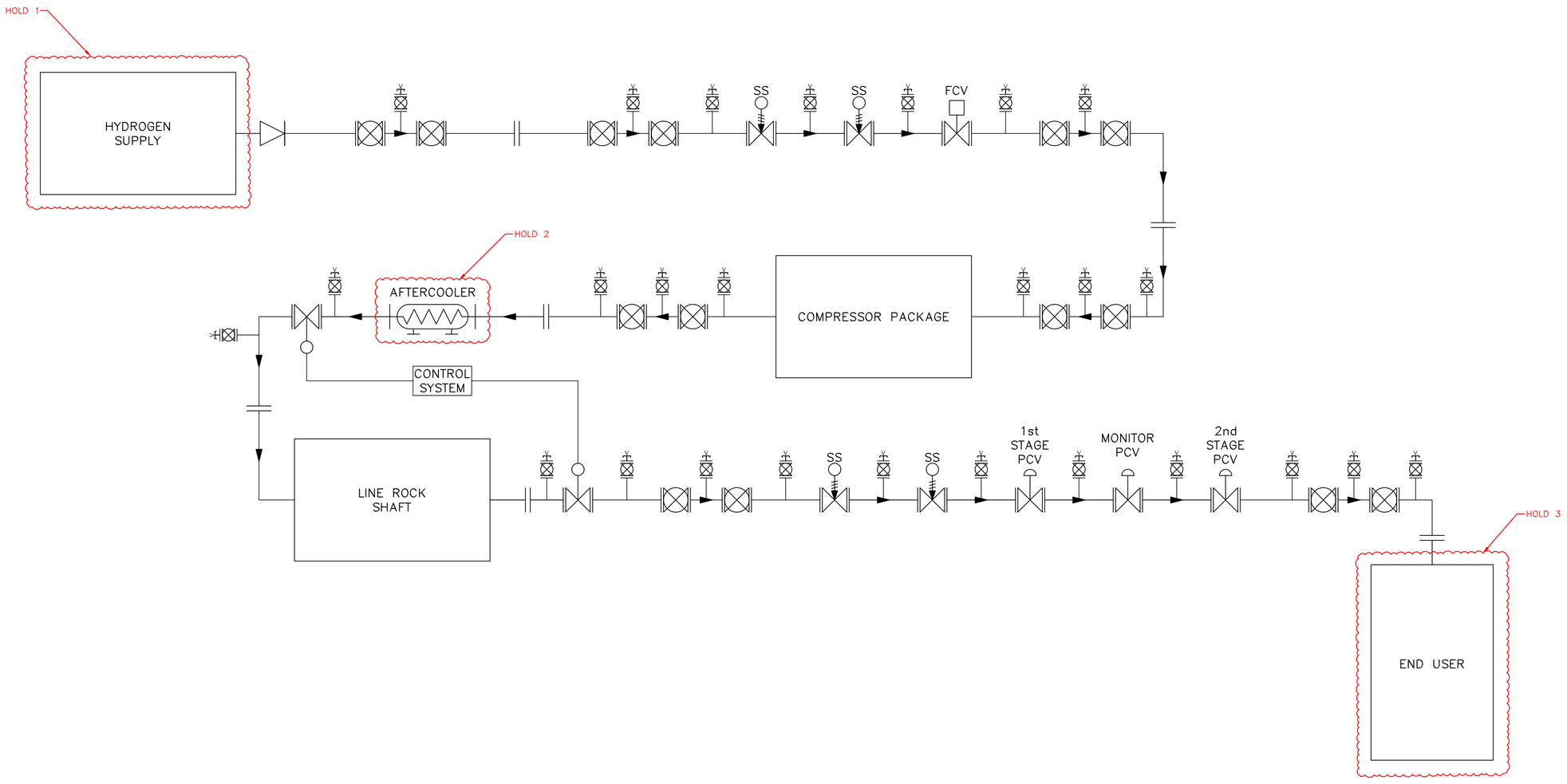
TITLE

PROCESS FLOW DIAGRAM
PROPOSED ARRANGEMENT

SHEET 1 OF 1 | SCALE NTS | DO NOT SCALE | A1

DRG. No. PRZ0025-ELD-0000-0001 | ISSUE A

DRG. No.
PRZ0025-ELD-0000-0002




## NOTES

1. SMALL BORE PIPEWORK OMITTED FROM DRAWING.
2. SAFETY DEVICE REQUIREMENTS ARE TO BE CONFIRMED.

## KEY

——/------ NEW GAS PIPEWORK AND EQUIPMENT

FCV FLOW CONTROL VALVE
PCV PRESSURE CONTROL VALVE
SS SLAMSHUT

## HOLD

1. PARAMETERS OF HYDROGEN SUPPLY TO BE CONFIRMED.
2. AFTERCOOLER REQUIREMENTS TO BE CONFIRMED.
3. THE END USER REQUIREMENTS TO BE CONFIRMED.

### PIPEWORK & FITTINGS

FLANGED CONNECTION
REDUCER
DOME END END CAP
VENTED PLUG
SOLID PLUG

### EQUIPMENT

FILTER
PIG TRAP
INSULATION JOINT
ISOLATING FLANGES
UNDER PRESSURE CONNECTIONS
FLOW METER
ORIFICE PLATE
TURBINE METER
VENTURI TUBE
METER WITH MOUNTED PLATE
ULTRASONIC METER

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BALL VALVE
PLUG VALVE
NON RETURN VALVE
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DOUBLE BLOCK & BLEED VALVE

### VALVE OPERATION

GENERIC
MANUAL HANDWHEEL
MOTORISED
DIAPHRAGM
SOLENOID
SLAM SHUT

### HEATERS

WATERBATH HEATER
INLINE HEAT EXCHANGER
ELECTRIC WATERBATH HEATER
ELECTRIC HEATER

### INSTRUMENTATION

X FIELD
X REMOTE
X LOCAL CONTROL PANEL

| | | | |
|---|---|---|---|
| A | ALARM | U | MULTIVARIABLE |
| C | CONTROL | X | BURSTING DISC |
| D | DIFFERENTIAL | Y | EVENT, STATE PRESENCE |
| E | DENSITY | Z | SHUT-DOWN |
| F | ELEMENT | N | GAS |
| G | FLOW | O | FIRE |
| H | POSITION | E | DOOR |
| I | HAND | GEN | GENERATOR |
| L | INDICATOR | VP | VALVE POSITION |
| P | LEVEL | FT | FLOW TRANSMITTER |
| Q | PRESSURE | SOV | SOLENOID VALVE |
| S | QUANTITY | | |
| T | SWITCH | | |
| TI | TEMPERATURE/TRANSMITTER | | |
| | TEMP. INDICATOR | | |

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PROJECT

B-LINEPACK+

TITLE

ENGINEERING LINE DIAGRAM
PROPOSED ARRANGEMENT

| | DATE | DRAWN | CHECKED | APPROVED | AMENDMENT |
|---|---|---|---|---|---|
| F | | | | | |
| E | | | | | |
| D | | | | | |
| C | | | | | |
| B | | | | | |
| A | 04/08/2025 | JJS | | | INITIAL ISSUE FOR REVIEW AND COMMENT |


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SHEET 1 OF 1 | SCALE NTS | DO NOT SCALE | A1

DRG. No. PRZ0025-ELD-0000-0002 | ISSUE A

# Appendix B Premtech Documents

| Document Title | Document Number | Included (Y/N) |
|---|---|---|
| Technical Query regarding applicability of IGEM/TD/13 Edition 3 | PRZ0025-TQ-0000-0001 | Y |

# Technical Query / Deviation Request Form

| Section 1 – General Information | | | | | |
|---|---|---|---|---|---|
| **Project Name / Location:** | | | **B-Linepack+** | | |
| **Project NGT WBS timesheet code:** | | | | | |
| **TQ / Deviation Request Initiator:** | | | **Adam Bradshaw-Jones** | **Tel:** | **07553 795122** |
| **Project Design Coordinator:** | | | | **Tel:** | |
| **Contractor / Designer Organisation:** | | | **Premtech Ltd** | | |
| **Date Received at Project Doc Control:** | | | Click or tap to enter a date. | | |
| **TQ** | ☒ | **Deviation** ☐ | **IGEM/TD/13 Applicability** | | |

| Section 2 – Unique TQ/Dev Reference and Version | | |
|---|---|---|
| **Contractor/Designer Ref No:** | **Project Ref No:** | **GT Ref No:** |
| **PRZ0025-TQ-0000-0001** | | |

**Section 3 – Relevant NGT Standard(s)**

IGEM/TD/13 Edition 3 Supplement 1 S2.1 – This Supplement gives additonal recommendations for installations with an upstream maximum operating pressure (MOP) not greater than 100 bar.

**Section 4 - Description and Supporting Information**

Linepack flexibility is key for National Gas Transmission (NGT) to provide system resilience by management of swings within operational limits. In a hydrogen world, it is known that the energy content per kilometre of linepack will decrease by up to 76%. Therefore, embedded resilience systems in the form of Lined Rock Shafts (LRS) are being investigated through a SIF funded innovation project to supplement loss in linepack capability.

The LRS designed by Gravitricity uses geology to withstand high pressure, whilst using a designed layered system to avoid any hydrogen escaping into the ground. This method allows the design to store high pressure hydrogen which shall replicate linepack flexibility.

In order to maximise the quantity of hydrogen stored in the LRS, the hydrogen is stored at high pressure; with stoage pressures up to 200 barg, subject to geology.

As part of the innovation project, a demonstrator facility is being designed in which a LRS with a storage capacity of 1 tonne is to be used for proof of concept.

The demonstator facility will consist of equipment aimed at replicating a hydrogen network. The expected pressure range for a hydrogen network, as considered within Project Union is 30 – 50 barg.

Therefore, both compression and pressure reduction are required, along with flow control, within the above ground system for the demonstrator facility.

T/SP/TR/18 15.2.3 states that IGEM/TD/13 shall be applied to all pressure and flow control installations. IGEM/TD/13 Edition 3 Supplement 1 covers Pressure Regulating Installations for Hydrogen at pressures exceeding 7 bar; however, the upstream maximum operating pressure is limited to 100 bar. This is lower than the 200 bar storage pressure proposed within this trial hence the arrangement is outside the scope of IGEM/TD/13.

As there is no equivalent standard for pressure regulation installations with 200 bar inlet pressures, the project has applied the principles of IGEM/TD/13 as good practice, particularly regarding the number of safety devices and the accuracy requirements for pressure regulators and slam-shut valves.

The key features of the design of the pressure reduction system include:

- 2 safety devices are included in the pressure reduction stream, proposed to both be slam shut valves (of differing types / makes to avoid common mode failure). As the demonstrator will be a closed loop, there is no downstream network to supply
- 2 regulators, including a rough cut and active regulator to control the pressure cut from circa 200 barg to circa 50 barg
- The second stage active regulator shall be suitable for the full pressure cut if the rough cut regulator fails, subject to vendor engangement
- No redundancy is included (2nd stream) due to having no downstream network to supply

The design shall be subject to safety studies to determine the required number of safety devics. We expect the studies to include, but are not limited to; HAZID, HAZOP and LOPA studies during the Beta phase if the project is successful in its funding application.

Please can National Gas confirm acceptance of the applying IGEM/TD/13 design principles to the proposed demonstrator facility.

| **CAPEX Impact:** | | **OPEX Impact (20 yr):** | |
|---|---|---|---|

**Section 5 – NGT Competent Engineer Response**

<The Project Engineering Team email box (for use only by National Gas Transmission; Contractors shall submit via the National Gas Transmission Design Coordinator): ukconstruction.technicalqueries@nationalgas.com>

| **Conditions / Pre-requisites:** | | |
|---|---|---|
| **Deviation Category:** | Choose an item. | Click to enter expiry date (if applicable) |

| **Name** | **Position** |
|---|---|
| | |

| **Date:** | |
|---|---|

| **Project Manager Approval** (for TQs answered within the Project Team) | **Name** | **Signature** |
|---|---|---|
| | N/A | N/A |

**Section 6 – Document Owner Manager Authorisation (for Deviations only)**

**Comments:** <For rejected deviations, you may enter a further supporting comment to clearly indicate a rejected deviation>

| **Deviation Decision:** | Choose an item. |
|---|---|

| **Name** | **Signature** |
|---|---|
| | |

| **Date:** | CLICK OR TAP TO ENTER A DATE. |
|---|---|

# B-Linepack+

# Alpha Phase

## Technical Interface Discussion Document (TIDD)

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| Issue | Description | Originator | Date | Checker | Date | Approver | Date |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| 01 | Initial Issue for Review and Comment | A Bradshaw-Jones | 02/07/25 | | | | |

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# Abbreviations

| | |
|---|---|
| AGI | Above Ground Installation |
| COMAH | Control of Major Accident Hazards |
| CP | Cathodic Protection |
| DNO | District Network Operator |
| DSEAR | Dangerous Substances and Explosive Atmospheres Regulations |
| ETZ | Energy Transition Zone |
| FCV | Flow Control Valve |
| GSMR | Gas Safety (Management) Regulations |
| HSWA | Health and Safety at Work etc Act 1974 |
| I&C | Instrumentation & Control |
| IJ | Insulation Joint |
| NGT | National Gas Transmission |
| PSR | Pipeline Safety Regulations |
| PSSR | Pressure Systems Safety Regulations |

# Executive Summary

In order to improve the capacity of a future hydrogen gas network, options are being considered for additional network hydrogen storage.

One option being considered is a Line Rock Shaft, which is currently a design under development as part of this innovation project. The line rock shaft operates by using the ground geometry to support the pressure, whilst a layered system is used to contain any hydrogen.

Above ground assets shall be required in order to ensure the parameters for both the line rock shaft and connecting network.

The arrangement requires proof of concept. The location for where this can be trialled and proved is to be confirmed.

The objective of this document is to describe and define the overall technical interface philosophy and design requirements at each of the technical interfaces.

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1.2 Project Objectives ..... 4

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2.2 Key Hydrogen Specific Standards, Specifications & Guidance Documents ..... 5

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5 Bibliography

**Appendix A** Interface Point Schedule

# Figures

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# 1 Introduction

## 1.1 General

The development of a hydrogen transportation network is a key avenue which National Gas Transmission (NGT) are exploring, with the development of Project Union.

Due to hydrogen having a lower calorific value in comparison with natural gas, more hydrogen is required to meet the same energy demand that natural gas currently supplies. Therefore, options for storing hydrogen on the network, as well as within the pipework, are being considered and explored.

One of these options is a Line Rock Shaft, which is an underground shaft which uses layers of material, as well as the ground geology to contain high-pressure hydrogen before transferring it into the network at periods of increased demand.

In order to facilitate the storage of hydrogen within a line rock shaft, above ground assets are required within an Above Ground Installation (AGI). The assets required are to be confirmed following confirmation of the parameters within this report.

## 1.2 Project Objectives

As the project is an innovation project, the phases of the project include Discovery, Alpha Phase and Beta Phase. The current phase of the project is Alpha Phase, during which the design parameters are to be confirmed, whilst the assets and layout for the test facility are to be proposed.

The test facility is designed to provide proof of concept for the Line Rock Shaft and to determine if it is a technology which should be further progressed.

The project is focussed on the design for the test facility. However, high level changes between the test facility and connecting the Line Rock Shaft into a future hydrogen network shall be considered.

The parameters and arrangement shall be considered to align as closely as possible with the requirements for tying-into a future hydrogen network to best reflect ant future arrangements.

# 2 Legislations and Specifications

## 2.1 Applicable Legislation

When considering hydrogen piping and AGIs, consideration shall be given to the following and other relevant legislation where applicable:

- Pressure Systems Safety Regulations (PSSR) 2000 [1]
- Pipeline Safety Regulations (PSR) 1996 [2]
- The Planning (Hazardous Substances) Regulations 2015 [3]
- Control of Major Accident Hazards (COMAH) Regulations 2015 [4]
- Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002 [5]
- Gas Act 1986 (amended 1995) [6]
- Gas Safety (Management) Regulations (GSMR) 1996 [7]
- Health and Safety at Work etc Act 1974 (HSWA) [8]
- Town and Country Planning Act 1990 [9]

Where the above legislation does not specifically apply to hydrogen, the principles and best practices outlined in the legislation have been appropriately applied, as it is noted that some of the above legislation will require updating to allow hydrogen to be stored and transported.

## 2.2 Key Hydrogen Specific Standards, Specifications & Guidance Documents

- IGEM/TD/13 Edition 3 – Pressure regulating pipeline installations exceeding 7 bar [10]
- IGEM/TD/13 Edition 3 Supplement 1 – Pressure regulating installations for Hydrogen at pressures exceeding 7 bar [11]
- IGEM/SR/25 Edition 2 – Hazardous area classification of Natural Gas installations [12]
- IGEM/SR/25 Edition 2 Supplement 1 – Hazardous area classification of installations using Hydrogen or blends of up to and including 20% by volume Hydrogen in Natural Gas [13]
- ASME B31.12 – Hydrogen Piping and Pipelines [14]

## 2.3 National Gas Standards and Specifications

Whilst not specific to hydrogen as a fluid, cognisance should be taken of existing National Gas pipeline design standards and specifications.

- T/SP/TR/18 – Engineering of Pipelines and Installations Operating at Above 7Barg [15]
- T/SP/TR/17 – Management Procedure for Isolation of Above 2 bar Plant and Equipment [16]
- T/SP/G/37 – Site Location and Layout Studies and Reviews [17]

# 3 Technical Interfaces

## 3.1 Location

The location for the test facility is currently unconfirmed. Several existing sites have been considered on the proposed Project Union, including Towton, Burley Bank and ICI Billingham. Following site surveys, these were not deemed as suitable options due to available space.

The Alpha Phase of the project is progressing based upon using the Aberdeen Energy Transition Zone (ETZ) as the proposed location for the test facility. This is a 250-hectare area near Aberdeen South Harbour, designed to support the transition to a net-zero economy.

Figure 1: Area associated with Aberdeen ETZ

As the details for the area are currently unknown, there will be some highlighted assumptions within this report which will need to be confirmed when the location of the test facility is confirmed.

# 4 Interface Philosophies

## 4.1 Mechanical

### 4.1.1 Hydrogen supply (M-TP01)

The hydrogen supply is to be delivered to site within a high-pressure tube trailer, which will form part of the testing arrangement. The pressure and interface connection of the tube trailer and hydrogen supply are to be confirmed.

### 4.1.2 Line Rock Shaft (M-TP02)

The connection between the Line Rock shaft and the above ground assets shall consist of an inlet and an outlet flanged connection. The location and size of these flanged connections shall be confirmed following the confirmation of the flow rates and pressures for the inlet and outlet of the Line Rock Shaft

## 4.2 Civil Interfaces

### 4.2.1 Site road (C-TP01)

The proposed site shall need a site road for traffic, including construction traffic. The location of the interface between the site road and an existing access road shall be determined following confirmation of the site location and layout.

### 4.2.2 Drainage (C-TP02)

A drainage system shall be required due to the additional infrastructure being installed. The type and location of the drainage interface shall be confirmed following confirmation of the site location and type, as well as all required assets.

### 4.2.3 Fencing (C-TP03)

A security fence shall be required for the test site to ensure there is no unauthorised access to the site which could risk both lives as well as damage to assets.

The type and location of the fence line shall be determined, along with how the fence interacts with other assets and areas of the Aberdeen ETZ.

## 4.3 Electrical Interfaces

### 4.3.1 Power Supply (E-TP01)

To provide power to any on site electrical equipment, a power supply from the local District Network Operator (DNO) is required. The details of any interface between National Gas and the DNO will be determined in subsequent phases following confirmation of the type of location of electrical supply connections.

### 4.3.2 Cathodic Protection (E-TP02)

The new test facility shall to contain buried assets and will be protected from external corrosion by a Cathodic Protection (CP) system, type to be determined during subsequent design phases. It is assumed that due to the site being within it's own area and not connected to any other assets that a single CP system shall be required and no electrical isolation shall be required. If multiple CP systems are required then electrical isolation in the form of Insulation Joints (IJs) or similar would be required.

## 4.4 Instrumentation and Control (I&C) interfaces

Instrumentation and control systems shall be required on site. Assets such as Flow Control Valves (FCVs), protection devices and Compressor packages shall all require instrumentation and control systems. However, it has assumed that these shall be on a local system and therefore shall not have specific interfaces.

## 4.5 Maintenance

Due to the nature of a trial site, maintenance through the project is not expected to be required. However, responsibility for the area before and after the trial needs to be agreed, including ground maintenance.

## 4.6 Venting

Venting may be required as part of the safety systems within the testing arrangement. Potential venting shall be considered with the impacts identified following confirmation of the arrangements.

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# Appendix A Interface Point Schedule

| Document Title | Document Number | Included (Y/N) |
|---|---|---|
| B-Linepack+ Technical Interface Register | PRZ0025-REG-0000-9000 | Y |

# Interface Schedule – B-Linepack+ Technical Interface

| ID | TP Name<br>*Terminal Point (or Interface Point)* | Process / design conditions (if applicable)<br>*inc. Max/Min Design and Max/Min Operating Conditions etc.* | Location<br>*Description or co-ordinates where available* | Interface Party<br>*Insert name of other organisation(s) where co-ordination is required* | Notes |
|---|---|---|---|---|---|
| **Mechanical / Process** *(e.g. fuel gas)* | | | | | |
| M-TP01 | Hydrogen Supply | MOP = TBC barg<br>SOL = TBC barg<br>Minimum pressure = TBC barg<br>Min / Max Design Temp = -20°C / +60°C<br>Size: TBC | TBC | TBC | |
| M-TP02 | Line Rock Shaft | MOP = TBC barg<br>SOL = 200 barg<br>Minimum pressure = TBC barg<br>Min / Max Design Temp = -20°C / +60°C<br>Size: TBC | | Gravitricity | Maximum pressure based upon Gravitiricty stated value of 200barg. This is dependent on ground conditions and is still to be confirmed. |
| **Electrical** *(e.g. earthing, power supply etc)* | | | | | |
| E-TP01 | Power Supply | TBC | TBC | TBC | |
| E-TP02 | Cathodic Protection | TBC | TBC | TBC | |
| **C&I** *(e.g. DCS connections, telemetry/metering connections, fire & gas detection, security/CCTV etc)* | | | | | |
| | | | | | |
| **Civil & Structural** *(e.g. drainage outfall, site access/egress roads)* | | | | | |
| C-TP01 | Site Road | TBC | TBC | TBC | |
| C-TP02 | Drainage | TBC | TBC | TBC | |
| C-TP03 | Fencing | TBC | TBC | TBC | |
| **Other** | | | | | |
| | | | | | |

DRAFT

national gas transmission

# B-Linepack+

# Alpha Phase

## Design Report

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| Issue | Description | Originator | Date | Checker | Date | Approver | Date |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |
| 01 | SIF Alpha Phase Issue | A Bradshaw-Jones | 26/01/26 | N Horan-Martin | 29/01/26 | N Horan-Martin | 30/01/26 |
| 00 | Initial Issue | A Bradshaw-Jones | | | | | |

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# Revision Index

| Revision | Summary of Changes |
|---|---|
| 00 | Initial Issue |
| 01 | Updated to finalise Alpha Phase Issue |
| | |
| | |
| | |

# Hold Record

| Hold | Hold Details |
|---|---|
| [HOLD 1] | The parameters of the provided hydrogen are to be confirmed. |
| [HOLD 2] | The SOL of the Lined Rock Shaft is dependent on the geology at the test site location. |

# Abbreviations

| | |
|---|---|
| AGI | Above Ground Installation |
| COMAH | Control of Major Accident Hazards |
| DSEAR | Dangerous Substances and Explosive Atmospheres Regulations |
| ETZ | Energy Transition Zone |
| FCV | Flow Control Valve |
| GSMR | Gas Safety (Management) Regulations |
| HAZCON | Hazards in Construction |
| HAZID | Hazard Identification |
| HAZOP | Hazards in Operability |
| HSWA | Health and Safety at Work etc Act 1974 |
| LOPA | Layer of Protection Analysis |
| LRS | Lined Rock Shaft |
| MOP | Maximum Operating Pressure |
| NB | Nominal Bore |
| NGT | National Gas Transmission |
| PCV | Pressure Control Valve |
| PSR | Pipeline Safety Regulations |
| PSSR | Pressure Systems Safety Regulations |
| SOL | Safe Operating Limit |
| SWDS | Safe Working Design Study |

# Executive Summary

As the UK looks to move towards Net Zero, hydrogen is being considered as an option to support the UK energy system. Projects are currently being undertaken to review whether the existing National Transmission System (NTS) can be repurposed for the use of hydrogen from natural gas. However, the energy content of hydrogen is significantly lower (circa 76% reduction) than that of methane and therefore the linepack availability of the network would be reduced in comparison to natural gas. Storage solutions are being developed to therefore increase the energy content available from a hydrogen network.

As part of a Strategic Innovation Funded Alpha phase project, National Gas Transmission, alongside other project partners, are looking at developing a technical demonstrator for Lined Rock Shaft (LRS) systems. Longitude, the developers of the LRS technology and a project partner, are looking to use the technical demonstrator as a proof of concept for their LRS.

The objective of this document is to detail the above ground system required to test and demonstrate the LRS, ahead of the project entering the Beta phase where a detailed design shall be developed.

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# 1 Introduction

## 1.1 General

Linepack flexibility is key for National Gas Transmission (NGT) to provide system resilience by management of swings within operational limits. In a hydrogen world, it is known that the energy content per kilometre of linepack will decrease by up to 76%. Therefore, embedded resilience systems in the form of Lined Rock Shafts (LRS) are being investigated to supplement loss in linepack capability. It is envisaged that these systems, if implemented, for hydrogen transmission will act in a similar manner to how, now decommissioned, natural gas holders were utilised for operational flexibility, pressure regulation, supply/demand mismatch management, load balancing, emergency backup and production buffering.

This project follows on from the previous discovery phase. In discovery, the feasibility of using intermediate scale geological hydrogen embedded resilience solutions to supplement linepack in a hydrogen transmission system were investigated. Due to the lower volumetric energy density of hydrogen, the energy content of linepack is only 1/3 of that of natural gas. Lined rock shafts were identified to have favourable characteristics for "Linepack+" supplementation due to:

- Fast deployability (2-3 years)
- Competitive levelised cost of storage (£250-550/kg-$H_2$)
- Increased safety due to subsurface nature
- Low footprint and visibility
- Geographical flexibility
- High cycling flexibility, up to 2 cycles per week with low degradation
- High purity and no implications of impurities being introduced due to steel liner utilised

The LRS technology was developed initially by Gravitricity but the role has been taken over midway through the alpha phase by Longitude.

## 1.2 Project Objectives

This project focuses on innovation in hydrogen embedded resilience solutions in the subsurface to develop a technical demonstrator for lined rock shafts. It also includes an energy system modelling work package to develop an integrated GB energy system model for Power 2 Gas to identify network flexibility and optimisation opportunities.

## 1.3 Document Objectives

The objective of this document is to provide detail on the conceptual design of the above ground system to demonstrate the LRS on a localised site. The document provides detail on the equipment and systems required, alongside the sizing and security of the system to ensure the overall test facility is suitable for the purpose.

# 2 Design Requirements

## 2.1 Legislation

When considering hydrogen piping and Above Ground Installation's (AGIs), consideration shall be given to the following legislation, which contains specific references to hydrogen:

- The Planning (Hazardous Substances) Regulations 2015 [1]
- Control of Major Accident Hazards (COMAH) Regulations 2015 [2]
- Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002 [3]
- Gas Act 1986 (amended 1995) [4]

Other, non-hydrogen specific legislation is also relevant, and where not directly referencing hydrogen, the best practices outlined within the legislation have been appropriately applied. This legislation is detailed below:

- Health and Safety at Work etc Act 1974 (HSWA) [5]
- Town and Country Planning Act 1990 [6]
- Gas Safety (Management) Regulations (GSMR) 1996 [7]
- Pressure Systems Safety Regulations (PSSR) 2000 [8]
- Pipeline Safety Regulations (PSR) 1996 [9]

It should be noted that COMAH does not apply to hydrogen systems which are less than 5 tonnes in size. The size of the demonstrator is 0.5 tonnes and therefore is under the lower tier threshold for COMAH to apply. However, it has still been considered in this project as best practice.

## 2.2 Specifications

### 2.2.1 Key Hydrogen Specific Standards, Specifications & Guidance Documents

- IGEM/TD/13 Edition 3 – Pressure regulating pipeline installations exceeding 7 bar [10][1]
- IGEM/TD/13 Edition 3 Supplement 1 – Pressure regulating installations for Hydrogen at pressures exceeding 7 bar [11]
- IGEM/SR/25 Edition 2 – Hazardous area classification of Natural Gas installations [12]
- IGEM/SR/25 Edition 2 Supplement 1 – Hazardous area classification of installations using Hydrogen or blends of up to and including 20% by volume Hydrogen in Natural Gas [13]
- ASME B31.12 – Hydrogen Piping and Pipelines [14]

### 2.2.2 National Gas Standards and Specifications

Whilst not specific to hydrogen as a fluid, cognisance has been taken of existing National Gas pipeline design standards and specifications.

- T/SP/TR/18 – Engineering of Pipelines and Installations Operating at Above 7Barg [15]

[1] It should be noted that IGEM/TD/13 Edition 3 Supplement 1 is only applicable for up to 100 barg. Therefore, although this system is outside of the scope of IGEM/TD/13, the principles of the standard have been used as best practice.

- T/SP/TR/17 – Management Procedure for Isolation of Above 2 bar Plant and Equipment [16]
- T/SP/G/37 – Site Location and Layout Studies and Reviews [17]

# 3 Site Location and Layout

## 3.1 Location

The proposed site location for the demonstrator facility is within Zone C of the Aberdeen ETZ (Energy Transition Zone).

Figure 1: Location of Zone C of the Aberdeen ETZ

An agreed area has been used for the design within the facility. This site will be adjacent to another development site containing a hydrogen electrolyser. Separation distances have been considered, with awareness to the electrolyser facility, as well as the neighbouring waste management facility and nearby business park.

The approximate distance between the demonstrator assets and the surrounding facilities are:

- Electrolyser Facility: 25m
- Waste Management Facility: 100m
- Business Park: 250m

Consequence modelling and a Quantitative Risk Assessment (QRA) shall be undertaken during the Beta phase to confirm the risks from the technical demonstrator are As Low As Reasonably Practicable (ALARP).

Figure 2: Aberdeen ETZ Zone C Layout

## 3.2 Layout

The site layout within Zone C of the Aberdeen ETZ is shown below.

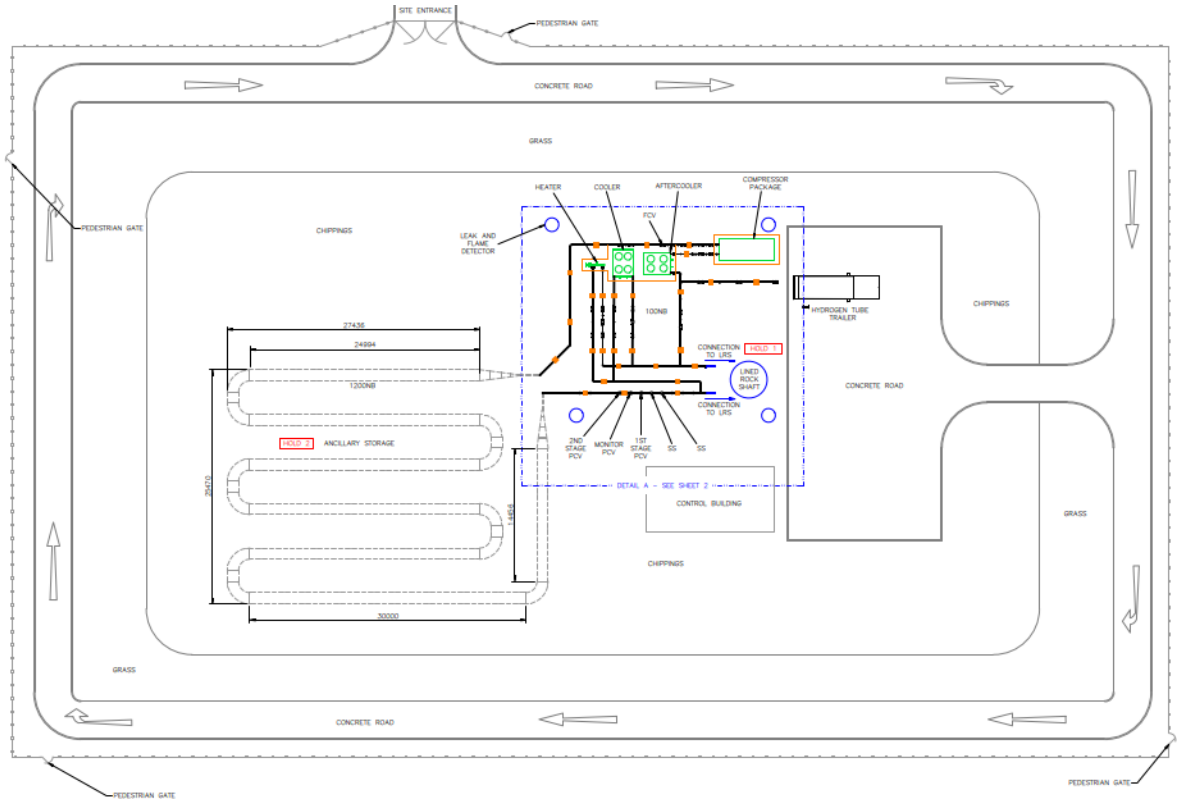


Figure 3: Demonstrator Facility Layout

The separation distances between the assets within the demonstrator facility have not been considered as escalation within the demonstrator facility is not a risk to the security of supply. However, access to all the assets is of paramount importance so a road is proposed to run around the facility but within the site fenceline.

# 4 Design Parameters

The project Basis of Design, PRZ0025-REP-0000-0001 reproduced in Appendix B, was used to determine the initial requirements for the technical demonstrator, such as line and equipment sizing.

## 4.1 Revised LRS Design Parameters

However, Longitude provided revised design parameters on 15th December 2025 following a reduction in the size of the LRS containment, please refer to email from S. Kirk dated 15/12/25 reproduced in Appendix A. The revised parameters are also included in Table 1 below for clarity.

Table 1: Revised LRS Design Parameters

| Property | Unit | Value | Notes |
|---|---|---|---|
| Storage capacity | T | 0.53 | Total hydrogen gas storage capacity assuming average storage temperature of 20°C. |
| Cushion gas | T | 0.09 | The amount of gas which is permanently stored in the sub-surface containment. It prevents unwanted loading on the liner and shaft walls when the working gas has been removed. |
| Working gas | T | 0.44 | Available gas for injection and withdrawal. |
| Maximum Operating Pressure (MOP) | barg | 200 | Maximum operating storage pressure. During commissioning this pressure will be incrementally increased from atmospheric pressure and liner/geological strains assessed before pressure is increased. |
| Inner storage diameter | m | 1.26 | Internal diameter of the gas-tight liner |
| Inner storage length | m | 29 | Internal length of the gas-tight liner |
| Internal storage volume | $m^3$ | 35 | Internal volume of the gas-tight liner |
| Overburden depth | m | 12 | Depth of backfill in competent rock to provide resistance to vessel uplift pressure. |
| Shaft diameter | m | 2.984 | Excavated diameter of shaft prior to liner installation |
| Shaft depth | m | 47 | Excavated depth of shaft prior to liner installation assuming 5m of superficial deposits. |

These parameters have been included within the design where possible / practicable. The most significant change was the change in MOP, which was increased from 188.1barg to 200barg. The relevant design calculations have been updated to consider the increased MOP and confirm it's suitability. However, the increased MOP has not been included within the supplier discussions, such as the compressor sizing. Although it should be noted that based on the initial discussions the change from 188.1 barg to 200 barg is unlikely to have an impact.

The reduction in LRS containment also affected the proposed flow rate for the technical demonstrator, see Table 2 below, as per the calculation reproduced within Appendix B.

Table 2: Revised Demonstrator Flow Rates

| Property | Unit | Value | Notes |
|---|---|---|---|
| Flow Rate | scmh | 409.51 | *Based on 0.44te of hydrogen and a 12-hour cycle time (PRZ0025-CAL-0000-0001 in Appendix B)* |
| Mass Flow Rate | kg/hr | 34.89 | *Based on 0.44te of hydrogen and a 12-hour cycle time* |
| Maximum Allowable Velocity | m/s | 40 | *Filtered Hydrogen is required for the system* |
| Calculated Gas Velocity (100NB) | m/s | 0.84 | *As per PRZ0025-CAL-0000-0001 in Appendix B* |

Although the maximum flow rate has decreased within the revised parameters, this has not been incorporated within the design, which is still suitable for the initial parameters as a worst-case scenario for the sizing / footprint of the site.

## 4.2 Revised Demonstrator Design Parameters

Based on section 4.1 above, the design parameters presented in the BoDD are modified as follows, giving the final design parameters used as part of the alpha phase.

Table 3: Summary of Design Parameters

| Parameter | Unit | Value | Comment |
|---|---|---|---|
| Line Rock Shaft Design Pressure | Barg | 200 | *As provided by Longitude* |
| Maximum Operating Pressure (MOP) | Barg | 200 | *SOL = MOP * 1.06 as per T/PM/PS/3* [18] |
| Lined Rock Shaft Safe Operating Limit (SOL) | Barg | 212[2] | *[HOLD 2]* |
| Maximum Entry Pressure into Compressor | Barg | 50 | *Based on Project Union BoDD* |
| Minimum Entry Pressure into Compressor | Barg | 30 | *Based on Project Union BoDD* |
| Flow Rate | scmh | 408 | *Based on 0.44te of hydrogen and a 12-hour cycle time* |
| Mass Flow Rate | kg/hr | 36.7 | *Based on 0.44te of hydrogen and a 12-hour cycle time* |
| Maximum Allowable Velocity | m/s | 40 | *Filtered Hydrogen is required for the system* |
| Material Design Temperature | °C | -20 to 60 | |
| Expected Normal Operating Temperature | °C | 10 to 30 | |
| Lined Rock Shaft Operational Temperature | °C | 10 to 70 | |
| Lined Rock Shaft Absolute Temperature | °C | 0 to 80 | |

[2] It is noted that the SOL of the line rock shaft will be dependent on the ground geology at the selected location and may vary. This is to be confirmed once ground investigations have been undertaken at the ETZ.

# 5 Operating Philosophy

This stage of the project is focussed on the proof of concept of the LRS and therefore is focused on the design of the technical demonstrator for the Lined Rock Shaft.

It is assumed that the hydrogen shall be delivered and stored on the test facility within a high-pressure tube trailer [HOLD 1].

Compression and pressure reduction are required, along with flow control to simulate a pipeline network and provide a cyclic duty for the LRS to demonstrate its application. Pressure protection devices are required to ensure that all risks associated with over pressurisation are suitably managed.

## 5.1 Pressure Protection

IGEM/TD/13 Edition 3 Supplement 1 [11] applies between 7 and 100 barg. As the 200 barg MOP of the LRS exceeds this limit, the technical demonstrator will, in part, operate outside of the scope of IGEM/TD/13 Edition 3 Supplement 1 [11]. However, as good practice, the design principles of IGEM/TD/13 Edition 3 [10] and IGEM/TD/13 Edition 3 Supplement 1 [11] have been adopted. In particular, the requirements regarding the number of safety devices and accuracy requirements for pressure regulators and slam-shut valve are to be used.

In accordance with IGEM/TD/13 Edition 3 [10], a decision algorithm is used to determine the number of safety devices. This algorithm is shown below:

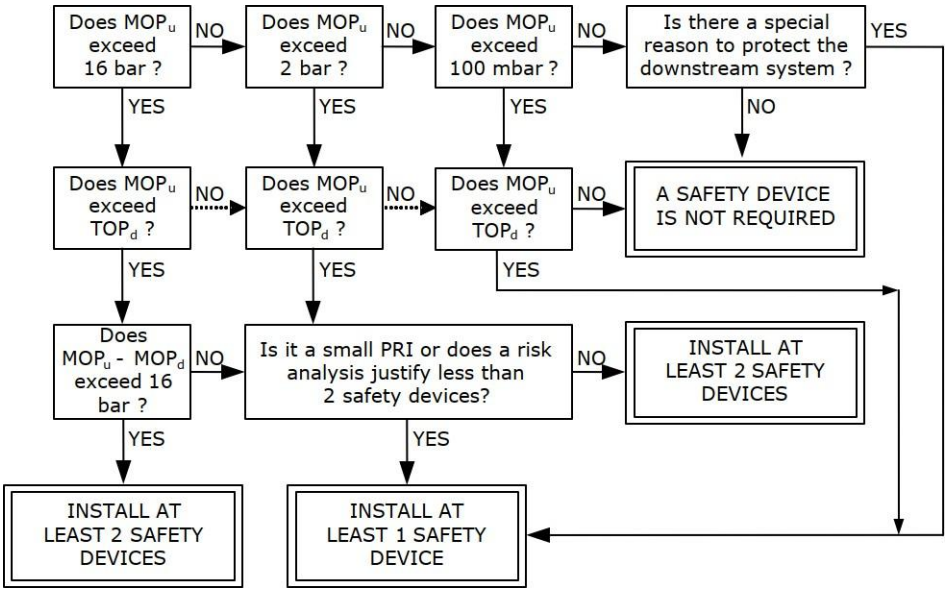


Figure 4: Decision algorithm for minimum number of safety devices from IGEM/TD/13 Edition 3

As detailed within Table 3, there is an inlet MOP of 200 barg and an outlet MOP of 50 barg. As the difference between upstream and downstream MOP is greater than 16 barg, at least two safety devices are required to be installed. As the technical demonstrator is a closed loop system security of supply is not a concern. As such, it is proposed to use two independent

slam shut devices as safety devices for the pressure reduction system. This requirement will need to be confirmed in Beta phase through sufficient safety studies such as HAZOP and LOPA.

## 5.2 Actuation

It is proposed to use a combination of electric and electro-hydraulic actuation for all the valves within the testing arrangement, depending on the valve function. Most valves shall be electrically actuated, whilst safety valves, such as slam-shuts shall be electro-hydraulic, so as they could operate in the scenario of a loss of electricity. These are considered preferable to pneumatic valves which require constant venting to operate, as well as using the hydrogen within the system to operate.

## 5.3 Venting and Flaring

Venting shall be minimised in the design of the technical demonstrator, to reduce the quantity of hydrogen released into the atmosphere. Therefore, the use of relief valves is to be avoided where possible, in preference on non-venting alternatives.

Flaring is generally used to ensure that large quantities of hydrogen are not released into the atmosphere. This causes a risk of explosion and over-pressurisation if delayed ignition occurs. Therefore. it is proposed to have a flare on site through the commissioning, demonstration and decommissioning.

The design and location of a flare stack will need to be confirmed during the Beta phase once the design of the flare stack is confirmed. This will allow the calculation of thermal radiation and overpressure contours to ensure the risks associated with flaring hydrogen are contained within the site boundary of the technical demonstrator as far as is reasonably practicable.

## 5.4 Redundancy

As the technical demonstrator will have a short operational life (circa 100 cycles of hydrogen) as detailed in an email from Longitude dated 14/01/2026 and reproduced in Appendix A, it is proposed to have no redundancy for any process equipment such as the compressor package or pressure and flow control stream.

Any faults or trips leading to the cessation of compression or activation of pressure protection devices will result in the suspension of the technical demonstration.

## 5.5 Leak and Flame Detection

As detailed within IGEM/TD/13 Edition 3 Supplement 1 [11], leak and flame detection has been included within the design. Four leak and flame detectors have been included within the design. They have been positioned in each of the four corners of the site to allow a line of site to all the assets.

However, the final location of the leak and flame detection equipment shall be determined and specified within the Beta phase based on the selected equipment and the coverage required to ensure there are no blind spots.

# 6 Mechanical System Design

## 6.1 Maximum Design Factor

Zone C of the Aberdeen ETZ is located adjacent to the Aberdeen waste transfer and disposal station and nearby to a business park,. Although there is not a confirmed number of people for these areas, a desktop review has identified that groups of people could gather in the offices within the business park or the waste management facility.

Therefore, it is proposed to progress based on the site located within an S type area.

Design factor limits in IGEM/TD/13 Supplement 1 [19] are based upon ASME B31.12 [14] design factors, incorporating material performance factors. These design factors are only valid for carbon steel pipe grades for pressures up to 137.9 barg.

As some of the technical demonstrator will operate at pressures of 200 barg, the design factors within IGEM/TD/1 Supplement 1 are not applicable and reference needs to be made to ASME B31.12 [14]. ASME B31.12 [14] Table IX-5A details the material performance factors for carbon steel pipelines and is shown below.

**Table IX-5A**
**Carbon Steel Pipeline Materials Performance Factor, $H_f$**

| Specified Min. Strength, ksi | | System Design Pressure, psig | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Tensile | Yield | ≤1,000 | 2,000 | 2,200 | 2,400 | 2,600 | 2,800 | 3,000 |
| 66 and under | ≤52 | 1.0 | 1.0 | 0.954 | 0.910 | 0.880 | 0.840 | 0.780 |
| Over 66 through 75 | ≤60 | 0.874 | 0.874 | 0.834 | 0.796 | 0.770 | 0.734 | 0.682 |
| Over 75 through 82 | ≤70 | 0.776 | 0.776 | 0.742 | 0.706 | 0.684 | 0.652 | 0.606 |
| Over 82 through 90 | ≤80 | 0.694 | 0.694 | 0.662 | 0.632 | 0.610 | 0.584 | 0.542 |

Figure 5: ASME B31.12 Table IX-5A Extract

The proposed 100NB pipework has a yield strength of ≤52ksi and the design pressure of 200barg aligns with 3,000psig. Therefore the performance factor is 0.780, which corresponds with a design factor of 0.39.

The design factor for the 1200NB pipework to be used as part of the ancillary storage within the technical demonstrator will be based on the material grade, as detailed in section S7.9.2.5 of IGEM/TD/13 Edition 3 Supplement 1 [11] and in Figure 6 below due to its MOP of 50 barg.

| MATERIAL GRADE | DESIGN FACTOR f | MATERIAL PERFORMANCE FACTOR h |
|---|---|---|
| L360 / X52 and below | 0.5 | 1.0 |
| L415 / X60 | 0.43 | 0.87 |
| L450 / X65 | 0.4 | 0.8 |
| L485 / X70 | 0.37 | 0.74 |

Figure 6: IGEM/TD/13 Edition 3 Supplement 1 – Maximum Design Factor Extract

Due to a material grade of L450, the design factor shall be 0.4 for the 1200NB pipework.

## 6.2 Proposed Pipework

The proposed pipework for the demonstrator facility is detailed below. It should be noted that pipework is normally specified to T/SP/DAT/6 [20]. However, due to the high operating and design pressure of part of the system; it has been necessary to specify thicker wall pipework than is specified in T/SP/DAT/6 [20]. Therefore, the 100mm NB pipework has been specified in accordance with ASME B36.10M [21].

Table 4: Proposed Pipework Details

| | | |
|---|---|---|
| Nominal Diameter | 100mm | 1200mm |
| Specification | ASME B36.10M [21] | T/SP/DAT/6 [20] |
| Material Grade | L245NE | L450MB |
| Outside Diameter (mm) | 114.3 | 1219 |
| Nominal Wall Thickness (mm) | 17.12 | 22.9 |
| External Coating | Painted to T/SP/PA/10 [22] | Coated to T/SP/CW/6 [23] |
| Internal Coating | The type of internal coating shall be confirmed during the beta phase but will be suitable for containing hydrogen | |

Table 5: Design Factor Calculations

| | 100NB | 1200NB |
|---|---|---|
| Nominal pipe diameter (mm) | 100 | 1200 |
| Outer Diameter (mm) | 114.3 | 1219 |
| Nominal Wall Thickness WT (mm) | 17.12 | 22.9 |
| Wall Thickness Under-tolerance | 12.5% | 1mm |
| Minimum Wall Thickness (mm) | 14.98 | 21.9 |
| Design Pressure (barg) | 200 | 50 |
| Material SMYS ($N/mm^2$) | 245 | 450 |
| Design Factor | 0.31 | 0.31 |
| Maximum Allowable Design Factor (IGEM/TD/1) | 0.39 | 0.4 |

The calculations above prove that the proposed pipework is suitable for operating a hydrogen demonstrator at the required design pressures. However, it is recommended that the pipework is subjected to a fracture mechanics assessment in beta phase in order to further qualify the proposed materials.

## 6.3 Maximum Velocity

It is proposed that the hydrogen used for the demonstrator shall be filtered and therefore, the maximum gas velocity shall not exceed $40ms^{-1}$. High gas velocity can result in excessive sound pressure levels and induced vibration, as well as internal piping erosion.

Calculations have been produced to confirm the gas velocity within the different pressure systems. These calculations have been reproduced within Appendix B.

## 6.4 Flow Control

A flow control valve stream has been included within the design, upstream of the compressor package, to ensure hydrogen flow rates are controlled through the system to correctly test the operation of LRS.

A single stream is proposed, without a standby stream as there is no risk of security of supply within the system as discussed in section 4.4.

The stream shall consist of a Flow Control Valve (FCV), a meter and isolation valves. No safety devices have been included as there is no risk of over-pressurisation of the downstream pipework as the MOP of the upstream and downstream pipework is the same.

Stream discrimination is not required as there is only a single stream included within the design.

The specific valves to be used within the stream are to be confirmed during the beta phase, alongside the exact valve set points. However, they are likely to be as per the Material Take Off (MTO) (PRZ0025-MTO-0000-0040), reproduced in Appendix C. The datasheet for the FCV, PRZ0025-DAT-0000-0301, is reproduced within Appendix B.

## 6.5 Compressor

The system consists of two operating pressure systems (50barg MOP and 200barg MOP). However, the whole system has been designed for the higher-pressure system (200barg MOP). In order to increase the pressure from 50barg to 200barg, a compressor package is required.

This compressor shall be suitable for operating with 100% hydrogen. Initial contact has been made with several compressor suppliers in order to gauge possible suitability, as well as gaining information around compressor footprints and power supplies for the system.

The parameters provided to compressor suppliers are detailed in the table below.

Table 6: Parameters provided to compressor suppliers

| Parameter | Unit | Value |
|---|---|---|
| **Inlet Pressure** | Barg | 30 – 50 |
| **Outlet Pressure** | Barg | 180 – 190 |
| **Option 1 Mass Flow Rate** | Kg/hr | 38 – 85 |
| **Option 2 Mass Flow Rate** | Kg/hr | 380 – 850 |
| **Elevation** | M | 45 |
| **Relative Humidity** | % | 80 |

Several compressor vendors returned information about suitable options, with the expected details included below.

Table 7: Proposed compressor parameters

| Parameter | Value |
|---|---|
| **Fluid** | >99.9% Dry Hydrogen |
| **Inlet Pressure** | 30 barg |
| **Outlet Pressure** | 190 barg |
| **Mass Flow Rate** | 35 – 85 kg/hr |
| **Compressor Footprint** | 6m x 2.5m |
| **Number of Stages** | 2 |
| **Number of Cylinders** | 2 |
| **Inlet Temperature Range** | -10 to +40°C |
| **Sound Pressure Level** | 85 barg |
| **Approximate Weight** | 8,000kg |
| **Approximate Power Requirement** | 600kW |
| **Approximate Lead Time** | 52 weeks |
| **Approximate Price** | £1,500,000 |

The provided lead time and price are for budgetary purposes only. Actual lead times and prices will be dictated by the actual specification of the compressor unit required and the vendor workload at the time of order.

An example of the potential compressor internal arrangement is shown in the image below.

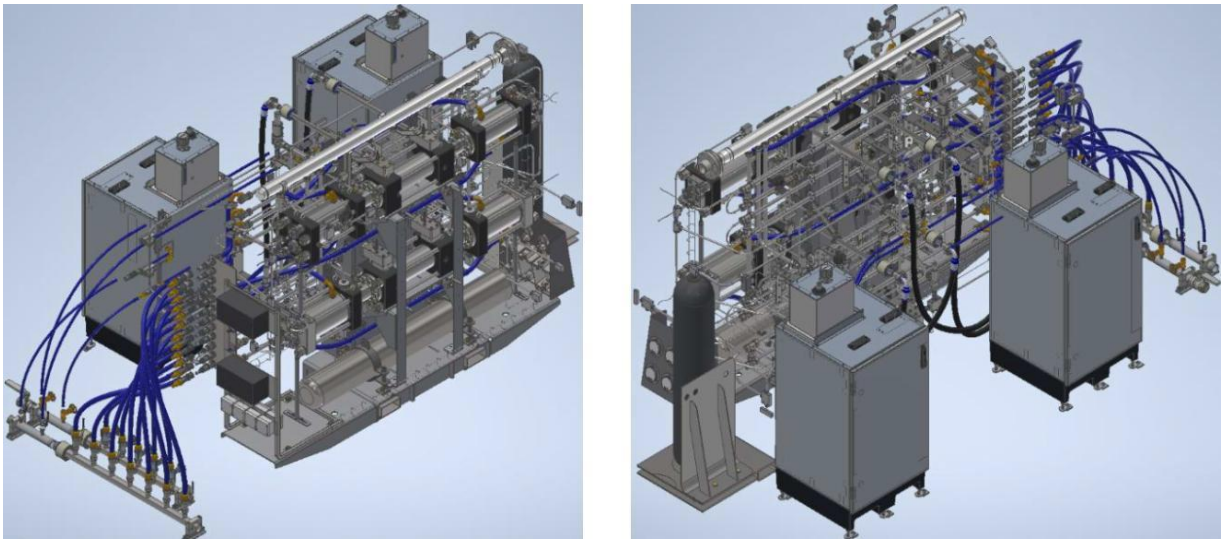

Figure 7: Potential Compressor Internal Arrangement

Due to the size of the compressor package its likely to be housed within a shipping container which will ease transportation and site layout.

## 6.6 Aftercooler

An aftercooler has been included within the arrangement due to the work done by the compressor leading to an increase in temperature of the hydrogen and the need to maintain the overall temperature within the design limits of the proposed materials.

Some of the options for compressor packages included an aftercooler within the package. Should one of these options be selected, then an independent aftercooler can be removed from the design.

The sizing of any independent aftercooler shall be undertaken during the beta phase to ensure the temperature within the system remains within a suitable range and shall be sized based upon the revised parameters detailed within Table 1.

## 6.7 Lined Rock Shaft Connection

The demonstrator is designed to test the Lined Rock Shaft (LRS) within a closed system. The design of the LRS is within Longitude's scope of work and is not detailed within this report. However, 100mm NB flanged connections for the LRS have been included within the design. The type of flanged connection is to be confirmed within the beta phase.

### 6.7.1 Recirculation Heating and Cooling

In order to maintain the temperature within the LRS, a system has been designed, which includes a heater and a cooler. Temperature sensors and a control system shall be used to ensure the hydrogen receives the correct heat input to maintain a hydrogen temperature within the operational limits of the LRS.

A re-circulation blower may be needed to control the flow of gas through the system, whilst Remotely Operable Valves (ROV's) are to be used to ensure the correct flow path is maintained. Non-return valves shall also be used to ensure no backflow through the system.

A thermodynamic model was created by Gravitricity. However, following Longitude taking over the role, the thermodynamic model is unavailable and therefore the required process data has not been able to be provided for these systems.

The system has been sized based on the maximum system flow rate and has utilised design information (footprints, sizes etc.) from previous projects, where applicable, to produce a layout for the system. Discussions have also been held with suppliers to assess the available options, including costs and sizing options.

These systems need to be correctly sized once the thermodynamic model has been completed by Longitude in the Beta phase.

## 6.8 Pressure Reduction Stream

A pressure reduction stream is required to reduce the pressure from 200barg to between 50barg and 30 barg. The stream shall consist of three Pressure Control Valves (PCVs) operating in a 1st stage, monitor and second stage arrangement. The 1st stage PCV shall be responsible for providing a 'rough cut', before the 2nd stage PCV shall reduce the pressure further to the agreed outlet pressure. A monitor PCV has been included within the pressure reduction stream to provide pressure reduction if one of the other PCVs fails.

Further pressure protection shall be provided by two slam shut valves, which shall protect against over pressurisation. As detailed in section 6.4, there is not a security of supply risk and therefore slamshut valves are the preferred form of pressure protection.

As only one stream is proposed, stream discrimination has not been included within the design.

The specific valves to be used within the stream are to be confirmed during the beta phase, alongside the exact valve set points, but are likely to align with the valves detailed on the MTO, PRZ0025-MTO-0000-0040, reproduced within Appendix C. The datasheet for the PCVs, PRZ0025-DAT-0000-0302, is reproduced within Appendix B

## 6.9 Ancillary Storage

The system is designed to cycle the hydrogen through the LRS. Ancillary Storage is required to contain the hydrogen whilst the LRS is empty (aside from the cushion gas). Longitude have done a Cost Benefit Analysis (CBA) for the ancillary storage, with the best option appearing to be a hydrogen tube trailer storing the gas at high pressure. However, an option has also considered the use of large bore pipe to store the gas within the system. The design currently includes the large bore pipework option as a worst-case scenario regarding site footprint.

This includes a 1200mm NB pipework to contain the hydrogen within the system. It is proposed that the ancillary storage is located with the 30 – 50 barg pressure range and therefore has been sized for 30 barg.

Calculations have been produced to confirm the length of 1200mm NB required to store the hydrogen at 30 barg and circa 160m of 1200mm NB pipework is required. Details of the pipework is included within Table 4.

In order to transition from the 100mm NB pipework to the 1200mm NB pipework, four back-to-back concentric reducers are required directly upstream and downstream of the ancillary storage.

The proposed design includes the 1200mm NB ancillary storage pipework in an arrangement as shown in Figure 8. The proposed arrangement is to be buried so as to maintain access to the rest of the assets on site. Cathodic Protection (CP) is required on the buried pipework to ensure that it does not corrode.

The pipework arrangement shall be located 600mm below the finished ground level.

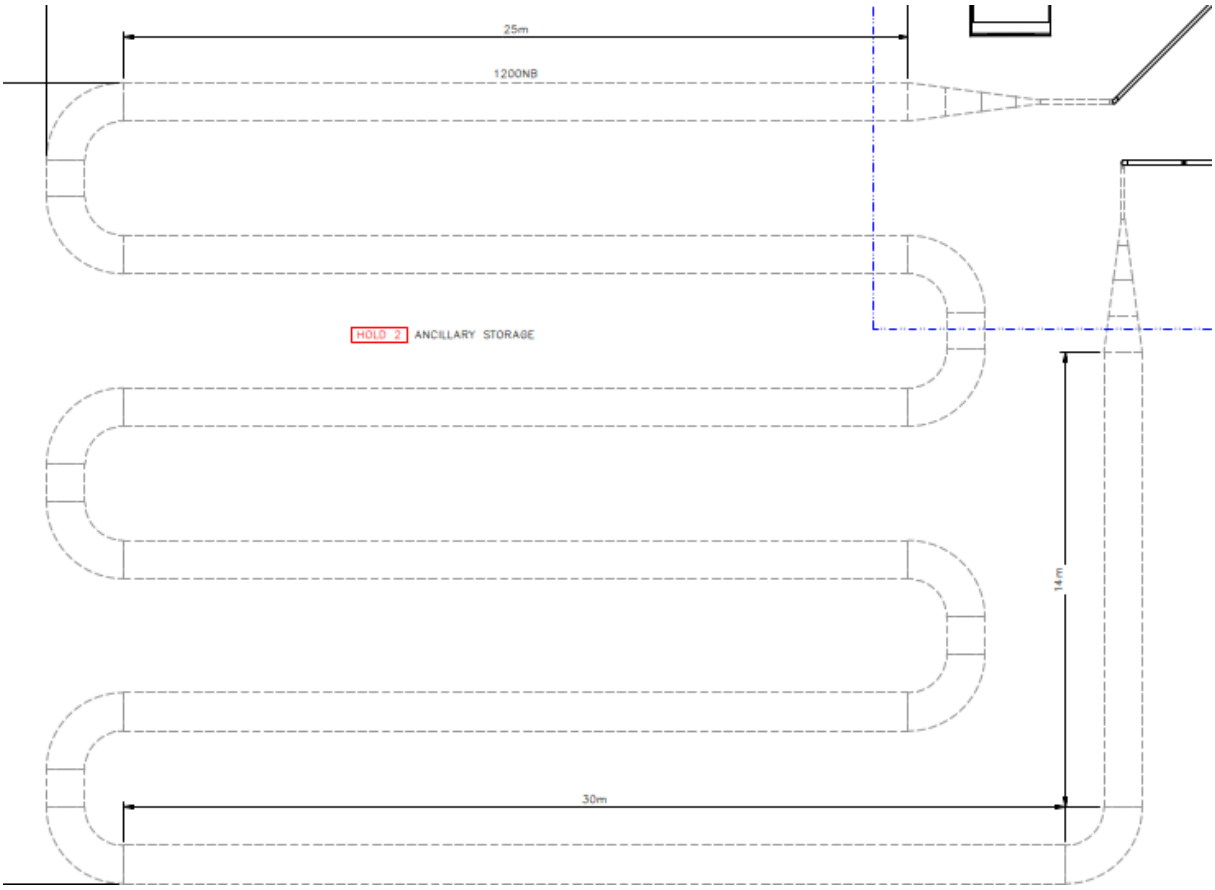


Figure 8: Ancillary Storage Arrangement

## 6.10 Materials

It should be noted that the existing suite of National Gas material standards are not suitable for hydrogen or class ratings greater than CL600 (MOP of 100 barg). Therefore, materials have been specified to industry standards such as ASME materials specifications e.g., ASME B16.5 [24]

### 6.10.1 Class Rating

It is proposed that the technical demonstrator consist of CL1500 materials, i.e., suitable for a pressure of 250 barg. Although the assets between the pressure reduction and compression would be suitable for CL300 / CL600 materials due to the 30 to 50 barg operating pressure, it is preferred to maintain for consistency across the trial equipment.

### 6.10.2 Valves

When selecting valves to be used as part of the technical demonstrator, the specific requirements of IGEM/TD/13 Edition 3 Supplement 1 [19] clause S7.4.4 shall be included in the valve specification. These requirements shall be included to prevent leakage across the valve and to atmosphere.

Therefore, to minimise the potential for leaks the following or equivalent requirement shall be specified:

- Double Block and Bleed valve arrangement
- Each casting to be hydraulically leak tested
- Soft seats in a metal retainer for in-line automatic valves and automatic vents; specify bubble tight shut-off
- Metal to metal seat of soft seats in a retainer for in-line manual valves; these should be combined with a means of positive isolation if used to block the flow path before attempting invasive maintenance or inspection inside the installation
- Metallic seat with valve outlet blocked
- Minimise through bolting, body flanges or threaded connections in assembly of the body of the valve unless gaskets are suitable for hydrogen service.
- Non-metallic materials present in seals shall be qualified for hydrogen service.
- Cast or ductile iron shall not be used for the valve shell

Non-return valves shall be used to ensure that gas flows in the correct direction through the system. They shall be located in several locations around the system.

### 6.10.3 Gaskets

Due to the flammability of hydrogen, where raised face flanges are used, the gasket shall be a Teflon or graphite spiral wound gasket. For ring type joint flanges, copper rings should be used.

### 6.10.4 Bolting, studs, nuts and washers

Where they may be exposed to hydrogen, bolting, studs, nuts and washers shall be suitable for use with hydrogen and compatible with the relevant fittings.

### 6.10.5 Pressure Regulators and Safety Systems

Pressure regulators and relief valves shall be designed with the inclusion of hardened seats and plugs. Relief Valves, if required, shall also be suitable for higher temperatures which shall be experienced where hydrogen is vented.

## 6.11 Overall Proposed Arrangement

The layout of the proposed arrangement is shown on the general arrangement drawings, PRZ0025-GEN-0000-0010 and PRZ0025-GEN-0000-0011, reproduced within Appendix C. An extract from one of the site layout drawings is shown below.

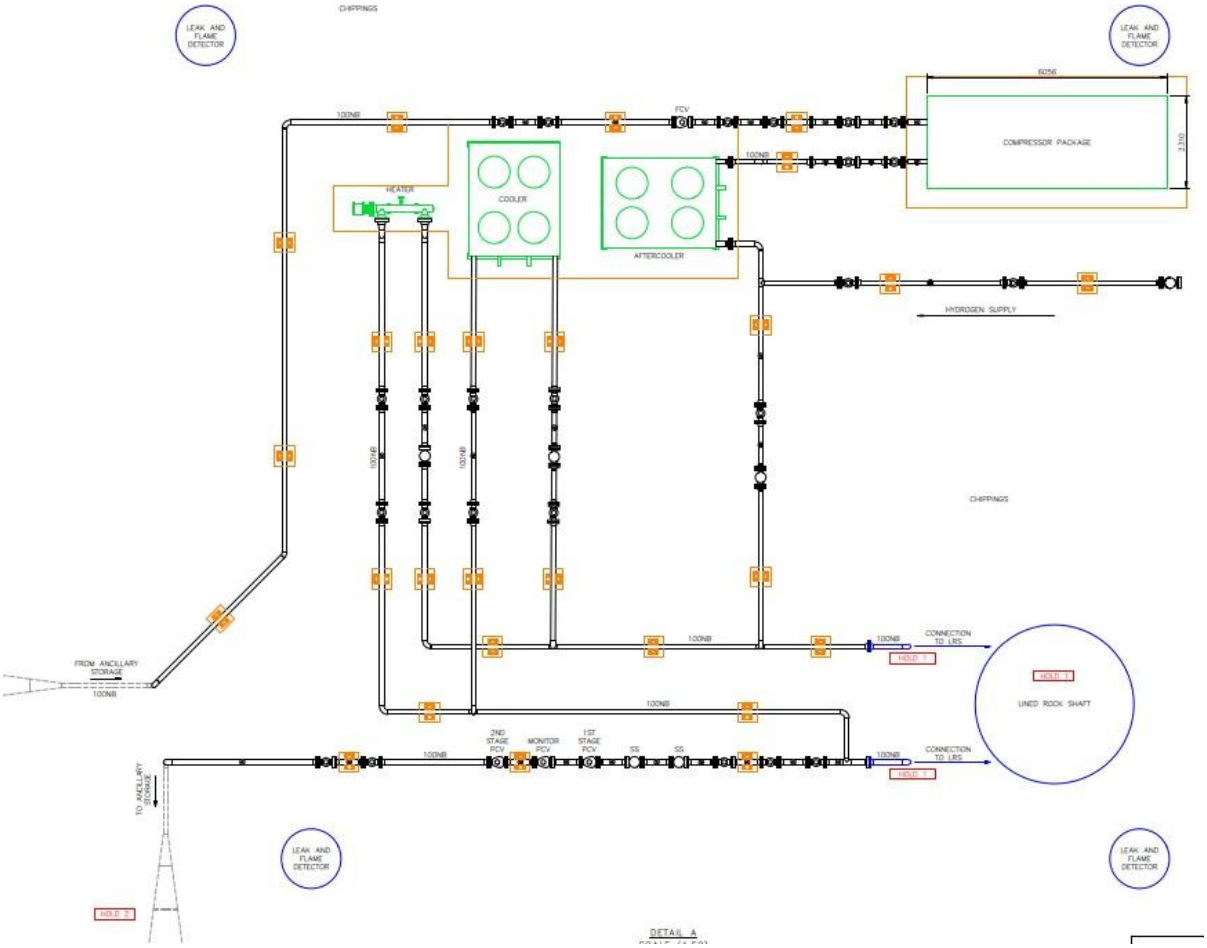


Figure 9: Above Ground Proposed Layout

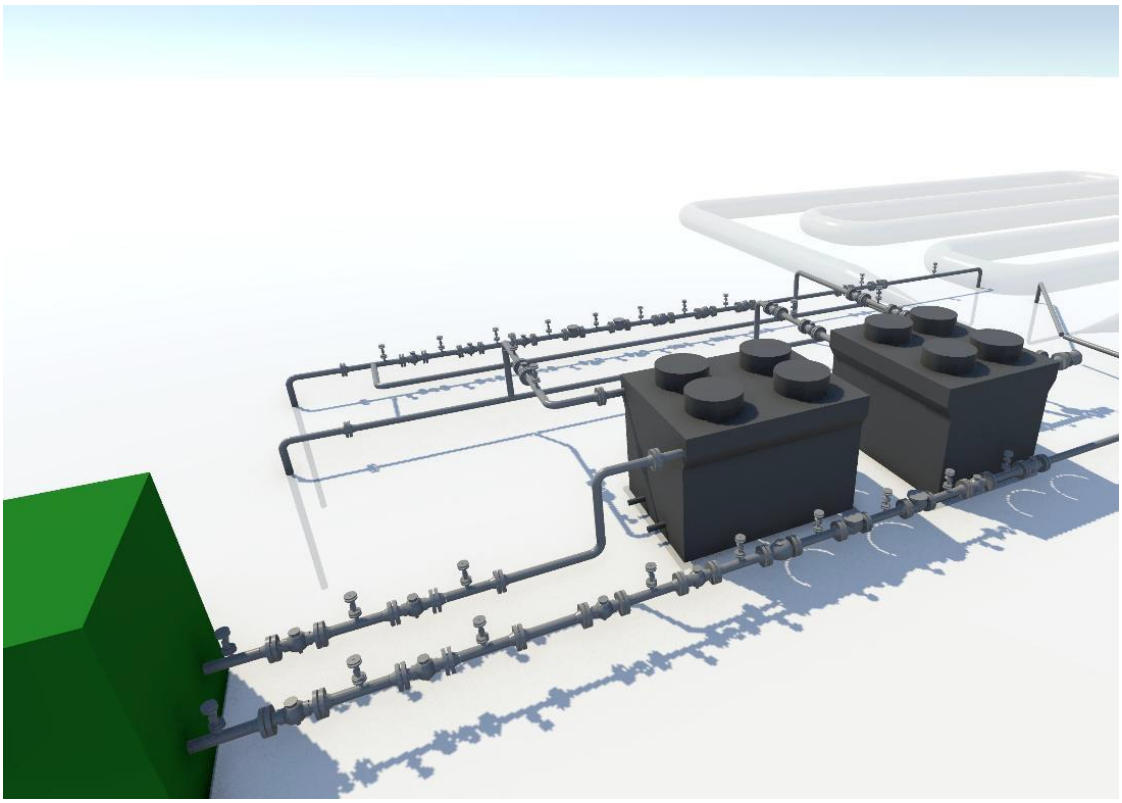

Figure 10: Visual Render of the Above Ground Assets

Additional Renders have been reproduced within Appendix D for reference.

# 7 Electrical and Instrumentation Design

## 7.1 Electrical Distribution

An Electrical Distribution Block Diagram PRZ0025-DIA-0000-2000 has been developed to show the potential LV power distribution network required to provide the necessary power for the hydrogen compressor and the associated compression loop, equipment and the associated control devices and instrumentation. The drawing is reproduced within Appendix C.

The proposed compressor provided by Atas Copco requires a 400 VAC 50 Hz 3 phase supply with a nominal power consumption of 53.1 kW. The compressor consists of 2x 84kW main pumps and 2 3kW Oil Circulation Pumps. Which will likely drive the peak power requirements.

It is expected that the site will require a 1:1 Isolating transformer and a separate earthing system to protect the installation from external earth fault currents, and ground fault occurrences. See PRZ0025-DIA-0000-2100 in Appendix C for the proposed Earthing arrangement.

The electrical distribution system shall be designed in accordance with National Gas specifications T/SP/EL50 [25] and T/SP/COMP/34 [26].

## 7.2 Control & Instrumentation System

The Compressor is to be provided with a dedicated control system that will likely need to be incorporated into a wider site control and instrumentation system. The overall site system will need to include Fire and Gas monitoring, ESD systems, and Valve Control Logic, for any electrically actuated control valves.

The full definition of these systems and the safety requirements of them shall be determined during the FPSA studies. The initial proposal for the Control and Instrumentation system is detailed on PRZ0025-DIA-0000-4200, reproduced within Appendix C.

The control and Instrumentation systems shall be designed in accordance with T/SP/COMP30 [27].

Any safety Instrumented systems shall be design ed to T/PM/INS/8 [28].

## 7.3 Installation Environment & ATEX

Where appropriate any field equipment shall be selected and located in accordance with the ATEX Directive 2014/34/EU as directed in T/SP/COMP34, all design documentation shall be checked and reviewed by CompEX12 qualified designers.

Equipment to be installed in the general hazardous areas shall be suitable for a Hydrogen hazardous area, Zone 0, 1, 2 as appropriate, Gas Group IIC, Temperature Class T1, unless directed otherwise based on Hazardous Area Classifications. See proposed hazardous area drawing PRZ0025-HAZ-0000-0030 in Appendix C.

# 8 Health and Safety

## 8.1 Hazardous Areas

A hazardous area drawing (PRZ0025-HAZ-0000-0030) for the proposed arrangement has been produced, showing flanged leakage and is reproduced within Appendix C. The hazardous areas; including any automatic venting such as relief valves, associated with the LRS, compressor package, heaters and coolers are currently unconfirmed and shall be confirmed when specific assets are procured during the beta phase.

## 8.2 Formal Process Safety Assessments

No Formal Process Safety Assessments (FPSAs) have been undertaken as part of the alpha phase of the project. However, FPSAs shall be undertaken during the beta phase of the project. The required FPSA's will be confirmed by Longitude but it is suggested they should include but not be limited to the following:

### 8.2.1 HAZID1

The HAZID study (Hazard Identification) is a structured process, which assists in determining what potential design hazards are associated with the design. This enables the hazards to be considered and either designed out or suitably mitigated during the design phase. The HAZID shall be conducted in accordance with T/SP/HAZ/8 [29].

### 8.2.2 HAZOP

The HAZOP study (Hazard and operability study) is a process of determining what the potential operational hazards associated with the project. This enables the hazards to be designed out or suitably mitigated through the design phase. The HAZOP shall be conducted in accordance with T/SP/HAZ/7 [30].

### 8.2.3 HAZCON

The HAZCON study (Hazards in Construction study) is a structured process to determine the protection hazards associated with the construction of the project. This enables the hazards to be designed out or suitably mitigated through the design and construction phases. The HAZCON shall be conducted in accordance with T/SP/HAZ/11 [31].

### 8.2.4 Safe Working Design Study (SWDS)

A SWDS is a structured technique to identify potentially unsafe working hazards and issues in order to deliver a design that is safe for operational staff to maintain and operate. The study shall be carried out in accordance with T/SP/G/38 [32].

### 8.2.5 LOPA

Any risks which are not suitably closed during the HAZOP study shall be subject to a Layer of Protection Assessment (LOPA). Within this, the risks shall be quantified against the layers of protection to confirm if the safeguards are suitable.

### 8.2.6 Quantitative Risk Assessment (QRA) and Consequence Modelling

In order to ensure the impact of the demonstrator facility shall not impinge on the neighbouring facilities, and determining the overall impact of the demonstrator facility, a QRA shall be required, alongside undertaking consequence modelling.

## 8.3 CDM Responsibilities

Premzero is a Designer under the CDM 2015 regulations and therefore are responsible for sharing any identified risks. In order to communicate the identified risks, a CDM Risk Register has been produced and included within Appendix B. These risks should be transferred onto the overall risk register to ensure that they are considered and mitigated through future project phases.

# 9 Bibliography

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[8] PSSR 2000, *The Pressure System Safety Regulations 2000,* legislation.gov.uk, 2000.

[9] PSR, *Pipeline Safety Regulations (PSR) 1996,* legislation.gov.uk, 1996.

[10] IGEM/TD/13 Edition 3, *Pressure Regulating Pipeline Installations Exceeding 7 bar,* IGEM, 2023.

[11] IGEM/TD/13 Edition 3 Supplement 1, *Pressure Regulating Installations for Hydrogen at Pressures Exceeding 7 bar,* IGEM, 2024.

[12] IGEM/SR/25 Edition 2, *Hazardous Area Classification of Natural Gas Installations,* IGEM, 2013.

[13] IGEM/SR/25 Edition 2 Supplement 1, *Hazardous Area Classification of Installations Using Hydrogen or Blends up to and including 20% by Volume Hydrogen in Natural Gas,* IGEM, 2022.

[14] ASME B31.12, *Hydrogen Piping and Pipelines,* The American Society of Mechanical Engineers, 2023.

[15] T/SP/TR/18, *Specification for Engineering of Pipelines and Installations Operating at Above 7 barg,* National Grid, 2021.

[16] T/SP/TR/17, *Management Procedure for Isolation of Above 2 Bar Plant and Equipment,* National Grid, 2017.

[17] T/SP/G/37, *Site Location and Layout Studies and Reviews,* National Gas Transmission, 2025.

[18] T/PM/PS/3, *Management Procedure for Ensuring Compliance with the Pressure Systems Safety Regulations 2000 General Compliance Duties,* National Grid, 2015.

[19] IGEM/TD/13 Edition 3 Supplement 1, *Pressure Regulating Installations for Hydrogen Transmission at Pressures Exceeding 7 bar,* IGEM, 2024.

[20] T/SP/DAT/6, *Specification for Standard Sizes of Carbon and Carbon Manganese Steel Pipe for Operating Pressures Greater than 7 bar,* National Grid, 2015.

[21] ASME B36.10M, *Welded and Seamless Wrought Steel Pipe,* ASME, 2018.

[22] T/SP/PA/10, *Specification for New and Maintenance Painting at Works and Site for Above Ground Pipeline and Plant Installations,* National Grid, 2005.

[23] T/SP/CW/6, *Specification for the External Protection of Steel Line Pipe and Fittings Using Fusion Bonded Powder and Other Coating Systems,* National Grid, 2007.

[24] ASME B16.5: 2017 , Pipe Flanges and Flanged Fittings: NPS 1/2 through NPS 24 Metric/Inch Standard, 2017.

[25] T/SP/EL/50, *Gas Transmission Electrical Specifications,* National Grid, 2022.

[26] T/SP/COMP/34 , *Specification for Electrical Equipment on Compressor Installations,* National Gas, 2016.

[27] T/SP/COMP/30, *Specification for Control and Instrumentation Systems on Compressor Installations,* National Grid, 2016.

[28] T/PM/INS/8 , *Management Procedure For Managing The Integrity Of Safety Instrumented Systems,* National Gas, 2024.

[29] T/SP/HAZ/8, *Specification for Hazard Identifications Studies,* National Grid, 2013.

[30] T/SP/HAZ/7, *Specification for the Application of Hazard and Operability Studies (HAZOPS) During Engineering Design Phases,* National Grid, 2013.

[31] T/SP/HAZ/11, *Specification for the Application of Construction Hazard Studies (HAZCON) During Engineering Design Phases,* National Grid, 2013.

[32] T/SP/G/38, *Specification for The Application of Safe Working Design Studies During Engineering Design Phases,* National Grid, 2013.

[33] T/SP/CM/1, Specification for Internal Coating Operations for Steel Line Pipe and Fittings, 2004.

# Appendix A Received Documents

| Document Title | Document Number | Included (Y/N) |
|---|---|---|
| ETZ Proposed Site Levels Drawing | ETZ-GOO-00-DR-C-50-2704 R02 | N |
| Green Hydrogen Demo FEED Site Layout Plan | 331201688-STN-LAY-CIV-0001 R01 | N |
| Lined Rock Shaft – B-Linepack+ Controls System Architecture | N/A | Y |
| B-Linepack+ Cause and Effect Matrix | N/A | Y |
| Atlas COPCO Compressor Proposal | E2509135 R1 R02 | Y |
| H2Y50 – Preliminary – P&ID Leakage Management System | N/A | Y |
| H2Y50 – Preliminary – P&ID Water Cooling System | N/A | Y |
| H2Y50 – Preliminary GA – Container with Compressor and Chiller | N/A | Y |
| H2Y50 – Preliminary – P&ID Main Gas | N/A | Y |
| Ex Heat FP Cast Line Heaters Datasheet | N/A | Y |
| Longitude email detailing Test Plans | N/A | Y |
| Longitude email detailing Revised Parameters | N/A | Y |

LONGITUDE
An ABL Group Company

# OFGEM SIF B-Linepack+

# Cause & Effect Matrix

| REPORT DETAILS | | | |
|---|---|---|---|
| Document Number | L-XX-XXX-XXXX-RXX | Client Name | National Gas Transmission |
| Revision | Revision number 00 | Client Reference | |
| Author | Steven Kirk | Issue Date | 23-Apr-21 |
| Task Name | xxxx | Task Number | xxxxx |

| REPORT AMENDMENT RECORD | | | | |
|---|---|---|---|---|
| Date | Description of Amendment | Author | Checked | Approved |
| 23/04/2021 | DRAFT | SK | | |
| | | | | |

| RECORD OF AMENDMENTS | | |
|---|---|---|
| Rev | Details of Changes | Page |
| 0 | - | - |
| | | |

| CONTACT DETAILS | | | |
|---|---|---|---|
| Issuing Office | Dundee | Email Address | info@osd-imt.com |

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## Overview

This worksheet provides a cause and effect matrix for the lined rock shaft (LRS) technology demonstrator being developed for the B-Linepack+ project.

The cause and effect matrix on tab "Cause&Effect_Matrix" is a tool used to link specific events (causes) with required actions (effects), This highlights the required controls system and process equipment response to maximise operational and asset safety. Should the process system be unable to mitigate against the cause then a system shutdown should be triggered.

**Shutdown level hierarchy**

If the process control system fails to correct a deviation in normal operating conditions such that a potentially dangerous situation arises then the plant should initiate the Emergency Shutdown System (ESD). This is designed to shutdown part or all of the plant to prevent escalation and protect personnel, the environment and the asset. Proposed system ESD levels:

ESD 0: Abandon plant
ESD 1: Emergency shutdown and depressurisation
ESD 2: Process shutdown for injection/withdrawal

## Assumptions

High-level approach. Further detail to be added folowing HAZOP and controls system developemnt
Assumes normal operational mode. Commissioing and H2 delivery not included
ESD levels above to be implemented later in design process

| Cause | Effect | Open vent valve from containment | Ignite vented H2 (from Vent and/or Leak Detection) | Close isolation valve outlet | Close isolation vale inlet | Close flow control valve | Start compressor | Stop compressor | Start heater | Stop heater | Start cooler | Stop Cooler | Start blower (heater) | Stop blower (heater) | Start blower (cooler) | Stop blower (cooler) | Operator visual and audible Alarm | Site Visual and Audible Alarm | Initiate emergency fire and gas response | Initiate emergency shutdown |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LRS | | | | | | | | | | | | | | | | | | | | |
| High Pressure (max operating pressure reached) | | | | | | | | x | | | | | | | | | x | | | |
| High High Pressure (approaching max design pressure) | | x | x | | | x | | x | | x | | x | | x | | x | x | x | x | x |
| Low Pressure (minimum operating pressure reached) | | | | x | | | | | | | | | | | | | x | | | |
| Low Low Pressure (negative pressure) | | | | x | | | | x | | x | | x | | x | | | x | x | | |
| High Containment Temperature (10 c < max op temp) | | | | | | | | | | x | x | | | | x | | x | | | |
| High High Containment Temperature (max op temp) | | x | x | x | x | x | | x | | x | | x | | x | | x | x | x | | |
| Low Containment Temperature (10 c > min op temp) | | | | | | | | | x | | | | x | | | | x | | | |
| Low Low Containment Temperature (min op temp) | | | | x | x | | | x | | x | | x | | x | | x | x | x | | |
| High strain in GTL (greater than expected strain) | | | | | | | | x | | x | | x | | x | | x | x | | | |
| High High strain in GTL (significantly above expected strain) | | x | x | x | x | x | | x | | x | | x | | x | | x | x | x | x | x |
| Low strain in GTL (less than expected strain) | | | | x | | | | | | | | | | | | | x | | | |
| Low Low strain in GTL (negative strain) | | x | x | x | x | | | x | | x | | x | | x | | x | x | x | x | x |
| High strain in SL (greater than expected strain) | | | | | | | | x | | x | | x | | x | | x | x | | | |
| High high strain in SL (significantly above expected strain) | | x | x | x | x | x | | x | | x | | x | | x | | x | x | x | x | x |
| Low strain in SL (below minimum strain) | | | | x | | | | | | | | | | | | | x | | | |
| Low low strain in SL (negative strain) | | x | x | x | x | | | x | | x | | x | | x | | x | x | x | x | x |
| Excessive ground movement | | x | x | x | x | x | | x | | x | | x | | x | | x | x | | | |
| Dangerous seismic activity | | x | x | x | x | x | | x | | x | | x | | x | | x | x | x | x | x |
| Power Failure (Mains) | | | | x | x | | | x | | x | | x | | x | | x | x | | | |
| Power Failure (UPS) | | | | x | x | | | x | | x | | x | | x | | x | | | | |
| Communication link failure (external or internal) | | | | x | x | | | x | | x | | x | | x | | x | | | | |
| Leak detected (Flow) | | x | x | x | x | | | x | | x | | x | | x | | x | | | | |
| Emergency Push Button activated (Manual) | | | | x | x | x | | x | | x | | x | | x | | x | x | x | x | x |
| Fire/smoke detected | | | | x | x | x | | x | | x | | x | | x | | x | x | x | x | x |
| High/low flow rate | | | | | | x | | x | | x | | x | | x | | x | | | | |
| Cyber attack | | | | x | x | x | | x | | x | | x | | x | | x | | | | |
| Loss of purity | | | | x | x | x | | x | | x | | x | | x | | x | | | | |
| External safety warning (site security) | | | | x | x | x | | x | | x | | x | | x | | x | x | | | |
| Topside process failure | | | | x | x | x | | x | | x | | x | | x | | x | | | | |
| Passive safety feature enabled (SSSV) | | x | x | x | x | x | | x | | x | | x | | x | | x | x | x | x | x |

# BUDGET OFFER

| | | | |
|---|---|---|---|
| **Date** | **19 November 2025** | | |
| Customer | AC United Kingdom | iC³ Project nº | E2509135 |
| Project | Premtech Limited | CRP Project/ Revision nº | R1 rev2 |

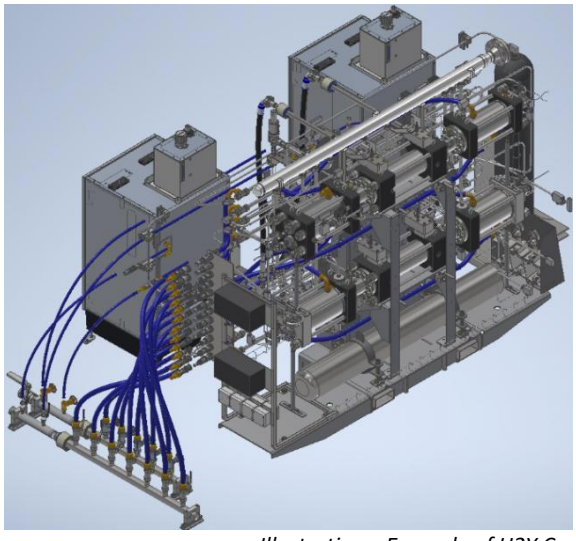
## ATLAS COPCO PROPOSAL1

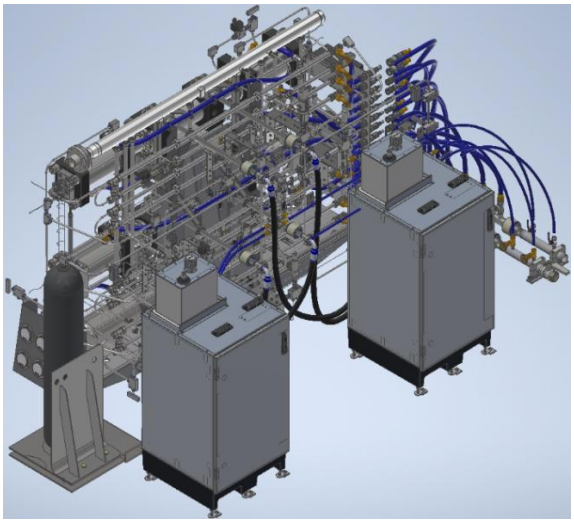
The proposed Atlas Copco solution consists in two compression packages, including each:
**Two** H2 compressor type **H2Y 50-2-500** to compress Dry Hydrogen from 30 to 190 bar g.

- The package includes, as well, a control cabinet, a Chiller and a 20ft container.
- The compressor mechanical parts are designed for ATEX zone and the HPU (Hydraulic Power Unit) is designed for safe area hence a gas tight wall will separate both zones inside the container. It must be installed indoors or at least under a shelter in case the container is not included in AC CRP scope.
- The control cabinet is designed for safe area in a separate room inside the container. It must be installed indoor or at least under a shelter in case the container is not in AC CRP scope.
- The Chiller is designed for safe area and will be installed on the roof of the 20ft container.

Our offer is based on proven design, suitable for the specified ambient conditions.
The Atlas Copco Group is constantly working with suppliers to ensure that they are aware of the UN terms of fair trading and our business code of practice.
We have implemented a supply chain quality process that we believe ensures the quality, safety, and reliability of the equipment we supply, including raw materials and therefore do not exclude any country from our material sourcing.

This package is an Oil free, Water Cooled with adjustable piston cadence.





*Illustrations: Example of H2Y Compressor – Non contractual photo*

# BUDGET OFFER

| | | | |
|---|---|---|---|
| **Date** | **19 November 2025** | | |
| Customer | AC United Kingdom | iC³ Project nº | E2509135 |
| Project | Premtech Limited | CRP Project/ Revision nº | R1 rev2 |

## I. STANDARDS AND SPECIFICATIONS

### I. 1.ATLAS COPCO CREPELLE SPECIFICATIONS

- Quality Management System: ISO 9001
- Environmental Management System: ISO 14001
- Health & Safety Management System: OHSAS 18001

### I. 2.APPLICABLE CODES AND STANDARDS

- Pressure vessels: CE / PED
- Electricity: IEC
- Flanges (inside the package): Manufacturer's standard
- Piping: Manufacturer's standard
- ATEX Conformity 2014/34/EU
- Other codes and standard: Standard Manufacturer
- Unless explicitly mentioned, the choice of sub-suppliers is at AC's charge

## II. SITE CONDITIONS

| | |
|---|---|
| Site location | United Kingdom |
| Application | Hydrogen Refueling |
| Gas inlet source | Electrolyzer |
| Ambient temperature mini/maxi | 0 / + 40 °C |
| Environment | Normal industrial environment (not corrosive) |
| Voltage | 400 V (+-10%) / 50Hz (+-2%) / 3Ph |
| Main motor voltage | 400 V (+-10%) / 50Hz (+-2%) / 3Ph |

**Note:** Since real site conditions have not been advised, we ask customer to kindly check above mentioned conditions before order. Any divergence from these site conditions may have an impact on compressor design and must be notified before order.

# III. Compressor design and performances

## III.1. Compressor Selection

| | |
|---|---|
| Type of compressor | H2Y 50-2-500 |
| Number of stages | 2 stages |
| Number of cylinders | 4 cylinders |

## III.2. Operating Conditions

| | | |
|---|---|---|
| Compressed Gas Composition | $H_2$ | 99.99 % |
| | $O_2$ | <0.5% |
| Gas Inlet Minimum/Maximum Allowed Temperature | -10 / +40 | °C |
| Gas Inlet Minimum/Maximum Allowed Pressure | 30 | bar g |
| Gas Discharge Working Pressure | 190 | bar g |
| Max pressure dew point at comp. inlet @51 bara[1] | -41.8 | °C |

**Note:** Since real site conditions have not been advised, we ask customer to kindly check above mentioned conditions before order. Any divergence from these site conditions may have an impact on compressor design and must be notified before order.

## III.3. Compressor Design Conditions / Performances

| **H2Y 50-2-500** | **Compressor performance** | |
|---|---|---|
| Gas Inlet Temperature | 20 | °C |
| Water Inlet Temperature | 10 | °C |
| Gas Discharge Pressure | 190 | bar g |
| Gas Inlet Pressure | 50 | bar g |
| Capacity at Discharge ± 5 % for **1** Machines | 52 | kg/h |
| Capacity at Discharge ± 5 % for **2** Machines | 104 | |
| Installed power for one machine * | 174 | kW |
| Installed power for Two machine * | 348 | |
| Electrical Power Consumption (± 6%)* per machine | 53.1 | kW |

[1] Max pressure dew point at compressor inlet at atmospheric pressure is -71.5 °C and corresponding to -20°C at 501 bara

| | | |
|---|---|---|
| SER (± 11%)* | 1.01 | kWh/ kg $H_2$ |

(*): The indicated total installed power is only for information and can be subject to modification during engineering phase, if needed, for better machine performance.
Note: Above mentioned flow rate is for the case with inlet pressure of 50 bar g. For inlet pressure of 30 bar g, the flow achieved will be less.

| | | |
|---|---|---|
| Sound pressure level[2] | 85 | dB(A) |
| Approximate weight per total package with the container | 8 000 | kg |
| Max required Cooling Water Flow | 15 | m3/h |

## IV. Electrical Equipment

Compressor Main drive motors (per package)

- Power — Main pumps: 2 x 84 kW
  Oil recirculation pumps: 2 x 3 kW
- Type — Servomotors

Control and starting panel (per package)

- Located in safe area, all instruments connected to junction boxes on compressor skid
- 1 Control and monitoring system (HMI)
- 2 x PLCs B&R (part of ABB): 1 PLC for control and 1 PLC for safety) with regular components and safety-oriented components of the series X20.

## V. Water cooling device (Chiller)

- Min / Max acceptable ambient temperature — -20 / +40 °C
- Cooling medium — Water-glycol up to 35-40 Vol% (for protection to -20°C)
- Max Installed power — 56 kW (400V ±10% / 3Ph+PE / 50Hz)

[2] Measured at 1m distance from the compressor without container, free radiation and low basic noise (acc. to ISO 3746). ±3dB(A).

## VI. 20ft standard container

- 1 Gas and flame detectors for ATEX zone
- 1 Ambient Temperature transmitter in ATEX zone
- 2 Extraction fans in ATEX zone
- Lamps and emergency shutdown in each compartment
- Container standard painting is **RAL 7011**
- Electrical connections for grounding

<u>Only included in case container is in our scope</u>

- Water hoses, Oil hoses and piping between the compressor, the chiller and the HPUs
- Cables and electrical cabling between the control panel and the compressor
- Cables and electrical cabling between the control panel and the HPUs

Illustrations: 20ft Container package – Non contractual photo

## VII. Standard documentation

- General arrangement for compressor, chiller and container
- P&ID (gas, Oil and Water)
- Instruction book (at machine delivery)
- Hazardous area drawing
- Utility consumption list
- Wiring diagram of junction boxes and local control cabinet

- Quality Control Plan (according to Atlas Copco standard)
- ASL (after machine delivery)
- EU Declaration of conformity 2014/ 68/ EU (including ATEX Declaration of Conformity 2014/ 34/ EU

## VIII. Exclusions (Unless quoted as optional)

In the present offer are not included:

- Travel and lodging expenses for customer personnel
- All civil work involved at site including foundations & Compressor house
- Installation and first commissioning at site, Oil, water and glycol, On-site piping and cabling (Power, Signal & Control) including incoming feeder line to the Motor / Control Power board
- Piping (Air/gas, water, drain) and electrical wiring outside the container
- Vent line outside of the container
- Compliance and certification against local codes, regulations and legalizations is not included in our scope and shall be Customer Company's liability, including but not limited to: Any extra documentation or inspection required for Local certification Any documentation not explicitly mentioned in VII. DOCUMENTATION
- Kit of special tools, any spare parts and Site supervision
- Risk assessment/HAZOP meeting with customer and any modification of design required by customer after order (for instance following HAZOP)
- C3, C4 and C5 protection for container and outside equipment
- Seismic container design
- Snow, wind, rain or seismic load calculations
- Remote control for start and stop
- FAT with Witnessing
- Everything that is not specifically mentioned as included in the proposal.

Please take note, that any specification relating to manufacturing and/or documentation is not considered unless explicitly confirmed. Our scope is strictly limited to the scope listed in detail above according to Atlas Copco standard. Alterations to our standard must be clarified in detail and are, if realizable, available against price adder.

## IX. Commercial offer

**CRP prices are ex-works (EXW) FORLOG, Belgium Non-Packed (Delivery at Place is not included in AC CRP scope. Customer needs to organize package and pick up of the machine from Belgium).**

| Quantity | Type | BUDGET PRICE |
|---|---|---|
| **Two** | H2Y 50-2-500 according to above technical description | **1, 459 549 EUR** |
| **Two** | Electrical control cabinet for Safe area | **(included)** |
| **Two** | Water cooling device (Chiller) | **(included)** |
| **Two** | 20ft container with standard scope | **(included)** |
| **Two** | Transportation from Lille to FORLOG BELGIUM | **(included)** |
| | **TOTAL** | **1,459 849 EUR** |

Options:

| Quantity | Type | BUDGET PRICE |
|---|---|---|
| **One** | FAT with witnessing for 1 machine / container | **6967** |
| | | |
| | **TOTAL** | **6967 EUR** |

**Note:**

- **This is our standard proposal with standard machine. No extra certifications added.**
- **Only installation proposal, scope limit (in/out Connections) dimensions and cable details will be provided in case container is not in AC CRP scope.**
- **Compressors are supplied with one independent control panel each. They are running totally independently from each other. No master PLC included in our scope.**
- **In case of FAT for all containers, extra cost can be provided. Due to space limitations/necessary logistic operations/test preparation, different visits will be necessary for FAT. Notification for each visit will be sent prior to each test.**
- **For transportation, the platform will be dismounted and delivered loose with the chiller fixed on it.**

Delivery, Lead-time and Transport:

- Lead-time = **52 working weeks estimated** (Christmas or August holidays excluded).
  Lead-Time starts from receipt of purchase order in CRP dispatch System.

# BUDGET OFFER

| | | | |
|---|---|---|---|
| **Date** | **19 November 2025** | | |
| Customer | AC United Kingdom | iC³ Project nº | E2509135 |
| Project | Premtech Limited | CRP Project/ Revision nº | R1 rev2 |

## Content and Validity of our Offer:

- Phase 1 = Budget quote (not usable for order, need to be phase 4). It is a Product selection with a rough Price & Lead-time.
- Budget quote validity is 3 months for price and lead-time.

# LEAKAGE RECOVERY (described for COMP-1 only - The same applies for COMP-2)

All materials supplied are in compliance with the requirements of the List of Prohibited Substances

EX ZONE

TO COMP 2

FROM COMP 2

ESV 50-1

HVX 51-3

HVX 51-4

SCAVENGING IN

VENT TO ATMOS.

RV 50

ESV 50-2

PI 50

PT50

PSV 50

COMP 1

FIL 50

LS 50

LI 50 H

LI 50 L

FROM COMP. 2

RTNK 50

DRAIN (OUT)

HVB 50-1

SP 50-1

BALL VALVE

NEEDLE VALVE

SOLENOID VALVE

NON RETURN VALVE

PRESSURE SAFETY VALVE

GAS

OIL

VENT LINE

CUSTOMER SCOPE | ATLAS COPCO SCOPE

CONFIDENTIAL:

This document is our property and shall not without our permission be altered, copied, used for manufacturing or communicated to any other person or company.

| Note | Position | Modified from | Date | Intr./Appd. |
|---|---|---|---|---|
| 01 | | FIRST ISSUE | 05/04/2023 | INEEXTsubo |

| Parent 3D Model | Ed. Version 3D |
|---|---|

Tolerances,if not indicated,according to: ATLAS COPCO STANDARD/Klasse/Class

| | | | |
|---|---|---|---|
| Name | P&ID LEKAGE MANAGEMENT SYSTEM | SMALL-2 | Confidentiality Class acc. to 1102K |
| Material | NOT APPLICABLE | | CONFIDENTIAL |
| Treatment | NOT APPLICABLE | | ACD |

| | | | | | |
|---|---|---|---|---|---|
| Scale | - | Family | A2 | Compare | Drawing owner |
| Drawn by | INEEXTsubo | Blank nr. | | Replaces | CRP |
| Version Dwg | 01 | Blank wt. Kg | Fini wt. Kg | Designation | Sheet ( ) 01 01 |
| STATUS: WorkInProgress | | Des checked. | Prod checked. | Approved. | Date 05-04-2023 |

# P&ID - LMS

REPORT.

LONGITUDE
An ABL Group Company

# Ofgem SIF B-Linepack+

# Special Conditions Report

| REPORT DETAILS | | | |
|---|---|---|---|
| Document Number | LGG-L057401-R11 | Client Name | National Gas Transmission |
| Revision | Revision number 00 | Client Reference | |
| Author | Jack Trevail | Issue Date | 03-Feb-2026 |
| Task Name | System Design | Task Number | 101 |

| REPORT AMENDMENT RECORD | | | | | |
|---|---|---|---|---|---|
| Rev | Date | Description of Amendment | Author | Checked | Approved |
| 00 | 03/02/2026 | Issue for Information | JT | SK | NV |
| | | | | | |
| | | | | | |
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| | | | | | |
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| RECORD OF AMENDMENTS | | |
|---|---|---|
| Rev | Details of Changes | Page |
| **00** | - | - |
| | | |
| | | |
| | | |
| | | |
| | | |

| CONTACT DETAILS | | | |
|---|---|---|---|
| Issuing Office | Dundee | Email Address | info@osd-imt.com |

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# 1.0 Introduction

This document provides a response to Special Conditions five and six as part of the Ofgem SIF B-Linepack+ storage demonstration project. Information is presented on how the project will overcome scalability, be capable of operating in isolation, and how the project would proceed without a comprehensive GB energy system.

How the project could operate in isolation is presented first. Potential use cases are detailed for the solution considering varying network sizes, then the Line Rock Shaft (LRS) storage technology in isolation from a gas network.

How the project would proceed without a comprehensive GB energy system is then presented. This references information regarding how the solution could operate in isolation, as many of the use cases detailed do not require a comprehensive GB energy system. Options outside the UK are also presented, considering gas networks around the world.

How the project will overcome scalability is then presented. This considers the number of systems proposed for the future UK gas network, and other use cases detailed in the sections regarding operating in isolation and without a comprehensive GB energy system.

## 1.1 Abbreviation

Abbreviations used in this report are outlined in **Error! Reference source not found.**.

*Table 1: Abbreviations*

| | |
|---|---|
| ***LRS*** | *Lined Rock Shaft* |
| ***NGT*** | *National Gas Transmission* |
| ***E-SAF*** | *Electro-Sustainable Aviation Fuel* |
| ***GHG*** | *Greenhouse Gas* |

## 2.0 Operation in isolation

The B-Linepack+ solution could operate in isolation in several different ways. These are detailed in the following sub-sections, first as a complete solution, then the LRS technology as a standalone gas storage solution.

### 2.1 B-Linepack+

The B-Linepack+ solution uses LRS technology to provide linepack supplementation to balance the gas pressure for a gas network in the event of differing injection/withdrawal rates from the network. This is achieved by the LRS providing additional gas storage capacity, with fast injection/withdrawal rates to facilitate balancing.

The solution is very scalable, as detailed in Section 0, therefore it can support a gas network of any size. Considering a complete UK-wide hydrogen gas network, many LRS systems could be deployed across the network, providing the B-Linepack+ solution network-wide. In a scenario where there are smaller or isolated networks, or smaller sections of existing networks being used for hydrogen, then fewer LRS system could be deployed.

In a completely isolated case, where the 'gas network' is a single site, user, or gas system, then an LRS (or multiple) could still be deployed, providing the benefits of B-Linepack+. The LRS storage could be used to maintain a consistent gas supply to the site/user at all times, with 'network offtake' being the use of the hydrogen, and the 'network injection' being gas re-supply via pipe or tube trailer etc.

In all the above use cases, the B-Linepack+ solution would provide network resilience and security of supply and is likely to provide financial benefits over other alternative storage solutions as detailed in other project reports. This is especially true in the more isolated cases, or if the system is operating in complete isolation. In these scenarios, it is less likely that they will be in proximity of, or connected to large geological gas storage facilitates, meaning that the only other viable existing storage technologies for supplementation are traditional pressure vessels/linepack etc. The LRS technology provides a lower cost of storage compared to these traditional techniques, providing an increased comparative capital cost saving.

### 2.2 LRS Technology

The LRS technology as a standalone storage option, can be used in isolation of gas networks, adding value to the wider hydrogen and gas storage industry. An LRS can be used to store hydrogen, natural gas, and other fuel gases. The scenarios where an LRS could operate and provide value in isolation of a gas network include:

- Buffer storage to ensure user demand profile is met given intermittent hydrogen production from renewables
- Buffer storage ensuring steady supply to industrial users receiving bulk hydrogen deliveries
- Buffer storage to provide back up for hydrogen production downtime
- Provide strategic support for energy security
- Supporting system-wide seasonal variation in demand and use
- Bunkering and fuel gas storage for intermittent off-take

Some of the key industrial use cases for hydrogen, for which the LRS storage technology could add value, are detailed in the following sections. In some cases, hydrogen is already used but generated using methods such as steam methane reforming (grey hydrogen), which uses fossil fuels. In other cases, hydrogen can replace a fossil fuel. It is assumed that the hydrogen used in the future scenarios is either green hydrogen (produced via electrolysis using energy from renewable energy sources), or blue hydrogen (produced by steam methane reforming with carbon capture and storage). For most scenarios detailed, when transitioning to green hydrogen, buffer storage is needed to balance the intermittency of renewable energy. For the large industrial use cases, large storage requirements make pressure vessels/pipeline storage uneconomical. This therefore becomes a good application for the LRS technology.

There are further applications that have not been discussed in detail in this report, that may also present viable use cases for LRS storage. These include other large-scale chemical processes including hydrogenation, hydrocracking, desulphurisation etc., fuel storage for other transport/machinery including non-road mobile machinery, coastal/river vessels, mining equipment, regional trucks etc., and other heating applications.

### 2.2.1 Ammonia

Hydrogen is used as a feedstock to produce ammonia using the Harber-Brosch process. A constant and reliable supply is always needed. Typically, grey hydrogen (or other carbon intense hydrogen production methods) is used, and no buffer storage is needed, because hydrogen is produced on demand. This can be replaced with blue or green hydrogen. Currently, of all hydrogen produced each year, around 43% is used for ammonia production (The International Energy Agency, 2019), with around 2% of annual global greenhouse gas (GHG) emissions coming from ammonia production (The Royal Society, 2021). Decarbonising UK fertiliser production alone (which requires ammonia) would require approximately 0.18-0.35 million tonnes of low-carbon hydrogen per year (National Gas Transmission, 2026).

### 2.2.2 Steel production

Hydrogen can be used as a direct reduction agent for iron ore, as a source of heat via combustion, and for other processing steps. Typically, fossil fuels are used for these processes. These can be replaced with blue or green hydrogen. The iron and steel industry accounts for 4% of European carbon emissions, and 9% globally (European Parliament, 2020). Decarbonising the UK steelmaking industry would require 0.75-1.0 million tonnes of hydrogen per year (National Gas Transmission, 2026).

The Hybrit project in Sweden has utilised a lined rock cavern (similar to the LRS technology, see document LGG-L057401-R09-Rev00 Geomechanical & Structural Design Note) for hydrogen storage to support low carbon steel production. This has shown that the cost of hydrogen production can be reduced by between 25-40%, therefore reducing the overall cost of low-carbon steel production (Vattenfall, 2026).

### 2.2.3 Cement Production

Cement production could use hydrogen for heat generation via combustion, replacing fossil fuels. Due to the very high temperatures required, non-combustion methods are not suitable. The cement industry accounts for approximately 7% of the world's industrial energy consumption, contributing 6-7% of annual global carbon emissions (Commision ET, 2018) (Andrew, 2018). It is estimated that for partial fuel switching, 80-100 kt of hydrogen would be required per year, and up to 200-250 kt per year for near-total replacement of fossil fuels (National Gas Transmission, 2026).

### 2.2.4 Glass production

Similar to cement production, glass production could use hydrogen for heat generation via combustion, replacing fossil fuels. Due to the very high temperatures required, non-combustion methods are not suitable. Glass industries contribute approximately 22 million tonnes of carbon emissions annually in Europe alone (Wan, 2024). For the UK glass sector, it is estimated that between 0.66-0.7 million tonnes of hydrogen would be required per year for full decarbonisation (National Gas Transmission, 2026).

### 2.2.5 Aluminium Production

Hydrogen could be used for both the production of new aluminium, and for melting scrap for recycling. Both processes require high heat, where fossil fuels can be replaced. The GHG emissions from global aluminium production accounted for 2% of total global emissions in 2018 (RMI, 2023). It is estimated in the UK that decarbonising production would require between 10-12 kt of hydrogen per year (National Gas Transmission, 2026).

### 2.2.6 Maritime fuels

For the maritime sector, hydrogen or hydrogen-based fuels can be used as a direct fuel replacement. This could be using pure hydrogen, or synthetic fuels such as e-ammonia, e-methanol and e-LNG. To facilitate the use of these fuels, hydrogen storage will be needed either for bunkering at terminals if pure hydrogen is used, or as buffer storage for facilities using hydrogen to produce synthetic fuels. Marine Transport accounts for nearly 3% of the world's energy demand, including 7% of the world's oil (DNV, 2022). With the International Maritime

Organization targeting 50% carbon emission reduction from 2008 to 2050, the main mechanism of achieving this will be switching from oil to natural gas and then low carbon fuels such as the hydrogen based fuels (DNV, 2022). It is estimated that the UK will require one to three million tonnes of hydrogen per year to facilitate maritime fuels by 2050 (National Gas Transmission, 2026).

### 2.2.7 Electro-Sustainable Aviation Fuel

To move away from fossil fuel use in the aviation industry, new fuels are being developed. One option is electro-sustainable aviation fuel (E-SAF). This is made by producing green or blue hydrogen, which is then processed with other chemicals, resulting in a fuel suitable for blending with, or fully replacing conventional jet fuel. It is estimated that 2.5% of global carbon dioxide emissions were emitted by the aviation industry in 2022 (DNV, 2022). By 2050 it is predicted that around 17% of the energy use in the sector will be using pure hydrogen or hydrogen-based e-fuels. By 2030, it is estimated that the UK will require approximately 195 kt of hydrogen per year for E-SAF production (National Gas Transmission, 2026).

### 2.2.8 Hydrogen Import and Export

To facilitate hydrogen import and export, via either shipping or pipelines, bunkering may be required. This will provide buffer storage for the hydrogen for the bulk transport via shipping, or while the import/export demand differs from production/delivery.

### 2.2.9 Hydrogen to power

The UK has a target to deliver clean power by 2030. Low carbon, dispatchable power generation using hydrogen will play a key role in achieving the target. This dispatchable power can provide flexibility, services for system operability, and provide supply adequacy during extended periods of low renewable output (Hydrogen UK, 2025). The current fleet of gas turbines providing dispatchable power generation in the UK using natural gas has a combined approximate capacity of 900MW. An equivalent system running on hydrogen would consume 45 tonnes of hydrogen per hour (Hydrogen UK, 2025).

It is recognised that given the large volumes of hydrogen required and the intermittency of renewable energy generation, significant hydrogen storage is required. It is estimated that 8TWh of hydrogen storage is required by 2035 for balancing (NIC, 2023). The timelines for other geological storage options such as salt caverns have much longer lead times than will allow for hydrogen to power to play a role in the 2030 UK energy mix. The National Engineering Policy Centre states that it is essential that the government assesses short term tactical options ahead of 2030, of which LRSs are a strong candidate.

Beyond timelines, the alternative geological storage options are constrained to regions of suitable geology, which won't always be the optimum location for storage. They will play a large role in meeting the 8TWh requirement, however there will likely be significant benefit in having additional mid-scale storage distributed more widely, such as LRS technology.

### 2.2.10 Line Rock Shaft Deployment

Considering most of the use cases described in the previous sections, the amount of hydrogen storage needed in the UK by 2050 and the number of LRS systems required has been estimated and is shown in Table 2 (National Gas Transmission, 2026). Further work is required to determine the number of LRS systems required for hydrogen to power and for imports/exports. It is assumed that a standard LRS has a working gas capacity of 57 tonnes, cycling twice per week for 26 weeks per year.

The hydrogen storage needed is defined as a percentage of the total energy required for each use case. The percentage is based on expected buffer storage or bunking required for each depending on the expected operating profiles. It may be that more or less storage is required as the hydrogen industry matures.

The operating profile and storage capacity of the LRS systems may also differ, and the exact design/operation will be determined for each specific use case.

In summary, the results show that between 69-146 LRS system could be required by 2050 to support the decarbonisation of the UK by using hydrogen in key industrial sectors. This presents a very strong need for the storage technology, in isolation from providing linepack supplementation.

*Table 2: LRS deployment for UK use cases*

| Use Case | Hydrogen demand per year (tonnes) | Energy (TWh) | Hydrogen Storage Needed (%) | Hydrogen Storage (TWh) | Estimated No of Lined rock shafts |
|---|---|---|---|---|---|
| **E-SAF** | 340k | 11.3 | 0.3-2 | 0.034-0.226 | 1-2 |
| **Steel** | 0.75 - 1M | 25-34 | 3-4 | 0.75-1.36 | 8-14 |
| **Cement** | 200-250k | 8-10 | 10-15 | 1-1.5 | 9-16 |
| **Maritime** | 1-3M | 33-100 | 2-5 | 2-5 | 21-51 |
| **Glass** | 0.6-0.7M | 20-24 | 10-20 | 2.4-4.8 | 25- 49 |
| **Aluminium** | 10-12k | 0.33-0.4 | 1-3 | 0.004-0.012 | 1 |
| **Ammonia** | 0.18-0.35M | 7.5-15 | 2-8 | 0.3-1.2 | 4-13 |
| **Total** | **3.08-5.652M** | **105.1-194.7** | **N/A** | **6.8-14.1** | **69-146** |

# 3.0 A Comprehensive GB Energy System

A comprehensive GB energy system is considered to be a gas network across the UK that operates with hydrogen, with significant production and use in line with future expectations. A modelling study to investigate the outlook of gas transmission infrastructure for 2050 showed that a GB-wide hydrogen network is required by 2050 for all scenarios, the scale and design of which depends on the hydrogen demand scenario (Guidehouse, 2023). It found that in all modelled scenarios, “hydrogen storage is critical in supporting whole energy system demand during peak demand periods and low wind days”.

If such a hydrogen network does not materialise, then the B-Linepack+ solution could still provide value in many scenarios. These are detailed in the following sub-sections.

## 3.1 Existing gas network

B-Linepack+ could be used to increase the storage capacity, security and resilience of the existing gas network. As detailed previously, it can be utilised for fuel-gas linepack supplementation, meaning that it can be used for existing natural gas systems.

## 3.2 Hydrogen Industry in Isolation

As detailed in Section 2.0, there are many scenarios for which the B-Linepack+ solution, or the LRS technology alone, could be utilised. This could include smaller networks, remote island networks, or single sites/hydrogen clusters. For the LRS technology, there are many opportunities for some of the world's largest energy consuming industries to decarbonise by transitioning away from fossil fuels to hydrogen, for which storage will be required.

## 3.3 Outside the GB Energy System

The modelling performed as part of this project has only considered deployment of B-Linepack+ in the UK. If a comprehensive GB energy system didn’t materialise there are many large-scale hydrogen gas networks being planned around the world.

One example is the European Hydrogen Backbone, an initiative that is well underway, with a vision for a dedicated hydrogen transport infrastructure across Europe. The initiative has 12 European gas transmission system operators, with a plan for a 39,700km pipeline spanning 21 countries by 2040, and further growth thereafter (Natran Group, 2026). Two-thirds of the network is based on repurposed natural gas pipelines, with the remainder built from new pipeline. As detailed comprehensively in this project, when a gas network transitions from natural gas to hydrogen, more storage is needed to facilitate linepack, hence the B-Linepack+ solution. It is therefore expected that B-Linepack+ could offer significant benefits to the development and operation of the proposed European hydrogen gas networks.

Pipelines are being planned/built more widely, such as networks within North America, Latin America and the middle east (World Economic Forum, 2023). These will also likely require linepack supplementation, needing additional storage that may present opportunities for the B-Linepack+ solution.

Deploying the B-Linepack+ solution outside the UK would still bring significant value to the UK, with most of the technical expertise held by project consortium members and sub-contractors based in the UK or having significant UK presence.

# 4.0 Scalability

The deployment of the B-Linepack+ solution will need to scale rapidly alongside the demonstration as part of the Ofgem SIF funded project. As detailed in other project reports, 16 systems are proposed around the UK to provide linepack supplementation. They are all planned to be operational by 2035. Design development of full-scale systems will be progressed alongside the demonstration project, outside the scope of the Ofgem SIF funded project, to facilitate this deployment.

The scaling for deployment will also need to account for the systems that may be developed to support alternative use cases, as detailed in Sections 2.0 and 3.0. An early conceptual deployment timeline for the use cases presented in Table 2 has been given in Table 3 in Appendix A. The timeline is based on the higher demand scenario. It is highly subject to change.

Considering the deployment timeline presented in Table 3, the requirement to build 16 systems before 2035 for B-Linepack+ solutions, and potential projects outside the UK, rapid deployment scaling is required to meet demand. The following aspects of the project have been considered, which are the detailed in the next sections.

- Technology
- Construction
- Supply chain
- Project consortium
- Storage demand
- Economics
- Timeline

## 4.1 Technology

The B-Linepack+ project will demonstrate the use of Lined Rock Shaft (LRS) storage technology to provide linepack supplementation for future hydrogen gas networks. The system proposed for the demonstration is detailed in the project deliverables. For more information, see the basis of design documents PRZ0025-REP-0000-0001 and LGG-L057401-R04 Basis of Design (Sub-surface Storage).

Considering scalability, the high level aims of the technology demonstrator project are to:

- Demonstrate the safety, performance, and commercial value of LRS technology to enable the deployment thereafter of full-scale commercial systems.
- Demonstrate the capability of the LRS technology in supplementing linepack to show the value it could provide to support future hydrogen gas networks.

Therefore, the demonstrator will aim, as-close-as possible, to replicate a full-scale LRS system providing linepack supplementation. The technology demonstrator LRS will be smaller than a full-scale system, however, work has been done to show that the learnings will be scalable for larger systems. This has been detailed in the following sub-sections.

Considering linepack supplementation, this is well understood by National Gas Transmission (NGT). Ancillary storage will be used for cycling the hydrogen in and out of the LRS, demonstrating the storage providing supplementation. The ancillary storage will be significantly smaller than a gas network, however the principle balancing mechanisms are directly transferable.

### 4.1.1 Geomechanical modelling

As detailed in the document LGG-L057401-R09 Geomechanical and Structural Design Note, geomechanical modelling has been performed to understand how the size of a LRS impacts the structural behaviour of the system. It showed that the size of the planned demonstrator will have similar behaviour to a full-scale system, and it is understood how the data from the demonstrator could be appropriately scaled to inform the design of full-scale systems.

### 4.1.2 Thermodynamic modelling

Similar to the geomechanical modelling, thermodynamic modelling has been performed for different sized LRS systems, and it has shown that similar behaviour of the hydrogen will be seen for the demonstrator scale compared to a full-scale system. The pressure and temperature changes will be similar, and therefore the data

from the demonstrator will be suitable to validate the thermodynamic model, informing the design of full-scale systems. For more information on the thermodynamic behaviour of the LRS, see document LGG-L057401-R08 Sub-Surface Process Design Note.

#### 4.1.3 Material behaviour

The LRS has a multi-layer lining system that provides gas containment. The dimensions of the different layers will be the same for the demonstrator as for a full-scale system, with the same materials used. The expected material behaviour was determined as part of the geomechanical modelling, and the demonstrator will be operated such that the same material response is seen.

#### 4.1.4 Parametric design model

As part of the Discovery phase, the development of a parametric model was explored, which would allow the system design to be scaled to determine the most suitable proposal for a given site/application. It was shown that this could provide the following benefits:

- Capture the design process not just the final result
- Enable design improvement feedback loops
- Encode engineering knowledge
- Enable fast concept iteration, design optimisation and performance-based design
- Reduce cost of changes
- Enable product-oriented approach to design

The development of a parametric model is outside the scope of the Ofgem SIF project but could support an optimised design process for future systems, helping to scale the technology as deployment increases.

#### 4.1.5 Multi-layer Liner Testing

As detailed in the document LGG-L057401-R09 Geomechanical and Structural Design Note, multi-layer liner testing will be performed as part of the technology development program. This will test the LRS lining system in a lab at the scale of the technology demonstrator. This will validate the expected behaviour of the lining system prior to the real-world deployment of the demonstrator, which will add confidence to the scalability expectations of the technology.

#### 4.1.6 Expertise

The behaviour of the LRS is relatively unique compared to standard industrial structural design. The deployment of the demonstrator will validate geomechanical and structural models allowing the system to become standardised and predictable for varying geologies. This will increase industry knowledge of the interaction behaviour between steel liners and surrounding geology and by standardising the design, the knowledge can be readily disseminated to allow for technology growth.

### 4.2 Construction

The construction of the demonstration project is detailed in LGG-L057401-R07 Construction Sequence. At all stages, the methods used will be the same as for full-scale systems. The only exception is the method of shaft sinking. For the demonstrator, a rotary piling rig will be used, whereas for full-scale systems, blind boring or reverse circulation drilling will be used. This difference is not expected to present any issues with scaling from a demonstrator scale LRS to full-scale. All methods are industry standard and very well understood. Expert contractors with extensive experience would be used. The method of shaft sinking is not expected to impact the design or operation of the LRS technology, nor impact its capacity to provide linepack supplementation.

### 4.3 Supply Chain

#### 4.3.1 Construction machinery

Large drilling rigs will be required to sink shafts for full-scale LRS systems. These rigs are available, however as the technology scales with more systems being deployed per year, more rigs will need to be made to support growth. The lead time to procure such rigs (or modify other types of rigs) is fairly long, and therefore early engagement with machinery providers will be required to prevent delays.

The machinery required for the fabrication, transport and installation of the steel liners is readily available, however reasonable workshop space will be required to support multiple systems being deployed per year.

For the mixing, handling and delivery of the cementitious liner materials, a large amount of machinery will be required. The required machinery exists for other industries; however it is expected that more equipment would need to be made available to support multiple system being deployed per year.

#### 4.3.2 Materials and equipment

For the LRS, the material required is principally the steel for the liners, concrete, and grout. The volumes of steel required will be large, however this is not expected to present any issues. The steel supplier, Outukumpu, is one of the largest global steel producers and would have the capacity to support significant demand. Significantly less steel would be required when compared to and if alternative surface storage technologies were used. For the concrete and grout, supply has been discussed with industry experts, and it is anticipated that the demand could be met by creating new production facilities.

For the sub-surface and top-side process equipment, the lead time for procurement is not expected to present significant issues for supplying future full-scale systems. The equipment is well known in the industry, but production rates may need to increase. For the linepack piping, either pipes previously used for natural gas transport will be re-purposed, or new pipe will be produced. The expected volume of steel required for new pipe is significant, but given sufficient lead times, this should not present issues.

## 4.4 Project Consortium

The project consortium required to scale the B-Linepack+ technology will be capable of supporting future system roll-out. Most consortium members are large organisations that have experience owning/developing/managing large technology projects. Smaller supporting companies will be capable of providing continued support where required. As the technology matures, and more systems are deployed, less input will be required from the wider consortium.

## 4.5 Storage Demand

As the need for linepack supplementation for future gas networks increases, the B-Linepack+ solution can be deployed to meet the demand. Given the modular and scalable design of the LRS technology, varying sized systems can be deployed, with multiple systems deployed at a single site, providing high flexibility of storage capacity. If the storage demand at a site increases, more systems can be installed, or if more storage is required across the entire network, new systems can be installed at the most beneficial locations.

The LRS technology and the B-linepack+ solution are suitable for both hydrogen and natural gas storage, therefore it can provide value in the short and long term. If the linepack supplementation demand only increases slightly due to the blending of hydrogen and natural gas, then fewer or smaller systems could be installed. If the blending continues and more hydrogen is used, requiring increased linepack supplementation, then more systems can be deployed. Even if no hydrogen is used on a network, the B-Linepack+ solution can still provide value, energy storage resilience and security of supply. LRS technology can also be scaled for network applications across both distribution networks in the UK.

## 4.6 Economics

As the B-Linepack+ technology is deployed more widely, the system will benefit from economies of scale, and cost savings as a result of learning. This will therefore result in the capital cost of systems reducing as the number of systems deployed increases. The operational costs are also likely to decrease, as the design and operation of the systems and the linepack supplementation is optimised.

The modelling performed as part of the Alpha phase, as detailed in other reports, shows the economic benefit of the B-Linepack+ as it is deployed with a large hydrogen gas network. These results are expected to scale, with value still seen for smaller or larger gas networks.

### 4.7 Timeline

Similar to the benefits discussed with scaling for economics, the time taken to design, build, and commission future B-Linepack+ systems is expected to reduce as learnings are made and the process is optimised. Given that the deployment time for the LRS technology is much less than other geological storage options, this provides even greater benefit. It means that the B-Linepack+ technology can be deployed in-line with network demand, rather than years later.

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# Appendix A : Deployment timeline

*Table 3: LRS deployment for isolated UK use cases*

| | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041 | 2042 | 2043 | 2044 | 2045 | 2046 | 2047 | 2048 | 2049 | 2050 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **E-SAF** | | | | | | | | | | | 1 | 1 | | | | | | | | | 2 |
| **Steel** | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | | | | | | | | | | | | | 14 |
| **Cement** | | 2 | 2 | 3 | 3 | 3 | 3 | | | | | | | | | | | | | | 16 |
| **Maritime** | | | | | | | | | | | | | 1 | 2 | 4 | 6 | 8 | 10 | 10 | 10 | 51 |
| **Glass** | | | 2 | 2 | 4 | 5 | 8 | 8 | 6 | 6 | 4 | 2 | 2 | | | | | | | | 49 |
| **Aluminium** | 1 | | | | | | | | | | | | | | | | | | | | 1 |
| **Ammonia** | 2 | 3 | 3 | 4 | 4 | | | | | | | | | | | | | | | | 16 |
| **Total** | 3 | 7 | 9 | 11 | 13 | 10 | 13 | 10 | 6 | 6 | 5 | 3 | 3 | 2 | 4 | 6 | 8 | 10 | 10 | 10 | |

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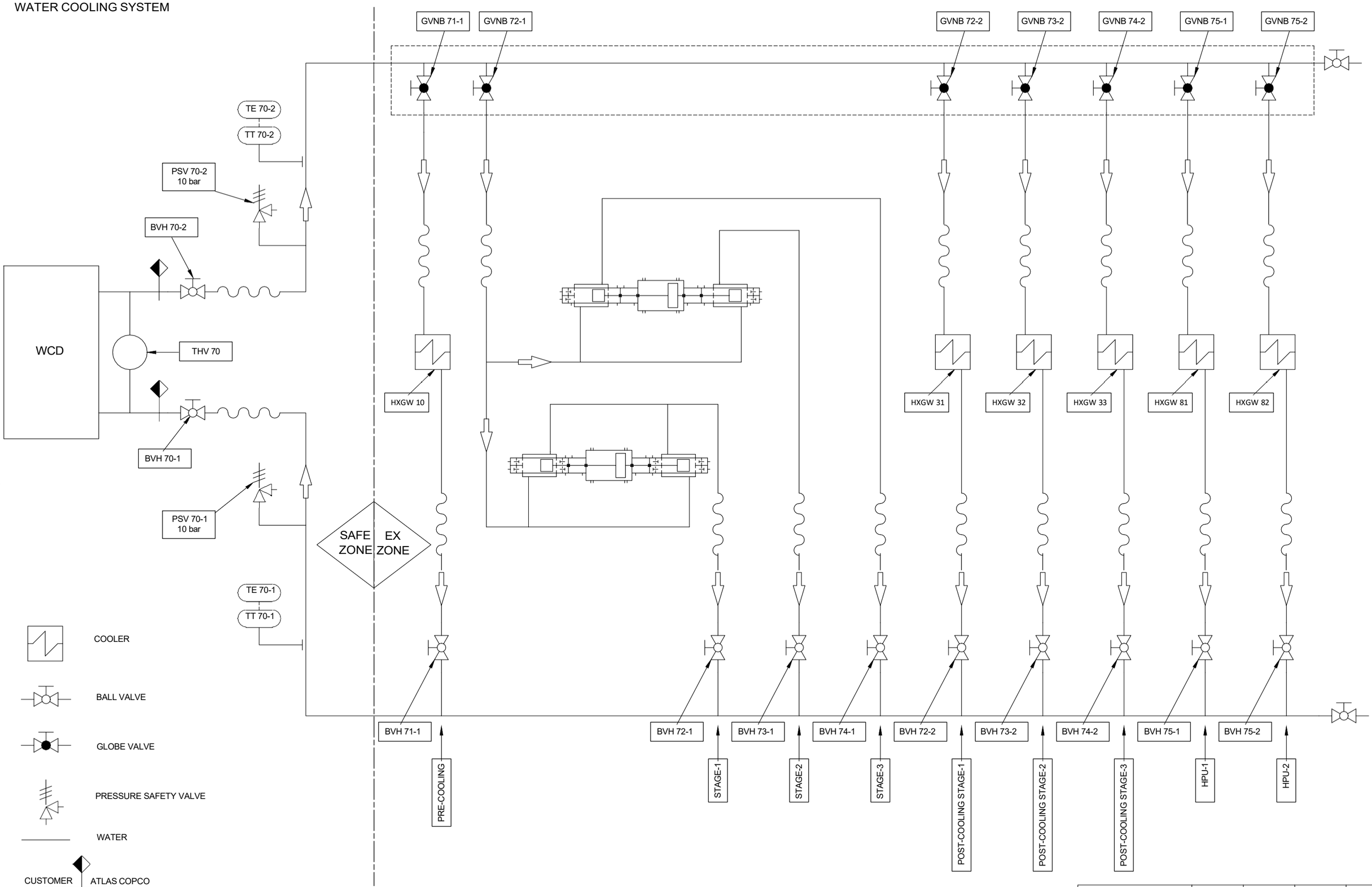
# WATER COOLING SYSTEM

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| Note | Revision | Modified from | Date | Init./Appd. |
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Tolerances,if not indicated,according to ATLAS COPCO STANDARD Class

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| Treatment | NOT APPLICABLE |
| Secrecy Class | 1102 K/ Confidential |
| | ACD |

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| Des checked | | Prod checked | Approved |
| Date | 13-04-2023 | | |

Drawing owner: CRP

Designation: P&ID - WCS

Sheet ( ) 01 01

Parent 3D Model | Ed. Version 3D

WorkInProgress

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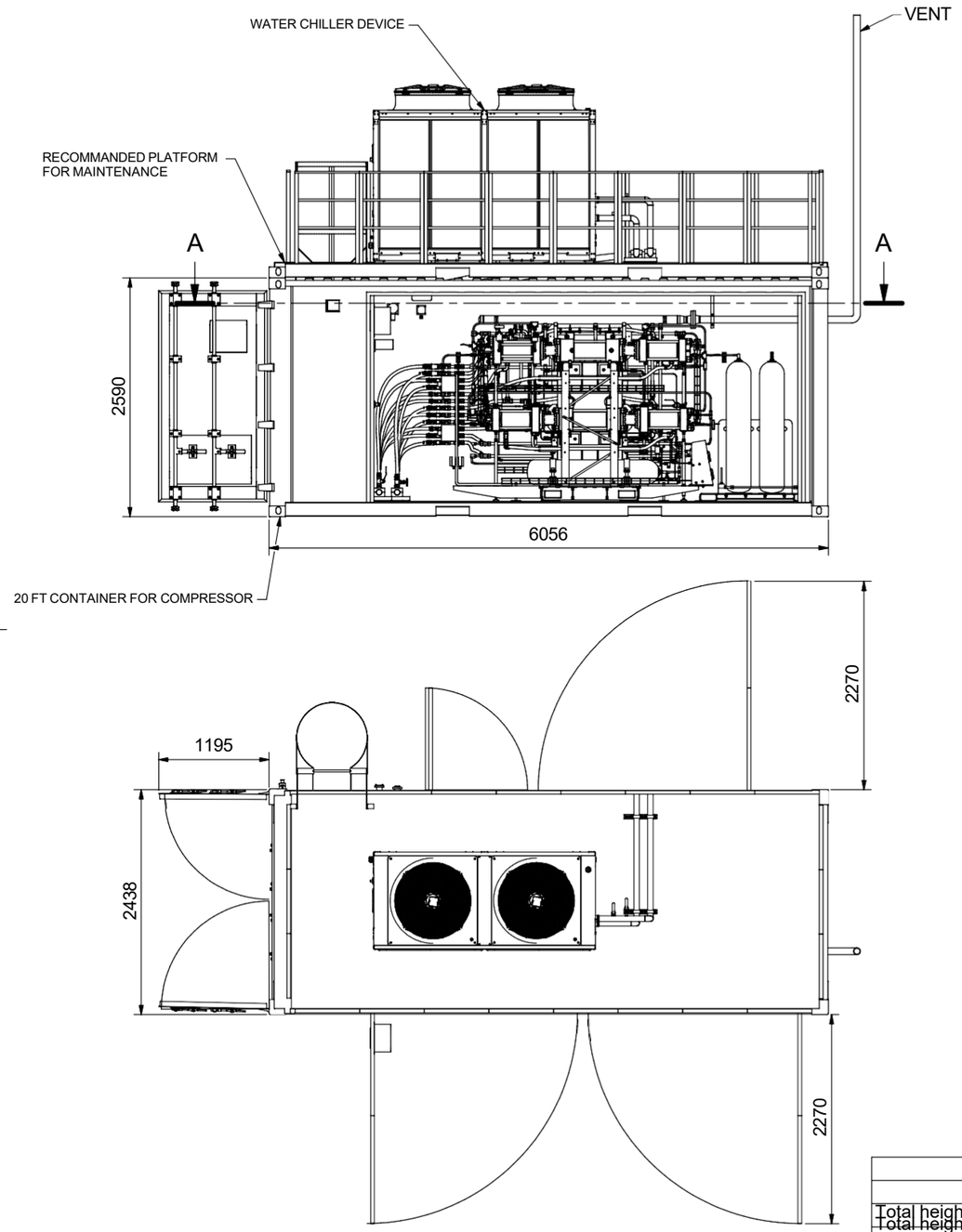


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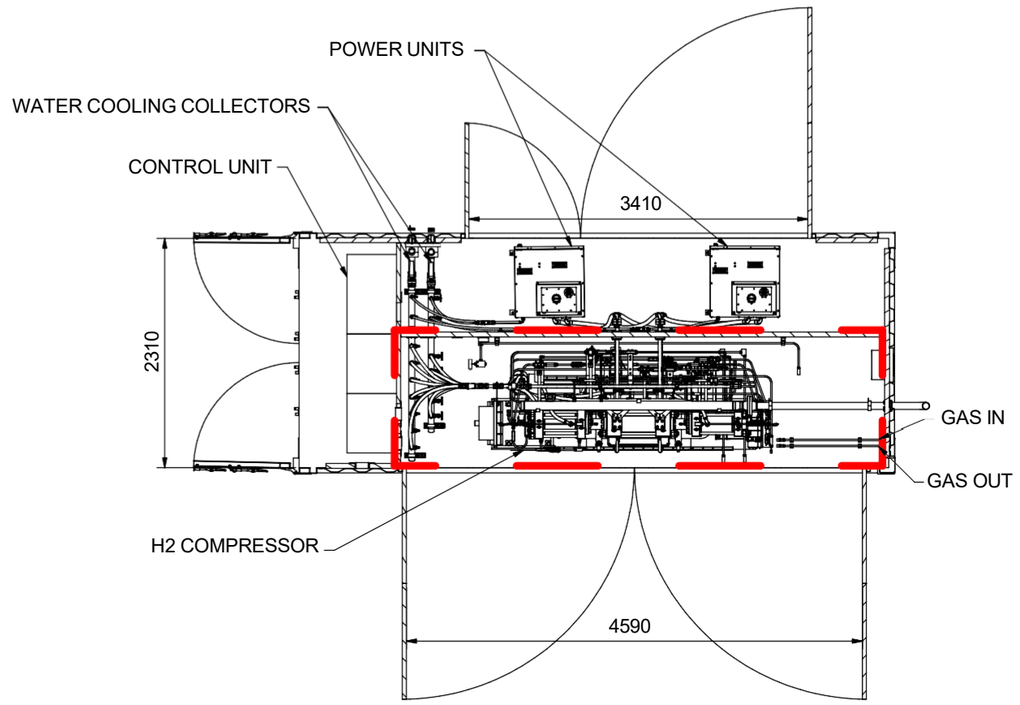


Note :
- Refer to the other pages for detail views
- All figures and data are preliminary and given for information only
- The displayed is not binding
- Vent lines and small equip. not represented, nor station safety equipment (e.g. gas and flame detectors, etc)
- The Water chiller device configuration is not representative of the finished product
- The HPU configuration is not representative of the finished product
- The ATEX zone given in the main view

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| Ground load max (calculated) | (daN/m2) | TBA |
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Tolerances, if not indicated, according to: ATLAS COPCO STANDARD CLASS

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Material See Drawing

Treatment

Confidentiality Class acc. to 1102 K: INV

Atlas Copco

STATUS: WorkInProgress

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Version Drwg | Blank wt. | Kg | Fini wt. N/A

Dwgs checked. | Prod checked. | Approved. | Date 25/08/2023

Drawing owner

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-SM1
SM1 container

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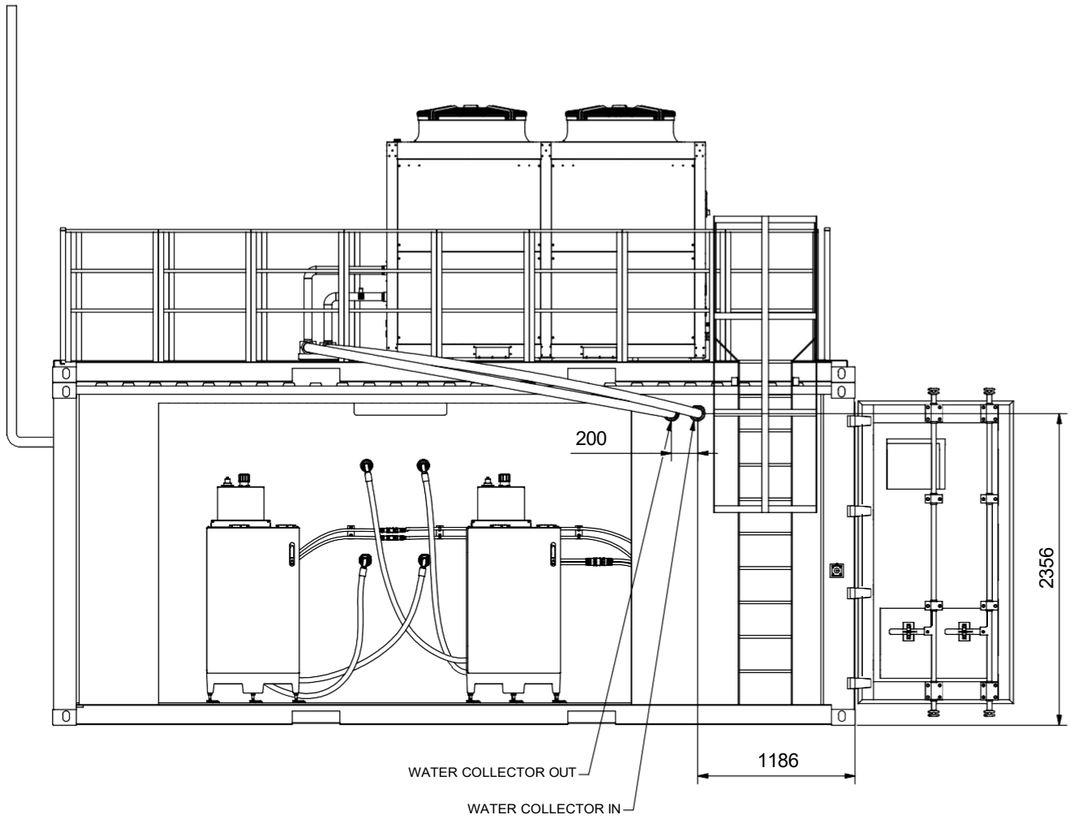
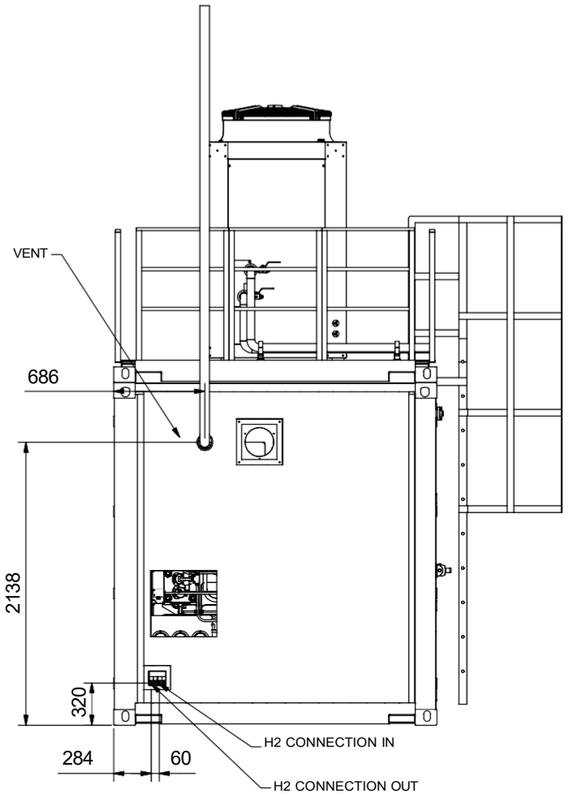
# FULL MODULE IN 20 FT ISO CONTAINER (WITH WATER CHILLER DEVICE ON ROOF OPTION)

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- All figures and data are preliminary and given for information only
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- Vent lines and small equip. not represented, nor station safety equipment (e.g. gas and flame detectors, etc)
- The Water chiller device configuration is not representative of the finished product
- The HPU configuration is not representative of the finished product

| PROCESS CONNECTIONS IN AND OUT | | |
|---|---|---|
| ~~CONNECTION~~ | ~~TYPE~~ | ~~SIZE~~ |
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| Gas OUT | HP 20'000 psi | 9/16" |
| Cooling fluid IN | "Rapid" water | 2" |
| Cooling fluid OUT | "Rapid" water | 2" |

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| Ed | Posi-tion | Modified from | Date | Intr./Appd. |
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Treatment

Confidentiality Class acc. to 1102 K: INV

Drawing owner

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STATUS: WorkInProgress

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Des checked. | Prod checked. | Approved. | Date 25/08/2023

Sheet 2 / 4

SM2 container - GA

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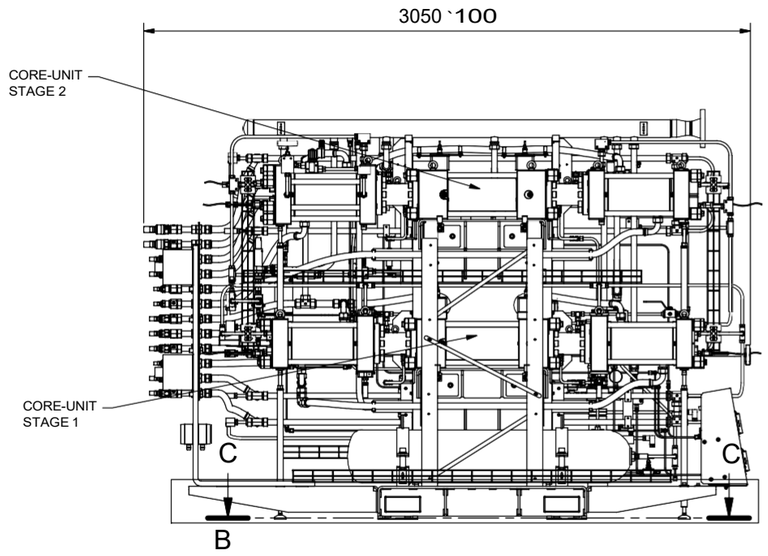
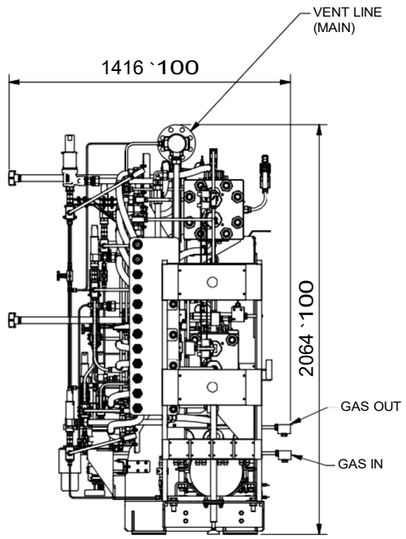
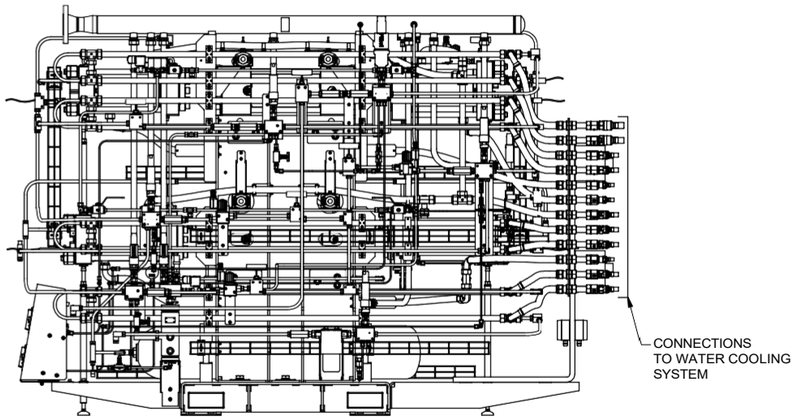
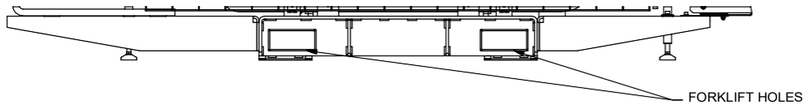
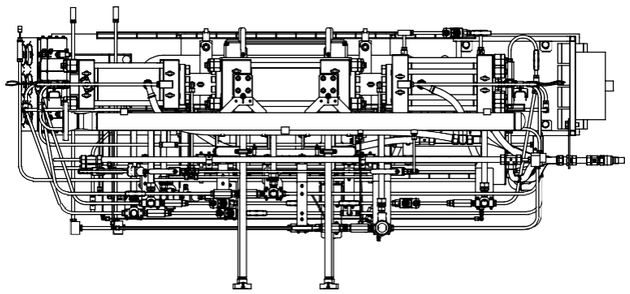


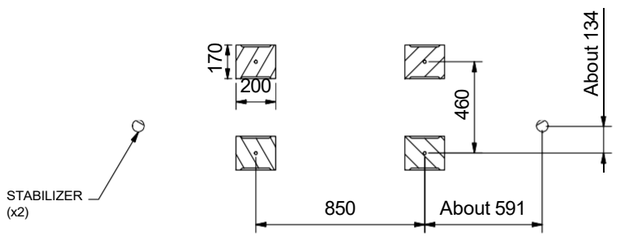




B ( 1 : 15 ) DETAIL TO FORKLIFT HOLES



C-C ( 1 : 20 ) GROUND CONTACT SURFACES




NOTE :
- Electric connections not indicated
- All figures and data preliminary given for information only
- The display is not binding

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| Total height required | (mm) | 2'200 |
| Total equipment weight (calculated) | (kg) | TBA |
| Ground load max (calculated) | (daN/m2) | TBA |
| Air Flow (In and Out - Chiller only) | (m3/h) | TBA |

| PROCESS CONNECTIONS IN AND OUT | | |
|---|---|---|
| CONNECTION | TYPE | SIZE |
| Gas IN | HP 20'000 psi | 9/16" |
| Gas OUT | HP 20'000 psi | 9/16" |

| Ed | Position | Modified from | Date | Intr./Appd. |
|---|---|---|---|---|
| N/A | | | | |

| Parent 3D model | Ed . Version 3D |
|---|---|
| INPROGRESS_SM2_ASSY_600_COMPRESSOR_FRA_M_STD-D140-D15V0_SD_WORK | |

| | | | | |
|---|---|---|---|---|
| Tolerances, if not indicated, according to: | | | | |
| ATLAS COPCO STANDARD CLASS | | | | |
| Name | | | Confidentiality Class acc. to 1102 K | |
| Material | | | | |
| Treatment | | | INV | Drawing owner |
| Scale 1 : 20 | Family | | A2 | Compare |
| Drawn by AIR27212_adm | Blank nr. | | | Replaces |
| Net wt. Kg | Fini wt. 2330,414 kg | | | Designation |
| WorkInProgress | Des checked. | Prod checked. | Approved. | Date 25/08/2023 |

Sheet 3 / 4

SM2 container - GA

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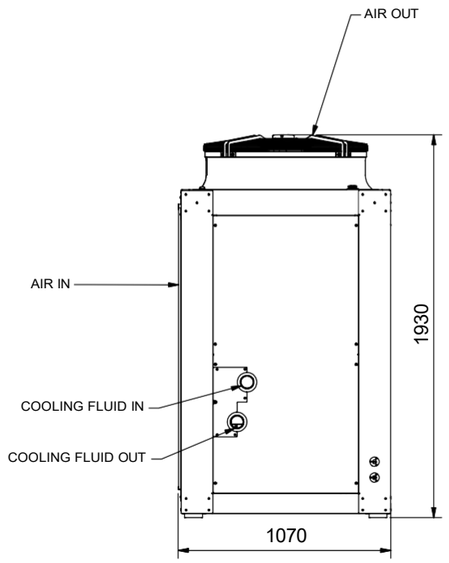
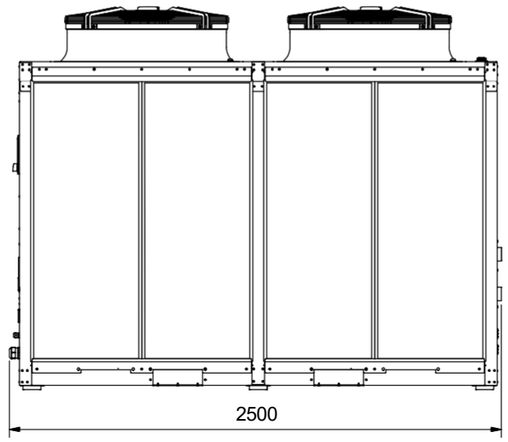
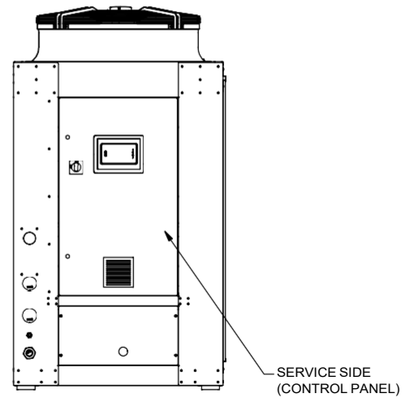
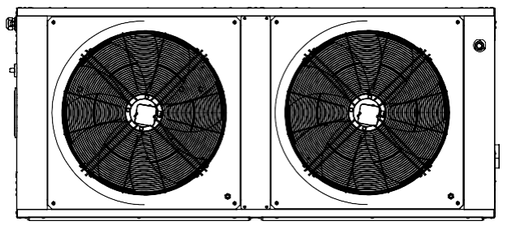
# WATER COOLING DEVICE (CHILLER) (DETAILED VIEWS)

All materials supplied are in compliance with the requirements of the List of Prohibited Substances



NOTE :
- Electric connections not indicated
- Dimensions affected by regular manufacturing tolerances
- All figures and data preliminary given for information only
- The display is not binding

| MAIN DATA | | |
|---|---|---|
| DESCRIPTION | UNIT | VALUE |
| Total height of the equipment | (mm) | 1'930 |
| Total height required | (mm) | TBA |
| Total equipment weight (calculated) | (kg) | 1'365 |
| Ground load max (calculated) | (daN/m2) | TBA |
| Air Flow (In and Out - Chiller only) | (m3/h) | 32'000 |

| PROCESS CONNECTIONS IN AND OUT | | |
|---|---|---|
| CONNECTION | TYPE | SIZE |
| Cooling fluid IN | "Rapid" water | 2" |
| Cooling fluid OUT | "Rapid" water | 2" |
| Filing | TBA | TBA |
| Drain | TBA | TBA |

| Ed | Position | Modified from | Date | Intr./Appd. |
|---|---|---|---|---|
| N/A | | | | |

| Parent 3D model | Ed . Version 3D |
|---|---|
| TCX55-90_CHASSIS_E2 | |

Tolerances, if not indicated, according to: ATLAS COPCO STANDARD CLASS

Name

Material Stainless Steel

Treatment

Confidentiality Class acc. to 1102 K: INV

Atlas Copco

STATUS: WorkInProgress

Scale 1 : 20 | Drawn by AIR27212_adm | Version Drwg | Blank wt. | Kg | Fini wt. 698,406 kg | Designes checked. | Prod checked. | Approved. | Date 25/08/2023

Family | Blank nr. | A2 | Compare | Replaces | Designation | Sheet 4 / 4

Drawing owner

SM2 container - GA

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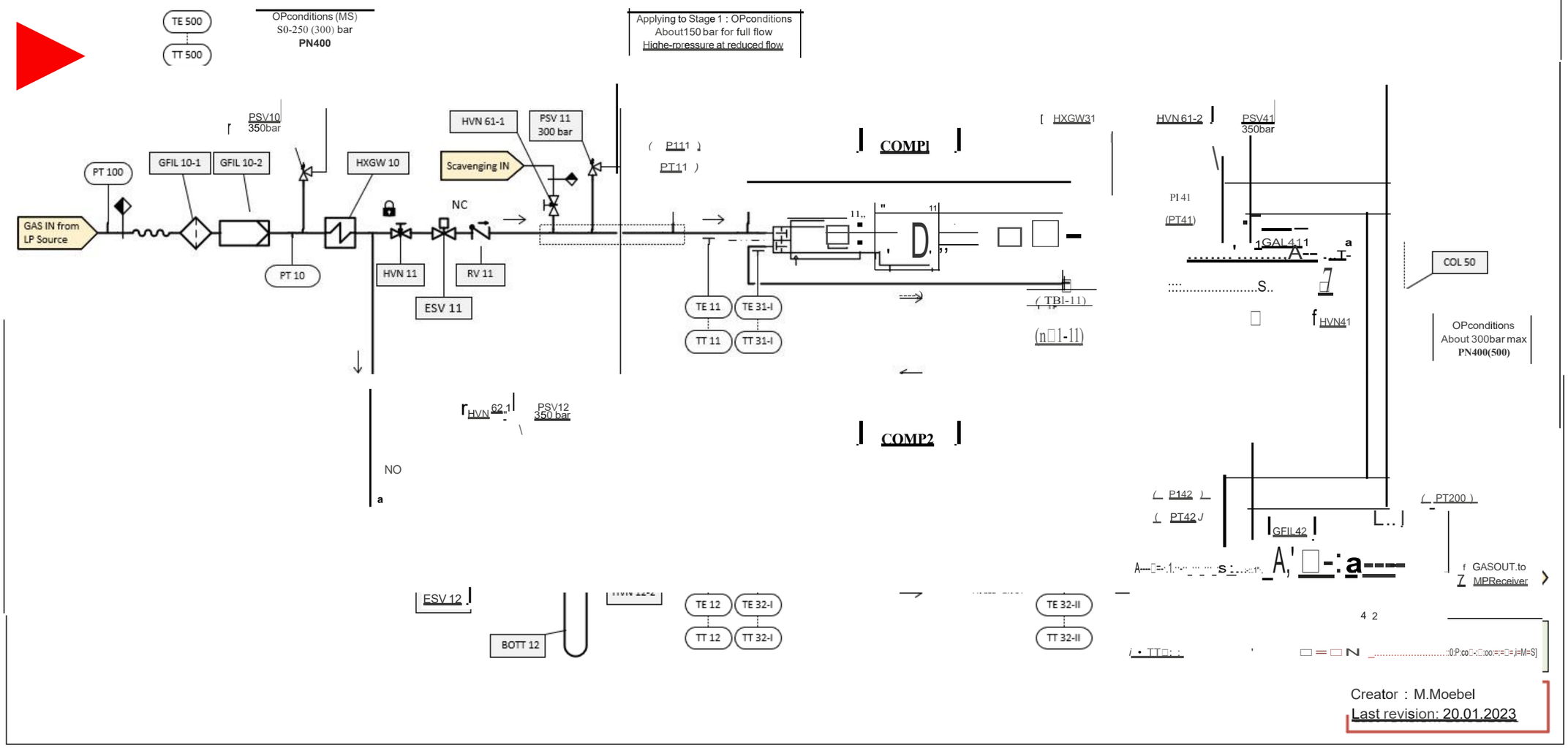
MAIN GAS LINES (only)




Creator : M.Moebel
Last revision: 20.01.2023

# FP Cast Line Heaters

EXHEAT's range of cast aluminium line heaters provide a compact and efficient heating solution for constant flow liquids or gases. Cast heaters are increasingly being selected over traditional pressure vessel type heaters for the following reasons:

- Suitable for high process design pressures
- Cost effective
- Increased safety due to the encasement
- Compact size with a reduced footprint
- Excellent heat transfer and residual heating from the aluminium casting
- High reliability and increased service life
- Uniform heat distribution
- Resistant to any internal vibrations
- Available on shorter lead times

The design incorporates electric heating elements and an indirect process heating coil embedded within marine grade cast aluminium. This provides excellent heat transfer properties combined with low surface temperatures.

## FEATURES

Certified to ATEX, IECEx or CSA standards

Certified under EN/IEC 60079-0, 60079-1, 60079-7, 60079-31 and standards per CEC/NEC 500

Flameproof IP66 rated terminal enclosure

Cellular glass insulated with stainless steel cladding

Maximum design pressure and temperature of 660 barg at up to 400°C

Process control and over-temperature protection sensors: RTD Pt100, thermocouple type K or thermostats

Wall or floor, vertical or horizontal mounting

Multiple heating elements allow for step control, alternatively, solid state relay or thyristor control can be employed

Coil materials: stainless steel 316L, duplex S31803, super duplex S32760 (others, including nickel alloys available on request)

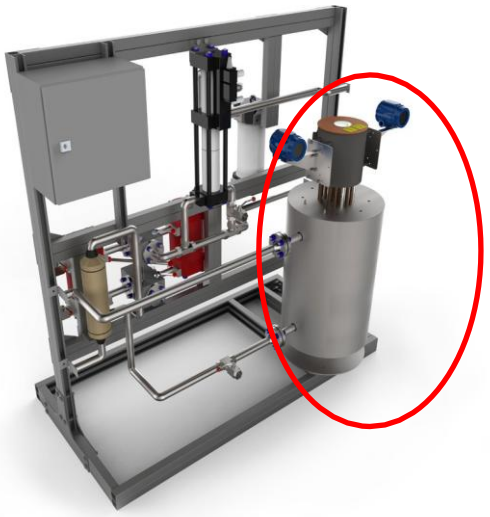
Process connections available using standard flanged or compression joints

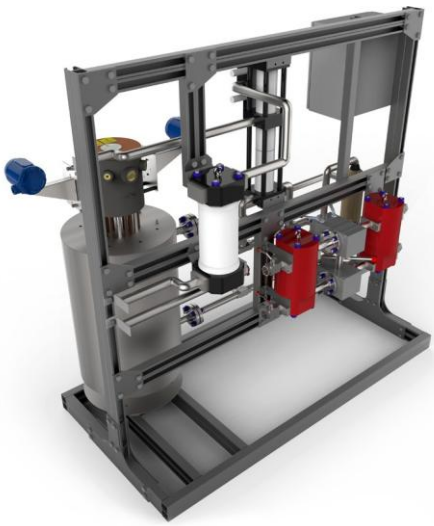
## TYPICAL APPLICATIONS

| | |
|---|---|
| Seal gas | Air |
| Natural gas | Biogas |
| Paint heating | Nitrogen |
| $CO_2$ | Solvent |
| Instrument air | Pasteurisation |

*Rev 1.2*

| | |
|---|---|
| **Certification** | ATEX / IECEx Ⓔx II 2 G/D<br>Ex d IIC T1 to T6 Gb<br>Ex tb IIIC T85 to T450°C Db IP66<br>EN/IEC 60079-0, EN/IEC 60079-1, EN/IEC 60079-7, EN/IEC 60079-31<br>CCOE (India), KGS (Korea), Inmetro (Brazil)<br>CSA (Canada and US), CU TR (formerly GOST) |
| **Enclosure** | Stainless steel or painted mild steel |
| **Elements** | X Small: Cartridge type stainless steel 316/L sheathed with 80/20 nickel chrome resistance wire embedded in high purity magnesium oxide<br>Small / Medium / Large: Hairpin type nickel alloy N08800 (Alloy 800) sheathed with 80/20 nickel chrome resistance wire embedded in high purity magnesium oxide |
| **Casting** | Marine grade aluminium Gr. LM25 (Al-Si7Mg) |
| **Cladding** | Stainless steel ASTM A366 TP316 2B finish |
| **Insulation** | Cellular glass insulation (-260°C / +430°C) |
| **Process Coil** | Stainless steel Gr. 316L<br>Duplex S31803<br>Super duplex S32760<br>Others, including nickel alloys available on request<br>All with NACE MR1075 compliance |
| **Design Code** | Designed SEP (Sound Engineering Practice) in accordance with the PED for installation within the European Union; designed in accordance with ASME B31.3, EN 13445 or PD5500 |
| **CE Marked** | In accordance with relevant EC Directives |
| **Voltage** | Up to 690VAC |
| **Delivery** | From 10 weeks, depending on options |
| **Duty** | X Small: up to 10kW<br>Small: up to 24kW<br>Medium: up to 40kW<br>Large: up to 70kW |





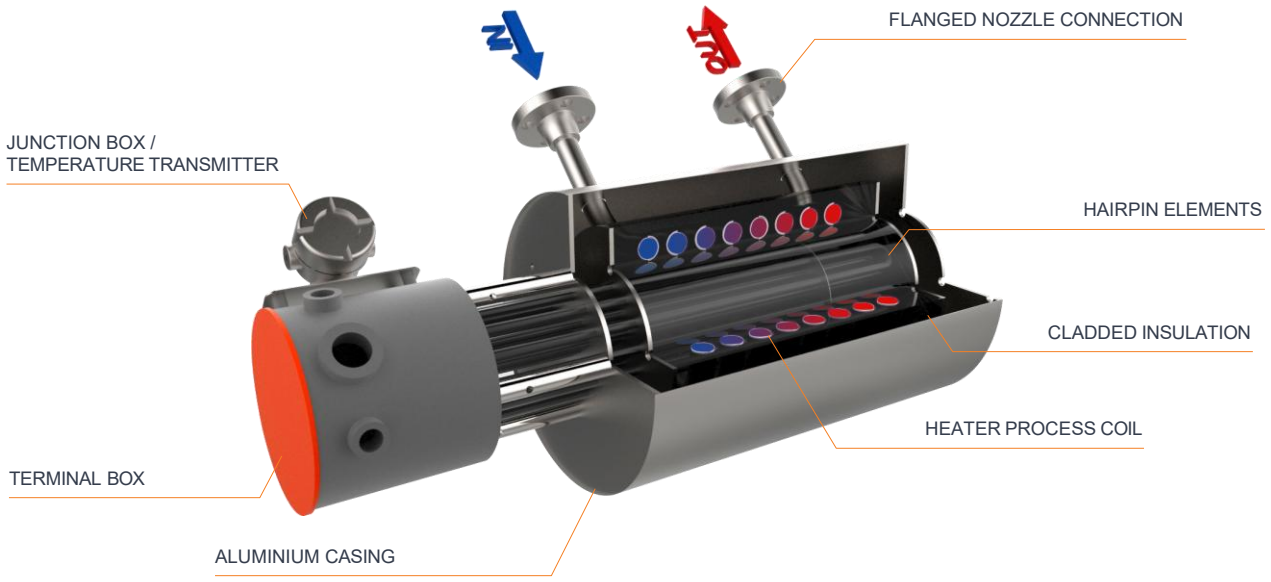
*Rev 1.2*

EXHEAT has developed a series of standard cast heaters which serve a broad variety of processes and design conditions. These heaters are highly cost effective, can be ordered simply by model number and are available with short lead times for delivery. If all standard options are taken, the engineering will be furnished by EXHEAT alongside the proposal. Upon receipt of PO, the goods will go straight into production and packing for dispatch without any engineering or documentation approval process post PO award.

If a bespoke design or additional options are required, then EXHEAT can also provide a unique designed solution. However, an engineering phase and special purchase items must be considered in the lead time of the project and the pricing.

| | Standard | Additional Options |
|---|---|---|
| Mounting | Natural finish<br>Floor or wall mounted | Painted<br>Floor or wall mounting |
| Terminal Box | Ex d stainless steel (natural finish)<br>Ex d carbon steel - painted (EXHEAT standard) | Ex e stainless steel - natural finish (not for CAN or USA)<br>Ex d stainless steel - painted (client specification)<br>Ex d carbon steel - painted (client specification) |
| Junction Box | Ex e<br>Ex d<br>Instrinsically safe * | Transmitters * |
| Sensors (Type) | RTD Pt100 simplex<br>RTD Pt100 duplex | Thermocouple type K simplex *<br>Thermocouple type K duplex *<br>Thermostats * |
| Sensors (Quantity) | 1 × over-temperature protection sensor<br>1 × process control sensor | Additional sensors to suit control system * |
| Sunshade | None | EXHEAT standard |
| Process Coil | Stainless steel 316L: SCH 10†, SCH 40, SCH 80<br>Duplex steel S31803: SCH 10†, SCH 40, SCH 80 | Any SCH 40§, SCH 160<br>Super duplex S32760<br>Nickel alloys<br>Others (please enquire) |
| Flanges | 150 to 2500lbs Raised Face (RF) flange<br>150 to 2500lbs Ring Type Joint (RTJ) flange | Graylock<br>NPT fittings<br>5000/10000 API flanges<br>PN25, PN32, PN50 flanges<br>Client specified flanges |

* Not available with EXHEAT standard control panel.
† Only for XX Small and X Small models.
§ Only for X Small models.




*Rev 1.2*

## Adam Bradshaw-Jones

**From:** Jack Trevail <jack.trevail@longitude-engineering.com>
**Sent:** 14 January 2026 16:31
**To:** Kelvin Shillinglaw; Steven Kirk; Nigel Voaden; Nick Horan-Martin
**Cc:** Steven Johnstone; Simon Avery; Adam Bradshaw-Jones
**Subject:** Re: Tube trailer and moving decom pipe costs

Afternoon all,

I thought I would provide an update on the ancillary storage options on this thread to keep the history for the costs for the pipe and tube trailer (see previous emails). I have included Nick and Adam from Premtech.

Regarding the decommissioned pipes, given the potential work and costs associated with using them as the ancillary storage, it doesn't seem like a viable option for this project.

Alternative rental options include using tube trailers as detailed below, or bundled/containerised tanks/canisters. Assuming that a tube trailer would be suitable for the cycling we plan to perform, considering 150 days of rental, that would cost £65k including 630kg of H2, using the costs you have provided below Kelvin.

For alternative options, I have received an indicative cost from Engas for the rental of 30 Manifolder Cylinder Pallets for 6 months containing 600kg of H2 at £256,500. I am currently in dialog with BOC who are in the process of putting together some options, I am expecting a call with their team early next week. Any additional cost options would be welcome if anyone has any info.

Once I have received more information from BOC, I will share. Regarding the tube trailer option, @Kelvin do you know whether we would be able to use the trailer for pressure cycling, assuming approx. 100 cycles of H2 from 30-200barg?

I am on leave for the rest of the week but will pick this up again when I am back on Monday.

Kind regards,
Jack

**Jack Trevail**

**Senior Engineer**

T: | M:

Longitude Engineering

Unit 36, City Quay, Camperdown Street, Dundee, DD1 3JA, United Kingdom

**See our website here:** https://longitude-engineering.com

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## Adam Bradshaw-Jones

**From:** Steven Kirk <steven.kirk@longitude-engineering.com>
**Sent:** 15 December 2025 11:29
**To:** Nick Horan-Martin; Adam Bradshaw-Jones
**Cc:** Nigel Voaden; Jack Trevail
**Subject:** Storage requirement

Hi Adam,

We have manged to reduce the size of the LRS containment and therefore the size of ancillary storage needed. Some info below.

| Property | Value | Notes |
|---|---|---|
| **Storage capacity** | 0.53 t | Total hydrogen gas storage capacity assuming average storage temperature of 20 degrees Celsius. |
| **Cushion gas** | 0.09 t | The amount of gas which is permanently stored in the sub-surface containment. It prevents unwanted loading on the liner and shaft walls when the working gas has been removed. |
| **Working gas** | 0.44 t | Available gas for injection and withdrawal. |
| **Maximum Operating Pressure** | 200 Barg | Maximum operating storage pressure. During commissioning this pressure will be incrementally increased from atmospheric pressure and liner/geological strains assessed before pressure is increased. |
| **Inner storage diameter** | 1.26 m | Internal diameter of the gas-tight liner |
| **Inner storage length** | 29 m | Internal length of the gas-tight liner |
| **Internal storage volume** | 35 m3 | Internal volume of the gas-tight liner |
| **Overburden depth** | 12 m | Depth of backfill in competent rock to provide resistance to vessel uplift pressure. |

| | | |
|---|---|---|
| **Shaft diameter** | 2.984 m | Excavated diameter of shaft prior to liner installation |
| **Shaft depth** | 47 m | Excavated depth of shaft prior to liner installation assuming 5m of superficial deposits. |

Thanks,

Steven

**Steven Kirk**

**Senior Engineer**

T: | M:

Longitude Engineering

Unit 36, City Quay, Camperdown Street, Dundee, DD1 3JA, United Kingdom

**See our website here:** https://longitude-engineering.com

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Longitude Engineering - part of ABL Group - is a global design and engineering consultancy specialising in marine and vessel design, marine operations engineering, and renewable energy design and engineering.

# Appendix B Premtech Documents

| Document Title | Document Number | Included (Y/N) |
|---|---|---|
| CDM Risk Register | PRZ0025-REG-0000-7110 | Y |
| Basis of Design Document | PRZ0025-REP-0000-0001 | N |
| Technical Interface Document | PRZ0025-REP-0000-0002 | N |
| 1200NB x 900NB Reducer Datasheet | PRZ0025-DAT-0000-0201 | Y |
| 900NB x 600NB Reducer Datasheet | PRZ0025-DAT-0000-0202 | Y |
| 600NB x 300NB Reducer Datasheet | PRZ0025-DAT-0000-0203 | Y |
| 300NB x 100NB Reducer Datasheet | PRZ0025-DAT-0000-0204 | Y |
| 150NB x 100NB Reducer Datasheet | PRZ0025-DAT-0000-0205 | Y |
| 1200NB 90deg Bend Datasheet | PRZ0025-DAT-0000-0206 | Y |
| 100NB 90deg Bend Datasheet | PRZ0025-DAT-0000-0207 | Y |
| 100NB 45deg Bend Datasheet | PRZ0025-DAT-0000-0208 | Y |
| 100NB x 100NB Equal Tee Datasheet | PRZ0025-DAT-0000-0209 | Y |
| FCV Datasheet | PRZ0025-DAT-0000-0301 | Y |
| PCV Datasheet | PRZ0025-DAT-0000-0302 | Y |
| 100NB Ball Valve Datasheet | PRZ0025-DAT-0000-0305 | Y |
| 25NB Plug Valve Datasheet | PRZ0025-DAT-0000-0306 | Y |
| Gas Velocity and Flow Rate Calculation | PRZ0025-CAL-0000-0001 | Y |

| | |
|---|---|
| **Project Title:** | *B-Linepack+ Alpha Phase* |
| **Document No:** | *PRZ0025-REG-0000-7110* |
| **Person Responsible for Risk Register:** | *Adam Bradshaw-Jones (Premzero)* |

*TBC*

| Risk Register Issue No. | Issue Date | Issued By | Comments (Only show last 3 revisions, hide previous revisions) |
|---|---|---|---|
| *000* | *27/01/26* | *Adam Bradshaw-Jones (Premzero)* | *Alpha Phase Issue* |
| | | | |
| | | | |

| Ref No. | Hazard and Location | Action No. | Design Action | Current Status | Action No. | Construction / Commissioning Action | Current Status | Residual Hazard | Residual Risk Scores (Likelihood x Impact) | Residual Risk Level (H, M, L) | Action No. | Operational Action | Current Status |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **Hazard**: Moving vehicles during construction.<br>**Location**: Site | D1.1 | Design to include buildability considerations as well as HAZCON during detailed design. | **Open** | | | **Open** | | 3 | L | | | Open |
| 2 | **Hazard:** Heavy plant and equipment operation in close proximity to live pipelines- fire / explosion.<br>**Location:** All site options | D2.1 | Design to include buildability considerations as well as HAZCON during detailed design. | **Open** | | | **Open** | | 5 | M | | | Open |
| 3 | **Hazard:** Potential challenges to construction traffic road access. Risk of congestion & RTA<br>**Location:** Site | D.31 | Design to include buildability considerations as well as HAZCON during detailed design. | **Open** | | | **Open** | | 2 | L | | | Open |
| 4 | **Hazard:** Potential for major hydrogen or natural gas pipeline release leading to far reaching fire and explosion effects to local populations.<br>**Location:** Site | D4.1 | QRA to evaluate risk profile of the site | **Open** | | | **Open** | | 5 | M | | Implement containment integrity assurance and ignition source control procedures | Open |
| | | D4.2 | Project to take into account the QRA when developing the strategy for land purchase in order to minimise risk of nearby 3rd party future developments having an impact on the risk profile of the site. | **Open** | | | | | | | | | |
| 5 | **Hazard:** Major accident domino effects potential with neighbouring high hazard process industries-potential risk of an intolerably high risk profile<br>**Location:** Site | D5.1 | Evaluate domino risks from nearby industrial facilities and incorporate into QRA | **Open** | | | **Open** | | 5 | M | | | Open |
| 6 | **Hazard:** Compressor relief and venting systems could give rise to unplanned hydrogen venting without warning. Risk of fire and explosion.<br>**Location:** Site | D6.1 | Design to provide a permanent exclusion for people and equipment around the automatic vent points. | **Open** | | | **Open** | | 4 | M | | Implement procedures to manage the station vent permanent exclusion zone. | Open |
| 7 | **Hazard:** Hydrogen requires a higher specification of ATEX equipment than that required for natural gas.<br>**Location:** Site | D7.1 | DSEAR risk assessment and Hazardous area classification and drawings | **Open** | | | **Open** | | 4 | M | | Periodic maintenance, inspection and testing of ATEX certified equipment | Open |
| | | D7.2 | All equipment specified to the more stringent (IIC T1) hydrogen requirements | **Open** | | | | | | | | | |
| 8 | **Hazard:** Site is at risk of being a terrorism target<br>**Location:** Site | D8.1 | Carry out design phase security risk assessment | **Open** | | | **Open** | | 4 | M | | Carry out ongoing periodic security risk assessment | Open |
| 9 | **Hazard:** Overpressurisation of lower pressure (50barg) pipework<br>**Location:** Site | D9.1 | Determine required safety devices and set points for the pressure reduction stream | **Open** | | | **Open** | | 3 | L | | | Open |
| 10 | **Hazard:** Unknown Ground Conditions leading to subsidence<br>**Location:** Site | D10.1 | Boreholes and other Ground Investigations to be undertaken during Beta Phase | **Open** | | | **Open** | | 4 | M | | | Open |

## STANDARD DATA SHEET FOR REDUCERS

### SHEET 1 – TO BE COMPLETED BY BUYER

1. Originating office: .....

   Tender number: .....

   National Grid Order/item number: .....

2. Matching pipe details (see appendix F):

   Nominal size: Maximum 1200 mm Minimum 900 mm

   Nominal wall thickness: 22.9 mm

3. Are pipe pups to be joined to the reducer by the SELLER? NO

   Are pipe pups to be supplied by National Grid? NO

   T/SP/F6 Data Sheet number for pipe pups to be manufactured by the SELLER

   .....

4. Reducer details:

   Length of plain reducer * 1158mm

   Length of pupped reducer * Unpupped mm

   Minimum material grade (see Appendix H) L450 (X65)

5. Coating details:

   Internal: T/SP/CM1

   Other coatings: **Internal coating suitable for 100% hydrogen**

   External: T/SP/PA/10

   T/SP/PA10 Supplements: .....

   Other coatings: .....

6. Maximum operating pressure: **200** bar

   Allowable test pressure: **300** bar

   Minimum operating temperature: **-20** °C

   Maximum operating temperature: **60** °C

7. Special requirements: **No Pipe Pups. To be suitable for 100% hydrogen**

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **22/01/26** | **ABJ** | | | | | | | | | | | | |

| | | |
|---|---|---|
| Signed : | Date : | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0201** | Sheet 1 of 2 |

## STANDARD DATA SHEET FOR REDUCERS

### SHEET 2 – TO BE COMPLETED BY THE SELLER

8. National Grid Tender number: .....

   National Grid order/item number: .....

   Unique identification number(s): .....

   .....

   SELLERS reference number .....

9. Material grade (see table 1): 245 / 290 / 360*

10. Are the reducers to be manufactured to a procedure that has been qualified to T/SP/MPQ2? YES / NO *

11. If the answer to item 10 is 'YES', give the following details of the procedure qualification:

    Date of qualification .....

    National Grid reference number .....

12. Give details of any differences between the qualified procedure and that to be used for the reducers to be manufactured (see T/SP/MPQ2) .....

    .....

    .....

    .....

13. Give details of any weldability tests relevant to the reducers to be manufactured that have been carried out since the procedure was qualified .....

    .....

    .....

    .....

14. If the answer to item 10 is 'NO' state the time required to qualify a reducer in accordance with T/SP/MPQ2

    .....

    .....

    .....

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **22/01/25** | **ABJ** | | | | | | | | | | | | |

| | | |
|---|---|---|
| Signed: | Date: | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0201** | Sheet 2 of 2 |

## STANDARD DATA SHEET FOR REDUCERS

### SHEET 1 – TO BE COMPLETED BY BUYER

1. Originating office: .....

   Tender number: .....

   National Grid Order/item number: .....

2. Matching pipe details (see appendix F):

   Nominal size: Maximum 900 mm Minimum 600 mm

   Nominal wall thickness: 15.9 mm

3. Are pipe pups to be joined to the reducer by the SELLER? NO

   Are pipe pups to be supplied by National Grid? NO

   T/SP/F6 Data Sheet number for pipe pups to be manufactured by the SELLER

   .....

4. Reducer details:

   Length of plain reducer * 1155mm

   Length of pupped reducer * Unpupped mm

   Minimum material grade (see Appendix H) L450 (X65)

5. Coating details:

   Internal: T/SP/CM1

   Other coatings: **Internal coating suitable for 100% hydrogen**

   External: T/SP/PA/10

   T/SP/PA10 Supplements: .....

   Other coatings: .....

6. Maximum operating pressure: **200** bar

   Allowable test pressure: **300** bar

   Minimum operating temperature: **-20** °C

   Maximum operating temperature: **60** °C

7. Special requirements: **No Pipe Pups. To be suitable for 100% hydrogen**

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **22/01/26** | **ABJ** | | | | | | | | | | | | |

| | | |
|---|---|---|
| Signed : | Date : | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0202** | Sheet 1 of 2 |

## STANDARD DATA SHEET FOR REDUCERS

### SHEET 2 – TO BE COMPLETED BY THE SELLER

8. National Grid Tender number: .....

   National Grid order/item number: .....

   Unique identification number(s): .....

   .....

   SELLERS reference number .....

9. Material grade (see table 1): 245 / 290 / 360*

10. Are the reducers to be manufactured to a procedure that has been qualified to T/SP/MPQ2? YES / NO *

11. If the answer to item 10 is 'YES', give the following details of the procedure qualification:

    Date of qualification .....

    National Grid reference number .....

12. Give details of any differences between the qualified procedure and that to be used for the reducers to be manufactured (see T/SP/MPQ2) .....

    .....

    .....

    .....

13. Give details of any weldability tests relevant to the reducers to be manufactured that have been carried out since the procedure was qualified .....

    .....

    .....

    .....

14. If the answer to item 10 is 'NO' state the time required to qualify a reducer in accordance with T/SP/MPQ2

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| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| | **22/01/25** | **ABJ** | | | | | | | | | | | | |

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| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0202** | Sheet 2 of 2 |

## STANDARD DATA SHEET FOR REDUCERS

### SHEET 1 – TO BE COMPLETED BY BUYER

1. Originating office: .....

   Tender number: .....

   National Grid Order/item number: .....

2. Matching pipe details (see appendix F):

   Nominal size: Maximum 600 mm Minimum 300 mm

   Nominal wall thickness: 14.3 mm

3. Are pipe pups to be joined to the reducer by the SELLER? NO

   Are pipe pups to be supplied by National Grid? NO

   T/SP/F6 Data Sheet number for pipe pups to be manufactured by the SELLER

   .....

4. Reducer details:

   Length of plain reducer * 1087mm

   Length of pupped reducer * Unpupped mm

   Minimum material grade (see Appendix H) L360 (X52)

5. Coating details:

   Internal: T/SP/CM1

   Other coatings: **Internal coating suitable for 100% hydrogen**

   External: T/SP/PA/10

   T/SP/PA10 Supplements: .....

   Other coatings: .....

6. Maximum operating pressure: **200** bar

   Allowable test pressure: **300** bar

   Minimum operating temperature: **-20** °C

   Maximum operating temperature: **60** °C

7. Special requirements: **No Pipe Pups. To be suitable for 100% hydrogen**

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Signed : | Date : | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0203** | Sheet 1 of 2 |

## STANDARD DATA SHEET FOR REDUCERS

### SHEET 2 – TO BE COMPLETED BY THE SELLER

8. National Grid Tender number: .....

   National Grid order/item number: .....

   Unique identification number(s): .....

   .....

   SELLERS reference number .....

9. Material grade (see table 1): 245 / 290 / 360*

10. Are the reducers to be manufactured to a procedure that has been qualified to T/SP/MPQ2? YES / NO *

11. If the answer to item 10 is 'YES', give the following details of the procedure qualification:

    Date of qualification .....

    National Grid reference number .....

12. Give details of any differences between the qualified procedure and that to be used for the reducers to be manufactured (see T/SP/MPQ2) .....

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13. Give details of any weldability tests relevant to the reducers to be manufactured that have been carried out since the procedure was qualified .....

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14. If the answer to item 10 is 'NO' state the time required to qualify a reducer in accordance with T/SP/MPQ2

    .....

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| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Signed: | Date: | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0203** | Sheet 2 of 2 |

## STANDARD DATA SHEET FOR REDUCERS

### SHEET 1 – TO BE COMPLETED BY BUYER

1. Originating office: .....

   Tender number: .....

   National Grid Order/item number: .....

2. Matching pipe details (see appendix F):

   Nominal size: Maximum 300 mm Minimum 100 mm

   Nominal wall thickness: 17.12 mm

3. Are pipe pups to be joined to the reducer by the SELLER? NO

   Are pipe pups to be supplied by National Grid? NO

   T/SP/F6 Data Sheet number for pipe pups to be manufactured by the SELLER

   .....

4. Reducer details:

   Length of plain reducer * 796mm

   Length of pupped reducer * Unpupped mm

   Minimum material grade (see Appendix H) L360 (X52)

5. Coating details:

   Internal: T/SP/CM1

   Other coatings: **Internal coating suitable for 100% hydrogen**

   External: T/SP/PA/10

   T/SP/PA10 Supplements: .....

   Other coatings: .....

6. Maximum operating pressure: **200** bar

   Allowable test pressure: **300** bar

   Minimum operating temperature: **-20** °C

   Maximum operating temperature: **60** °C

7. Special requirements: **No Pipe Pups. To be suitable for 100% hydrogen**

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Signed : | Date : | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0204** | Sheet 1 of 2 |

## STANDARD DATA SHEET FOR REDUCERS

### SHEET 2 – TO BE COMPLETED BY THE SELLER

8. National Grid Tender number: .....

   National Grid order/item number: .....

   Unique identification number(s): .....

   .....

   SELLERS reference number .....

9. Material grade (see table 1): 245 / 290 / 360*

10. Are the reducers to be manufactured to a procedure that has been qualified to T/SP/MPQ2? YES / NO *

11. If the answer to item 10 is 'YES', give the following details of the procedure qualification:

    Date of qualification .....

    National Grid reference number .....

12. Give details of any differences between the qualified procedure and that to be used for the reducers to be manufactured (see T/SP/MPQ2) .....

    .....

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    .....

13. Give details of any weldability tests relevant to the reducers to be manufactured that have been carried out since the procedure was qualified .....

    .....

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14. If the answer to item 10 is 'NO' state the time required to qualify a reducer in accordance with T/SP/MPQ2

    .....

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| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Signed: | Date: | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0204** | Sheet 2 of 2 |

## STANDARD DATA SHEET FOR REDUCERS

### SHEET 1 – TO BE COMPLETED BY BUYER

1. Originating office: .....

   Tender number: .....

   National Grid Order/item number: .....

2. Matching pipe details (see appendix F):

   Nominal size: Maximum 150 mm Minimum 100 mm

   Nominal wall thickness: 17.12 mm

3. Are pipe pups to be joined to the reducer by the SELLER? NO

   Are pipe pups to be supplied by National Grid? NO

   T/SP/F6 Data Sheet number for pipe pups to be manufactured by the SELLER

   .....

4. Reducer details:

   Length of plain reducer * 140mm

   Length of pupped reducer * Unpupped mm

   Minimum material grade (see Appendix H) L360 (X52)

5. Coating details:

   Internal: T/SP/CM1

   Other coatings: **Internal coating suitable for 100% hydrogen**

   External: T/SP/PA/10

   T/SP/PA10 Supplements: .....

   Other coatings: .....

6. Maximum operating pressure: **200** bar

   Allowable test pressure: **300** bar

   Minimum operating temperature: **-20** °C

   Maximum operating temperature: **60** °C

7. Special requirements: **No Pipe Pups. To be suitable for 100% hydrogen**

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Signed : | Date : | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0205** | Sheet 1 of 2 |

## STANDARD DATA SHEET FOR REDUCERS

### SHEET 2 – TO BE COMPLETED BY THE SELLER

8. National Grid Tender number: .....

   National Grid order/item number: .....

   Unique identification number(s): .....

   .....

   SELLERS reference number .....

9. Material grade (see table 1): 245 / 290 / 360*

10. Are the reducers to be manufactured to a procedure that has been qualified to T/SP/MPQ2? YES / NO *

11. If the answer to item 10 is 'YES', give the following details of the procedure qualification:

    Date of qualification .....

    National Grid reference number .....

12. Give details of any differences between the qualified procedure and that to be used for the reducers to be manufactured (see T/SP/MPQ2) .....

    .....

    .....

    .....

13. Give details of any weldability tests relevant to the reducers to be manufactured that have been carried out since the procedure was qualified .....

    .....

    .....

    .....

14. If the answer to item 10 is 'NO' state the time required to qualify a reducer in accordance with T/SP/MPQ2

    .....

    .....

    .....

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Signed: | Date: | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0205** | Sheet 2 of 2 |

# STANDARD DATA SHEET FOR BENDS EQUAL TO OR GREATER THAN DN 450

## SHEET 1 – TO BE COMPLETED BY BUYER

1. Originating office: .....
   National Grid Gas tender number: .....
   National Grid Gas Order/item number: .....

2. Matching pipe details:
   Nominal size: **1200** mm
   Nominal wall thickness: **22.9** mm

3. Bend details:
   Bend angle – 5° 37.5' / 11° 15' / 22° 30' / 45° / 90° *
   Bend radius – 3D / 1.5D *
   Minimum material grade (see Table 4 and Appendix B)

4. Are pipe pups to be joined to the bend by the SELLER? ..... YES/NO *
   Are pipe pups to be supplied by National Grid Gas? ..... YES/NO *
   T/SP/F6 Data Sheet number for pipe pups to be manufactured by the SELLER
   .....

5. Coating details:
   Internal: T/SP/CM1/ Other coating / Leave Bare * .....
   Other coatings: **Suitable for 100% Hydrogen** .....
   External: T/SP/CW6 / Other coatings / leave bare * .....
   T/SP/PA10 Supplements: .....
   Other coatings: .....

6. Maximum operating pressure: **200** bar
   Allowable test pressure: **300** bar
   Minimum operating temperature: **-20** °C
   Maximum operating temperature: **60** °C

7. Special requirements: **No Pipe Pups. To be suitable for 100% hydrogen.** .....
   .....
   .....

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Identification No: | Project Name: **B-Linepack+** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0206** | Sheet 1 of 2 |

## STANDARD DATA SHEET FOR BENDS EQUAL TO OR GREATER THAN DN 450

### SHEET 2 – TO BE COMPLETED BY THE SELLER

8. National Grid Gas tender number: .....

   National Grid Gas order/item number: .....

   Unique identification number(s): .....

   .....

   SELLERS reference number .....

9. Material grade (see Table 4 and Appendix B): 360 / 415 / 450/ 485 *

10. Are the bends to be manufactured to a procedure that has been qualified to APPENDIX M? YES / NO *

11. If the answer to item 10 is 'YES', give the following details of the procedure qualification:

    Date of qualification .....

    National Grid reference number .....

12. Give details of any difference between the qualified procedure and that to be used for the bends to be manufactured (see APPENDIX M) .....

    .....

    .....

13. Give details of any weldability tests relevant to the bends to be manufactured that have been carried out since the procedure was qualified .....

    .....

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14. If the answer to item 9 is 'NO' state the time required to qualify a bend in accordance with APPENDIX M

    .....

    .....

    .....

| | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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## STANDARD DATA SHEET FOR BENDS EQUAL TO OR GREATER THAN DN 450

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| **Delete as applicable* | Data Sheet No: PRZ0025-DAT-0000-0206 | Sheet 2 of 2 |

## STANDARD DATA SHEET FOR BENDS DN 50 TO DN 400 INCLUSIVE

### SHEET 1 – TO BE COMPLETED BY BUYER

1. Originating office: .....

   Tender number: .....

   National Grid Order/item number: .....

2. Matching pipe details:

   Nominal size: ..... 100 mm

   Nominal wall thickness: ..... 17.12 mm

3. Bend details:

   Bend angle – **90º**

   Bend radius – **1.5D**

4. Coating details :

   Internal: Coated to **T/SP/CM/1** .....

   Other coatings: **To be suitable for 100% hydrogen** .....

   External: Coated to **T/SP/PA/10 or T/SP/CW/6**

   T/SP/PA10 Supplements: .....

   Other coatings: .....

5. Maximum operating pressure: ..... **200** bar

   Allowable test pressure: ..... **300** bar

   Minimum operating temperature: ..... **-20** °C

   Maximum operating temperature: ..... **60** °C

6. Special requirements: **Design pressure: 200 barg. To be suitable for 100% hydrogen** .....

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0207** | Sheet 1 of 2 |

## STANDARD DATA SHEET FOR BENDS DN 50 TO DN 400 INCLUSIVE

### SHEET 2 – TO BE COMPLETED BY THE SELLER

7. National Grid Tender number: .....

   National Grid order/item number: .....

   Unique identification number(s): .....

   .....

   SELLERS reference number .....

8. Material grade (see table 1): 245 / 290 / 360 *
   (higher grades must be notified to the BUYER at the tender stage).

9. Are the bends to be manufactured to a procedure that has been qualified to T/SP/MPQ2? YES / NO*

10. If the answer to item 9 is 'YES', give the following details of the procedure qualification:

    Date of qualification .....

    National Grid reference number .....

11. Give details of any differences between the qualified procedure and that to be used for the bends to be manufactured (see T/SP/MPQ2) .....

    .....

    .....

12. Give details of any weldability tests relevant to the bends to be manufactured that have been carried out since the procedure was qualified .....

    .....

    .....

13. If the answer to item 9 is 'NO' state the time required to qualify a bend in accordance with T/SP/MPQ2

    .....

    .....

    .....

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Signed : | Date : | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0207** | Sheet 2 of 2 |

# STANDARD DATA SHEET FOR BENDS DN 50 TO DN 400 INCLUSIVE

## SHEET 1 – TO BE COMPLETED BY BUYER

1. Originating office: .....

   Tender number: .....

   National Grid Order/item number: .....

2. Matching pipe details:

   Nominal size: ..... 100 mm

   Nominal wall thickness: ..... 17.12 mm

3. Bend details:

   Bend angle – **45º**

   Bend radius – **1.5D**

4. Coating details :

   Internal: Coated to **T/SP/CM/1** .....

   Other coatings: **To be suitable for 100% hydrogen** .....

   External: Coated to **T/SP/PA/10**

   T/SP/PA10 Supplements: .....

   Other coatings: .....

5. Maximum operating pressure: ..... **200** bar

   Allowable test pressure: ..... **300** bar

   Minimum operating temperature: ..... **-20** °C

   Maximum operating temperature: ..... **60** °C

6. Special requirements: **Design pressure: 200 barg. To be suitable for 100% hydrogen** .....

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Signed : | Date : | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0208** | Sheet 1 of 2 |

## STANDARD DATA SHEET FOR BENDS DN 50 TO DN 400 INCLUSIVE

### SHEET 2 – TO BE COMPLETED BY THE SELLER

7. National Grid Tender number: .....

   National Grid order/item number: .....

   Unique identification number(s): .....

   .....

   SELLERS reference number .....

8. Material grade (see table 1): 245 / 290 / 360 *
   (higher grades must be notified to the BUYER at the tender stage).

9. Are the bends to be manufactured to a procedure that has been qualified to T/SP/MPQ2? YES / NO*

10. If the answer to item 9 is 'YES', give the following details of the procedure qualification:

    Date of qualification .....

    National Grid reference number .....

11. Give details of any differences between the qualified procedure and that to be used for the bends to be manufactured (see T/SP/MPQ2) .....

    .....

    .....

12. Give details of any weldability tests relevant to the bends to be manufactured that have been carried out since the procedure was qualified .....

    .....

    .....

13. If the answer to item 9 is 'NO' state the time required to qualify a bend in accordance with T/SP/MPQ2

    .....

    .....

    .....

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| | **22/01/26** | **ABJ** | | | | | | | | | | | | |

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| Signed : | Date : | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0208** | Sheet 2 of 2 |

## STANDARD DATA SHEET FOR TEES DN 50 TO DN 450 INCLUSIVE

### SHEET 1 – TO BE COMPLETED BY BUYER

1. Originating office:

   Tender number:

   National Grid Order/item number:

2. Matching pipe details.

| | Header | Branch |
|---|---|---|
| Nominal size: | 100 mm | 100 mm |
| Nominal wall thickness: | 17.12 mm | 17.12 mm |

3. Are guide bars required? (see Appendix H) NO

4. Minimum material grade of tees (see Table 1 & Appendix C) L245 (B)

5. This item is only applicable to tees equal to or greater than DN 100, intended for a maximum operating pressure of 103 bar, for use where standard pigging Operations will not be carried out.

   Is the passage of a gauging mandrel (see Appendix J) required?

   If 'NO' what minimum inside diameter is required for the header? mm

6. Coating details :

   Internal: T/SP/CM1

   Other coatings: **Internally Coated Suitable for Hydrogen**

   External: T/SP/PA/10

   T/SP/PA10 Supplements:

   Other coatings:

7. Maximum operating pressure: **200** bar

   Allowable test pressure: **300** bar

   Minimum operating temperature: **-20** °C

   Maximum operating temperature: **60** °C

8. Special requirements: **The tee must meet the validity limits within Figure 1.**

   **Design pressure 200 barg**

   **To be suitable for 100% hydrogen**

| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Signed : | Date : | |
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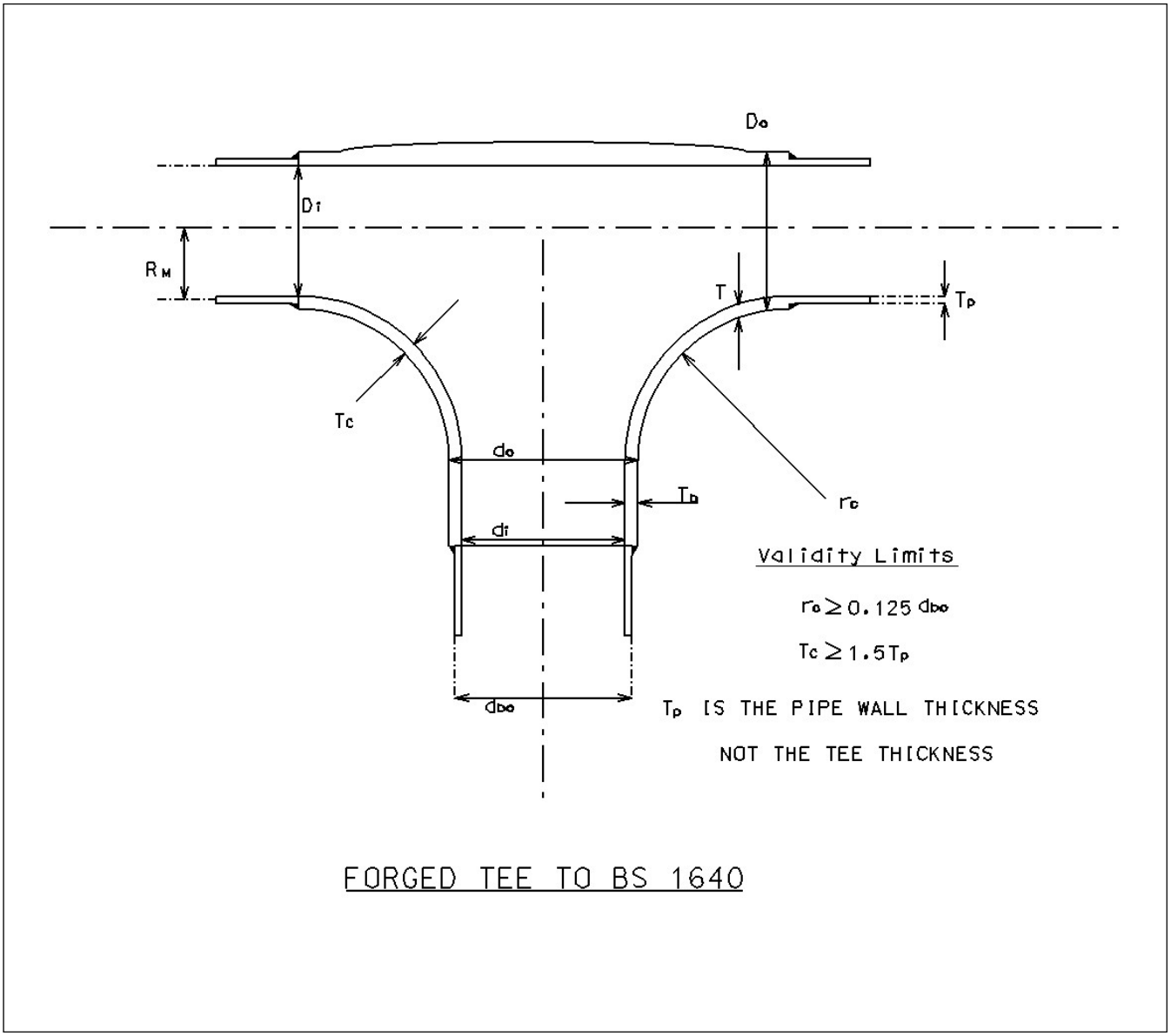
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0209** | Sheet 1 of 3 |

## STANDARD DATA SHEET FOR TEES DN 50 TO DN 450 INCLUSIVE

### SHEET 2 – FIGURE 1




FORGED TEE TO BS 1640

## STANDARD DATA SHEET FOR TEES DN 50 TO DN 450 INCLUSIVE

### SHEET 3 – TO BE COMPLETED BY THE SELLER

9. National Grid Tender number: .....

   National Grid order/item number: .....

   Unique identification number(s): .....

   .....

   SELLERS reference number .....

10. Material grade (see table 1): 245 / 290 / 360*

11. Are the tees to be manufactured to a procedure that has been qualified to T/SP/MPQ2? YES / NO*

12. If the answer to item 11 is 'YES', give the following details of the procedure qualification:

    Date of qualification .....

    National Grid reference number .....

13. Give details of any differences between the qualified procedure and that to be used for the tees to be manufactured

    (see T/SP/MPQ2) .....

    .....

    .....

    .....

14. Give details of any weldability tests relevant to the tees to be manufactured that have been carried out since the procedure was qualified .....

    .....

    .....

    .....

15. If the answer to item 11 is 'NO' state the time required to qualify a tee in accordance with T/SP/MPQ2

    .....

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| First Issue | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By | Rev | Date | By |
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| Signed: | Date: | |
| Identification No: | Project Name: **B-Linepack+ Alpha Phase** | |
| **Delete as applicable* | Data Sheet No: **PRZ0025-DAT-0000-0209** | Sheet 3 of 3 |

# Appendix A Part 1 Data Sheet Operating & Design Conditions

## Site Name: Aberdeen ETZ

### General Requirements & Mode of Operation

| | Parameter | Requirement |
|---|---|---|
| 1 | Number of flow control valves per stream | 1 (one) |
| 2 | Number of streams | 1 (one) |
| 3 | Control (flow, pressure or both) | Flow |
| 4 | Mode of operation (tandem / series) | N/A |
| 5 | FCV positioner type (electronic or pneumatic) | Electronic |
| 6 | FCV position characteristic (if not linear) | Linear |
| 7 | FCV stroke speed requirements | Not Required |
| 8 | Actuator type (electric / pneumatic or electrohydraulic) | Electric |
| 9 | Actuator Failure Mode (Fail Open / Fail Closed or Stay Put etc.) | TBC |
| 10 | Overrides required (electronic, pneumatic or both) | Electric |
| 9 | FCV location (above or below ground) | Above Ground |
| 10 | SIL Target Requirement | N/A |
| 11 | BS4800 colour shade for FCV and actuator | TBC |
| 12 | Compression fitting type requirement (Swagelok, Waverley Brownhall Duoloc etc… | Swagelok |
| 13 | Hazardous location of FCV (zone 0, zone 1 or zone 2) | Hydrogen Zone 2 |

### Design Conditions

| | Design Parameter | Value | Unit |
|---|---|---|---|
| 1 | Design pressure | 200 | Barg |
| 2 | Maximum inlet pressure | 50 | Barg |
| 3 | Minimum inlet pressure | 30 | Barg |
| 4 | Maximum outlet pressure | 50 | Barg |
| 5 | Maximum flow (per stream) | 945 | $sm^3/hr$ |
| 6 | Minimum flow (per stream) | 426 | $sm^3/hr$ |
| 7 | Maximum design temperature | +60 | °C |
| 8 | Minimum design temperature | -20 | °C |
| 9 | Maximum gas inlet temperature | +20 | °C |

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## Flow and Pressure Conditions – Per Stream or FCV - Forward flow

| | Flow ($sm^3/hr$) | Inlet Pressure (Barg) | Outlet Pressure (Barg) | Comments |
|---|---|---|---|---|
| 1 | 945 | 50 | 30 | Maximum noise – Case 1 |
| 1a | 945 | 50 | 35 | Maximum noise – Case 2 |
| 2 | 426 | 50 | 30 | Minimum CV |
| 3 | 945 | 32 | 30 | Maximum CV – Case 1 |
| 3a | 945 | 50 | 48 | Maximum CV – Case 2 |

## Flow and Pressure Conditions – Per Stream or FCV - Reverse flow

| | Flow ($sm^3/hr$) | Inlet Pressure (Barg) | Outlet Pressure (Barg) | Comments |
|---|---|---|---|---|
| 1 | N/A | N/A | N/A | Maximum noise – Case 1 |
| 1a | N/A | N/A | N/A | Maximum noise – Case 2 |
| 2 | N/A | N/A | N/A | Minimum CV |
| 3 | N/A | N/A | N/A | Maximum CV – Case 1 |
| 3a | N/A | N/A | N/A | Maximum CV – Case 2 |

## Noise Emission - Per Stream - Forward or Reverse flow

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Preferred | 80.0 | dBA at 1m |
| 2 | Limiting | 85.0 | dBA at 1m |

## Pipework Details

| | | Outside Diameter (mm) | Nominal Bore (mm) | Wall Thickness (mm) |
|---|---|---|---|---|
| 1 | Inlet pipe work | 114.3 | 100 | 17.12 |
| 2 | Interstage pipe work (if applicable) | N/A | N/A | N/A |
| 3 | Outlet pipework | 114.3 | 100 | 17.12 |

## Additional Notes:

1) The FCV shall be suitable for 100% hydrogen

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# Appendix B Part 2 Data Sheet - Tender Return Data

## Site Name: Aberdeen ETZ

## Actuator Characteristics

### i) Pneumatic / Pneumatic / Hydraulic Actuator characteristics

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Length of stroke | | mm |
| 2 | Time to stroke fully open | | sec |
| 4 | Time to stroke fully closed | | sec |
| 5 | Power Gas Pressure | | Barg |
| 6 | Quantity for full stroke | | l |
| 7 | Emissions from the FCV, including all instrumentation fitted to and supplied with the FCV, including the positioner steady state consumption. | | $m^3$ / hr |

### ii) Electric Actuator characteristics

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Time to stroke fully open | | sec |
| 2 | Time to stroke fully closed | | sec |
| 3 | Voltage | | V |
| 4 | Power | | W |

### iii) Electro-hydraulic Actuator characteristics

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Time to stroke fully open | | sec |
| 2 | Time to stroke fully closed | | sec |
| 3 | Voltage | | V |
| 4 | Power | | W |
| **Hydraulic Fluid Details** | | | |
| 5 | Volume of oil | | l |
| 6 | Peak operating pressure | | Barg |

## FCV position indicator details

| | Manufacturer | Model |
|---|---|---|
| Primary Option | | |
| Alternative 1 | | |
| Alternative 2 | | |

Provide full technical details. Ref. No.....

## FCV Positioner details

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Recommended Vent Internal Diameter | | mm |
| 2 | Maximum Length | | mm |

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## FCV details

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Minimum FCV trim passageway dimension | | mm |
| 2 | Recommended filtration level (mesh size) for gas prior to FCV | | µm |

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# Appendix A Part 1 Data Sheet Operating & Design Conditions

## Site Name: Aberdeen ETZ

### General Requirements & Mode of Operation

| | Parameter | Requirement |
|---|---|---|
| 1 | Number of flow control valves per stream | 0 (zero)<br>3 x PCVs on stream |
| 2 | Number of streams | 1 (one) |
| 3 | Control (flow, pressure or both) | Pressure |
| 4 | Mode of operation (tandem / series) | N/A |
| 5 | FCV positioner type (electronic or pneumatic) | Electronic |
| 6 | FCV position characteristic (if not linear) | Linear |
| 7 | FCV stroke speed requirements | Not Required |
| 8 | Actuator type (electric / pneumatic or electrohydraulic) | Electric |
| 9 | Actuator Failure Mode (Fail Open / Fail Closed or Stay Put etc.) | TBC |
| 10 | Overrides required (electronic, pneumatic or both) | Electric |
| 9 | FCV location (above or below ground) | Above Ground |
| 10 | SIL Target Requirement | N/A |
| 11 | BS4800 colour shade for FCV and actuator | TBC |
| 12 | Compression fitting type requirement (Swagelok, Waverley Brownhall Duoloc etc… | Swagelok |
| 13 | Hazardous location of FCV (zone 0, zone 1 or zone 2) | Hydrogen Zone 2 |

### Design Conditions

| | Design Parameter | Value | Unit |
|---|---|---|---|
| 1 | Design pressure | 200 | Barg |
| 2 | Maximum inlet pressure | 200 | Barg |
| 3 | Minimum inlet pressure | 180 | Barg |
| 4 | Maximum outlet pressure | 50 | Barg |
| 5 | Maximum flow (per stream) | 945 | $sm^3/hr$ |
| 6 | Minimum flow (per stream) | 426 | $sm^3/hr$ |
| 7 | Maximum design temperature | +60 | °C |
| 8 | Minimum design temperature | -20 | °C |
| 9 | Maximum gas inlet temperature | +20 | °C |

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## Flow and Pressure Conditions – Per Stream or FCV - Forward flow

| | Flow ($sm^3/hr$) | Inlet Pressure (Barg) | Outlet Pressure (Barg) | Comments |
|---|---|---|---|---|
| 1 | 945 | 200 | 50 | |
| 1a | 945 | 200 | 30 | |
| 2 | 426 | 180 | 50 | |
| 3 | 945 | 200 | 70 | |
| 3a | 945 | 70 | 50 | |

## Flow and Pressure Conditions – Per Stream or FCV - Reverse flow

| | Flow ($sm^3/hr$) | Inlet Pressure (Barg) | Outlet Pressure (Barg) | Comments |
|---|---|---|---|---|
| 1 | N/A | N/A | N/A | Maximum noise – Case 1 |
| 1a | N/A | N/A | N/A | Maximum noise – Case 2 |
| 2 | N/A | N/A | N/A | Minimum CV |
| 3 | N/A | N/A | N/A | Maximum CV – Case 1 |
| 3a | N/A | N/A | N/A | Maximum CV – Case 2 |

## Noise Emission - Per Stream - Forward or Reverse flow

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Preferred | 80.0 | dBA at 1m |
| 2 | Limiting | 85.0 | dBA at 1m |

## Pipework Details

| | | Outside Diameter (mm) | Nominal Bore (mm) | Wall Thickness (mm) |
|---|---|---|---|---|
| 1 | Inlet pipe work | 114.3 | 100 | 17.12 |
| 2 | Interstage pipe work (if applicable) | N/A | N/A | N/A |
| 3 | Outlet pipework | 114.3 | 100 | 17.12 |

## Additional Notes:

1) The FCV shall be suitable for 100% hydrogen

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# Appendix B Part 2 Data Sheet - Tender Return Data

## Site Name: Aberdeen ETZ

## Actuator Characteristics

### i) Pneumatic / Pneumatic / Hydraulic Actuator characteristics

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Length of stroke | | mm |
| 2 | Time to stroke fully open | | sec |
| 4 | Time to stroke fully closed | | sec |
| 5 | Power Gas Pressure | | Barg |
| 6 | Quantity for full stroke | | l |
| 7 | Emissions from the FCV, including all instrumentation fitted to and supplied with the FCV, including the positioner steady state consumption. | | $m^3$ / hr |

### ii) Electric Actuator characteristics

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Time to stroke fully open | | sec |
| 2 | Time to stroke fully closed | | sec |
| 3 | Voltage | | V |
| 4 | Power | | W |

### iii) Electro-hydraulic Actuator characteristics

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Time to stroke fully open | | sec |
| 2 | Time to stroke fully closed | | sec |
| 3 | Voltage | | V |
| 4 | Power | | W |
| **Hydraulic Fluid Details** | | | |
| 5 | Volume of oil | | l |
| 6 | Peak operating pressure | | Barg |

## FCV position indicator details

| | Manufacturer | Model |
|---|---|---|
| Primary Option | | |
| Alternative 1 | | |
| Alternative 2 | | |

Provide full technical details. Ref. No.....

## FCV Positioner details

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Recommended Vent Internal Diameter | | mm |
| 2 | Maximum Length | | mm |

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## FCV details

| | Parameter | Value | Unit |
|---|---|---|---|
| 1 | Minimum FCV trim passageway dimension | | mm |
| 2 | Recommended filtration level (mesh size) for gas prior to FCV | | µm |

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## VALVE DATA SHEET
## SECTION 1 BUYER VALVE DATA

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ENQUIRY | 1 | B-Linepack+ | | | | Ref: | PRZ0025-DAT-0000-0305 | |
| ORDER | 2 | | | | | Date: | 22/01/25 | |
| VALVE TYPE (Please Specify as per section 5.1) | 3 | Ball Valve | | | | | | |
| SIZE | 4 | DN | | 100 | | | | |
| PRESSURE RATING | 5 | PN | | Class: | 1500 | | | |
| SERVICE | 6 | Above Ground: | ☑ | Below Ground | ☐ | | | |
| | 7 | Max / Min Temperature: | -20 C / +60 C | | | | | |
| | 8 | Max Differential pressure (bar g): | Max Class Pressure | | | | | |
| | 9 | Max. Flow rate (scmh) | | | | | | |
| END CONNECTIONS | 10 | Flanged | ☑ | Flanged & Butt welded | ☐ | | | |
| | 11 | Pupped | ☐ | Flanged & Pupped | ☐ | | | |
| | 12 | Butt welded | ☐ | | | | | |
| | 13 | Overall valve Length: | As per T/SP/V/6 | | | | | |
| | 14 | Pipe pups to be provided by BUYER: | Yes | ☐ | No | ☐ | | |
| | 15 | Flange facing: Raised Face: | ☐ | Ring joint | ☑ | | | |
| CONNECTING PIPE | 16 | Grade: | | | | | | |
| | 17 | Outside Diameter: | | | | | | |
| | 18 | Wall Thickness | | | | | | |
| DESIGN | 19 | Bore (normally Full for ball valve, Reduced for plug valve) | Full | ☑ | Reduced | ☐ | | |
| | 20 | Valve sealing action | Double block and bleed (see 3.2) | Yes | ☑ | No | ☐ | |
| | | | Double Isolation and Bleed (see 3.3) | Yes | ☐ | No | ☑ | |
| | 21 | Ball valve: seat action (see 5.1.3) | No preference | Yes | ☐ | No | ☐ | |
| | | | Both Uni Directional | Yes | ☐ | No | ☐ | |
| | | | Both Bi Directional | Yes | ☑ | No | ☐ | |
| | | | One Uni and One Bi Directional | Yes | ☐ | No | ☐ | |
| | 22 | Plug valve: pattern Regular (normally Regular) | Regular | ☐ | Venturi | ☐ | Short | ☐ |
| | 23 | Check valve: design configuration (see 5.1.4) | Type | n/a | | | | |
| | | | Pattern | n/a | | | | |
| | 24a | Fire safe (normally Yes) | Yes ☑ | No ☐ | | | | |
| | 24b | Hazardous Area Zone (see 6.1) | Zone | 2 | | | | |
| ADDITIONAL DETAILS | 25 | Handing of valve | Right Hand | ☐ | Left Hand | ☐ | | |
| | 26 | Ref for handing i.e. when view from | Flanged End | ☐ | Upstream End | ☐ | | |
| | 27 | Valve Stem Orientation | Horizontal | ☐ | Vertical | ☑ | | |
| | 28 | Valve Bore Orientation | Horizontal | ☑ | Vertical | ☐ | | |
| | 29 | Stem Extension | Required | ☐ | Not required | ☑ | | |
| | 30 | Length of Stem Extension | | | | | | |
| | 31 | Reference Dimension (see Fig. B.1) | | A ☐ | B | ☐ | | |
| | 32 | Vent Extension | Required | ☐ | Not Required | ☑ | | |
| | 33 | Drain Extension | Required | ☐ | Not Required | ☑ | | |
| | 34 | Sealant Injection (≥ DN 100) | Required | ☑ | Not Required | ☐ | | |
| | 35 | Sealant Extension | Required | ☐ | Not Required | ☑ | | |
| | 36 | Type of Welding / Vent, Drain & Sealant Extensions | | | | | | |
| | | | Screwed | ☐ | Socket Weld | ☐ | | |
| | 37 | Connection into Valve | Threaded (BSPT) | ☐ | Socket Weld | ☑ | | |
| | 38 | Vent and Drain Valves supplied by | BUYER | ☐ | Manufacturer | ☑ | | |
| | 39 | Sealant Valves Supplied by | BUYER | ☐ | Manufacturer | ☑ | | |
| | 40 | Gearbox Manual Operation | Required | ☑ | Not Required | ☐ | | |
| | 41 | Provision / Gearbox for power operation Refer to actr data sheet ref | Required Data sheet ref | ☐ | Not Required | ☐ | | |
| | 42 | Direct Mounted Power Actuator | Required | ☐ | Not Required | ☑ | | |
| | 43 | Flange Protection | Required | ☑ | Not Required | ☐ | | |
| | 44 | Locking Device | Required | ☑ | ~~Not Required~~ | ☐ | | |
| CORROSION PROTECTION | 45 | Type (To be advised) | Painting – T/SP/PA/10: | ☑ | Coating – Annex E: | ☐ | | |
| SPECIAL REQUIREMENTS | 46 | | | | | | | |

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|---|---|---|
| A | A Bradshaw-Jones | 22/01/26 |

**VALVE DATA SHEET**

**SECTION 2**

**MANUFACTURER VALVE DATA**

| | | | | | | |
|---|---|---|---|---|---|---|
| **SPECIFICATION** | **47** | | | | | |
| **MANUFACTURER'S DESIGNATION** | **48** | | | | | |
| **VALVE DESIGN / MODEL** | **49** | | | | | |
| **ATEX EQUIPMENT CATEGORY** (see 13) | **50** | | | | | |
| | | | | | | |
| **TECHNICAL DESCRIPTION** | **51** | Ball Support | Trunnion | ☐ | Floating Ball | ☐ |
| | **52** | Sealing Action | | | | |
| | **53** | Body Construction | Fully Welded | ☐ | Bolted | ☐ |
| | | | Cast | ☐ | Forged | ☐ |
| | | | | | | |
| **ACTUATOR** | **54** | Manufacturer | | | | |
| | **55** | Type | | | | |
| | | | | | | |
| **END CONNECTIONS: PUPS** | **56** | If finished pups are supplied free-issue | Length of pup required | | mm | |
| | | | Type of weld end preparation required on valve end of pipe ups | | | |
| | **57** | If pipe is supplied free-issue | Length of pipe required for pup | | mm | |
| | | | | | | |
| **VALVE CHARACTERISTICS** | **58** | End to End dimension | mm | | | |
| | **59** | Weight | Kg | | | |
| | **60** | Maximum Sealant Gun Injection Pressure | bar | | | |
| | | | | | | |
| **SPECIAL REQUIREMENTS** | **61** | | | | | |
| | | | | | | |
| **REMARKS** | Section 1 BUYER Data to be completed where blank, or altered by Manufacturer according to proposed valve details | | | | | |
| | Section 2 Manufacturer Valve Data to be completed by the Manufacturer | | | | | |
| | | | | | | |
| | All items to be completed (put --, none, or n/a where appropriate). | | | | | |
| | Both BUYER and Manufacturer to sign and date relevant section and update Datasheet issue number | | | | | |

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**VALVE DATA SHEET**
**SECTION 1 BUYER VALVE DATA**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ENQUIRY | 1 | B-Linepack+ | | | | Ref: | PRZ0025-DAT-0000-0306 | |
| ORDER | 2 | | | | | Date: | 22/01/25 | |
| VALVE TYPE (Please Specify as per section 5.1) | 3 | Plug Valve | | | | | | |
| SIZE | 4 | DN | | 100 | | | | |
| PRESSURE RATING | 5 | PN | | Class: | 1500 | | | |
| SERVICE | 6 | Above Ground: | ☑ | Below Ground | ☐ | | | |
| | 7 | Max / Min Temperature: | -20 C / +60 C | | | | | |
| | 8 | Max Differential pressure (bar g): | Max Class Pressure | | | | | |
| | 9 | Max. Flow rate (scmh) | | | | | | |
| END CONNECTIONS | 10 | Flanged | ☑ | Flanged & Butt welded | ☐ | | | |
| | 11 | Pupped | ☐ | Flanged & Pupped | ☐ | | | |
| | 12 | Butt welded | ☐ | | | | | |
| | 13 | Overall valve Length: | As per T/SP/V/6 | | | | | |
| | 14 | Pipe pups to be provided by BUYER: | Yes | ☐ | No | ☐ | | |
| | 15 | Flange facing: Raised Face: | ☐ | Ring joint | ☑ | | | |
| CONNECTING PIPE | 16 | Grade: | | | | | | |
| | 17 | Outside Diameter: | | | | | | |
| | 18 | Wall Thickness | | | | | | |
| DESIGN | 19 | Bore (normally Full for ball valve, Reduced for plug valve) | Full | ☐ | Reduced | ☑ | | |
| | 20 | Valve sealing action | Double block and bleed (see 3.2) | Yes ☐ | No ☐ | | | |
| | | | Double Isolation and Bleed (see 3.3) | Yes ☐ | No ☐ | | | |
| | 21 | Ball valve: seat action (see 5.1.3) | No preference | Yes ☐ | No ☐ | | | |
| | | | Both Uni Directional | Yes ☐ | No ☐ | | | |
| | | | Both Bi Directional | Yes ☐ | No ☐ | | | |
| | | | One Uni and One Bi Directional | Yes ☐ | No ☐ | | | |
| | 22 | Plug valve: pattern Regular (normally Regular) | Regular | ☑ | Venturi ☐ | Short ☐ | | |
| | 23 | Check valve: design configuration (see 5.1.4) | Type | n/a | | | | |
| | | | Pattern | n/a | | | | |
| | 24a | Fire safe (normally Yes) | Yes ☑ | No ☐ | | | | |
| | 24b | Hazardous Area Zone (see 6.1) | Zone | 2 | | | | |
| ADDITIONAL DETAILS | 25 | Handing of valve | Right Hand | ☐ | Left Hand | ☐ | | |
| | 26 | Ref for handing i.e. when view from | Flanged End | ☐ | Upstream End | ☐ | | |
| | 27 | Valve Stem Orientation | Horizontal | ☑ | Vertical | ☐ | | |
| | 28 | Valve Bore Orientation | Horizontal | ☐ | Vertical | ☑ | | |
| | 29 | Stem Extension | Required | ☐ | Not required | ☑ | | |
| | 30 | Length of Stem Extension | | | | | | |
| | 31 | Reference Dimension (see Fig. B.1) | | A ☐ | B ☐ | | | |
| | 32 | Vent Extension | Required | ☐ | Not Required | ☑ | | |
| | 33 | Drain Extension | Required | ☐ | Not Required | ☑ | | |
| | 34 | Sealant Injection (≥ DN 100) | Required | ☐ | Not Required | ☑ | | |
| | 35 | Sealant Extension | Required | ☐ | Not Required | ☑ | | |
| | 36 | Type of Welding / Vent, Drain & Sealant Extensions | | | | | | |
| | | | Screwed | ☐ | Socket Weld | ☐ | | |
| | 37 | Connection into Valve | Threaded (BSPT) | ☐ | Socket Weld | ☐ | | |
| | 38 | Vent and Drain Valves supplied by | BUYER | ☐ | Manufacturer | ☐ | | |
| | 39 | Sealant Valves Supplied by | BUYER | ☐ | Manufacturer | ☐ | | |
| | 40 | Gearbox Manual Operation | Required | ☐ | Not Required | ☐ | | |
| | 41 | Provision / Gearbox for power operation Refer to actr data sheet ref | Required Data sheet ref | ☐ | Not Required | ☑ | | |
| | 42 | Direct Mounted Power Actuator | Required | ☐ | Not Required | ☑ | | |
| | 43 | Flange Protection | Required | ☑ | Not Required | ☐ | | |
| | 44 | Locking Device | Required | ☑ | ~~Not Required~~ | ☐ | | |
| CORROSION PROTECTION | 45 | Type (To be advised) | Painting – T/SP/PA/10: | ☑ | Coating – Annex E: | ☐ | | |
| SPECIAL REQUIREMENTS | 46 | Lever Operated | | | | | | |

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|---|---|---|
| A | A Bradshaw-Jones | 22/01/26 |

**VALVE DATA SHEET**

**SECTION 2**

**MANUFACTURER VALVE DATA**

| | | | | | | |
|---|---|---|---|---|---|---|
| **SPECIFICATION** | **47** | | | | | |
| **MANUFACTURER'S DESIGNATION** | **48** | | | | | |
| **VALVE DESIGN / MODEL** | **49** | | | | | |
| **ATEX EQUIPMENT CATEGORY** (see 13) | **50** | | | | | |
| | | | | | | |
| **TECHNICAL DESCRIPTION** | **51** | Ball Support | Trunnion | ☐ | Floating Ball | ☐ |
| | **52** | Sealing Action | | | | |
| | **53** | Body Construction | Fully Welded | ☐ | Bolted | ☐ |
| | | | Cast | ☐ | Forged | ☐ |
| | | | | | | |
| **ACTUATOR** | **54** | Manufacturer | | | | |
| | **55** | Type | | | | |
| | | | | | | |
| **END CONNECTIONS: PUPS** | **56** | If finished pups are supplied free-issue | Length of pup required | | mm | |
| | | | Type of weld end preparation required on valve end of pipe ups | | | |
| | **57** | If pipe is supplied free-issue | Length of pipe required for pup | | mm | |
| | | | | | | |
| **VALVE CHARACTERISTICS** | **58** | End to End dimension | mm | | | |
| | **59** | Weight | Kg | | | |
| | **60** | Maximum Sealant Gun Injection Pressure | bar | | | |
| | | | | | | |
| **SPECIAL REQUIREMENTS** | **61** | | | | | |
| | | | | | | |
| **REMARKS** | Section 1 BUYER Data to be completed where blank, or altered by Manufacturer according to proposed valve details | | | | | |
| | Section 2 Manufacturer Valve Data to be completed by the Manufacturer | | | | | |
| | | | | | | |
| | All items to be completed (put --, none, or n/a where appropriate). | | | | | |
| | Both BUYER and Manufacturer to sign and date relevant section and update Datasheet issue number | | | | | |

| **ISSUE** | **BY** | **DATED** |
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# Standard to Volumetric Flow Rate Calculation (with Mass Flow)

**Project:** PRZ0025
**Site:** Technical Demonstrator
**Calc. No.:** PRZ0025-CAL-0000-0001
**Revision:** 1

## Standard and Volumetric Flows

$$Q_0 = \frac{PT_0Z_0Q}{P_0TZ}$$

$$Q = \frac{P_0TZQ_0}{PT_0Z_0}$$

| | | std | actual |
|---|---|---|---|
| Q | Flow Rate | scmh | m3h |
| P | Pressure | bar | bar |
| T | Temperature | deg C | deg C |
| Z | Compressibility | - | - |

Standard Conditions for UK Gas Industry

| | | | |
|---|---|---|---|
| $T_0$ | 15 | deg C | 288.2 |
| $P_0$ | 1.01325 | bar | 1E+05 |
| $Z_0$ (NG) | 0.9978 | | |
| $Z_0$ (h2) | 1.0006 | | |

| | | | | | |
|---|---|---|---|---|---|
| $Q_0$ = | 409.51 | scm/h | | | |
| Q = | | m3/h | | | |
| P = | 30 | barg | 31.01325 | bara | 3101325 Pa |
| T = | 10 | deg C | 283.15 | K | |
| Gas Type | Hydrogen | | | | |
| | | | NG | H2 | |
| Z = | 1.0189 | | 0.8798 | 1.018858783 | |

*Z Factor Approximated from Empirical Data from NIST (2023), valid 0 - 60 deg, up to 100 bar*

| | | NG | H2 |
|---|---|---|---|
| Standard Flow Rate, $Q_0$ | 409.51 scm/h | | |
| Volumetric Flow Rate, Q | 13.387062 m3/h | 11.59237026 | 13.38706219 |

## Gas Velocity in Pipe

| | | | | |
|---|---|---|---|---|
| OD = | 114.3 | Pipe Outer Diameter (mm) | | |
| WT = | 17.12 | Nominal Wall Thickness (mm) | | |
| TOL = | 15 | Over Thickness Tolerance | mm | % |
| TOL TYPE = | % | Tolerance Type (mm or %) | 32.12 | 19.688 |
| | | | 0.05006 | 0.074924 |
| Ø = | 0.0749 | internal diameter (m) | | |
| A = | 0.0044 | cross sectional area ($m^2$) | | |

| | |
|---|---|
| Velocity, V | 0.84 m/s |

**Prepared by:** Adam Bradshaw-Jones **Checked by:** N Horan-Martin **Date:** 15/01/2026

**Mass Flow Rate**

$$PV = ZnRT \qquad m = nM$$

$$m = \frac{PVM}{ZRT}$$

| | Natural Gas* | Hydrogen |
|---|---|---|
| M (kg/mole) | 0.01718 | 0.00201588 |
| R (J/mol K) | 8.314462618 | |

**Mean Bacton Gas*

| | | |
|---|---|---|
| Qm = | 34.89 | kg /h |
| | 0.00969 | kg /s |

Std 298.2002305 34.89253256
Act 298.2002305 34.89253256

Note: Use goal seek to determine flow rate to achieve desired mass flow.

Desired mass flow

Qm= 0.010648148 kg/s

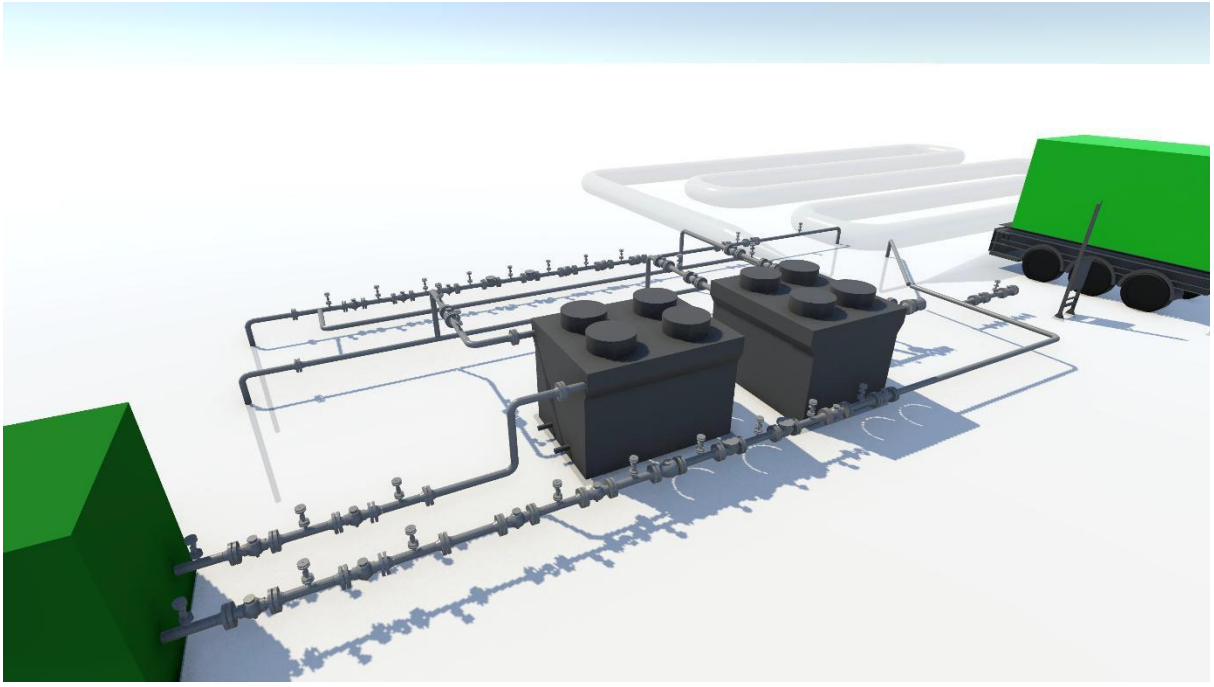
Click to calculate Std Volume flow

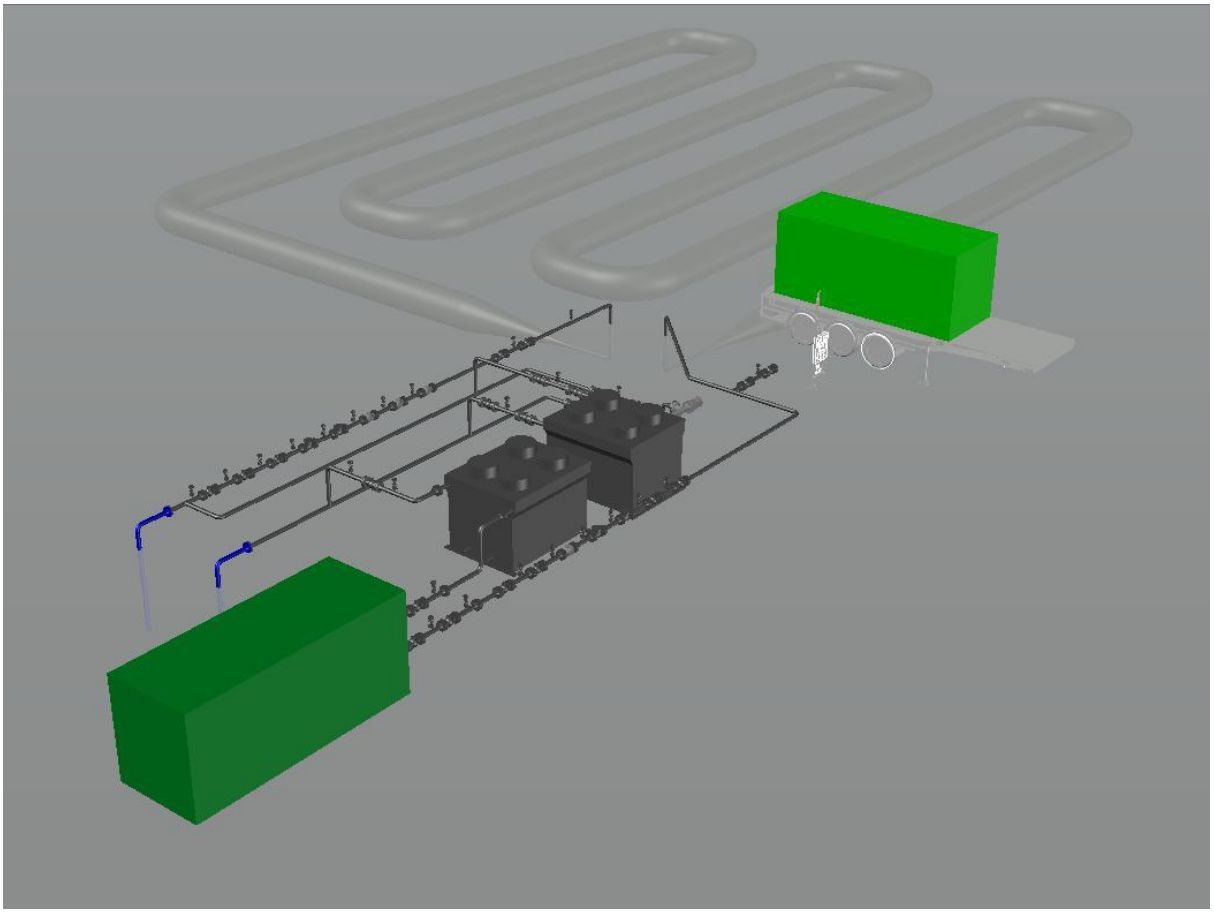
**Prepared by:** Adam Bradshaw-Jones **Checked by:** N Horan-Martin **Date:** 15/01/2026

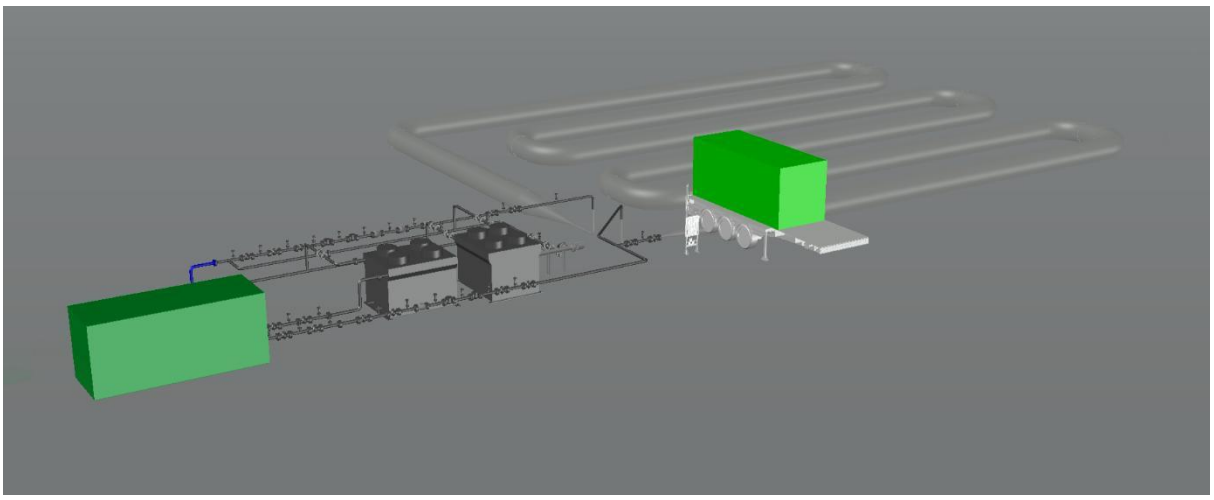
# Appendix C Premtech Drawings

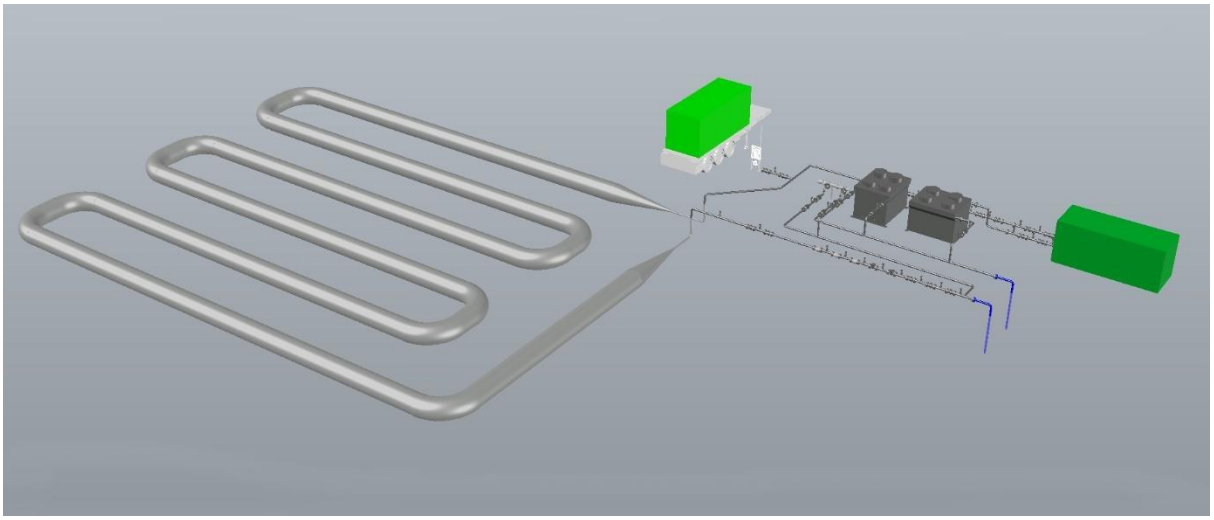
| Document Title | Document Number | Included (Y/N) |
|---|---|---|
| Process Flow and Design Battery Limits Diagram | PRZ0025-ELD-0000-0001 | N |
| Engineering Line Diagram | PRZ0025-ELD-0000-0002 | N |
| General Arrangement Overall Site Arrangement | PRZ0025-GEN-0000-0010 | N |
| General Arrangement Local Arrangement | PRZ0025-GEN-0000-0011 | N |
| Hazardous Area Drawing | PRZ0025-HAZ-0000-0030 | N |
| Material Take Off | PRZ0025-MTO-0000-0040 | N |
| Earthing Diagram | PRZ0025-DIA-0000-2100 | N |
| Block Cable Diagram | PRZ0025-DIA-0000-2200 | N |
| Overall Block Diagram | PRZ0025-DIA-0000-4200 | N |

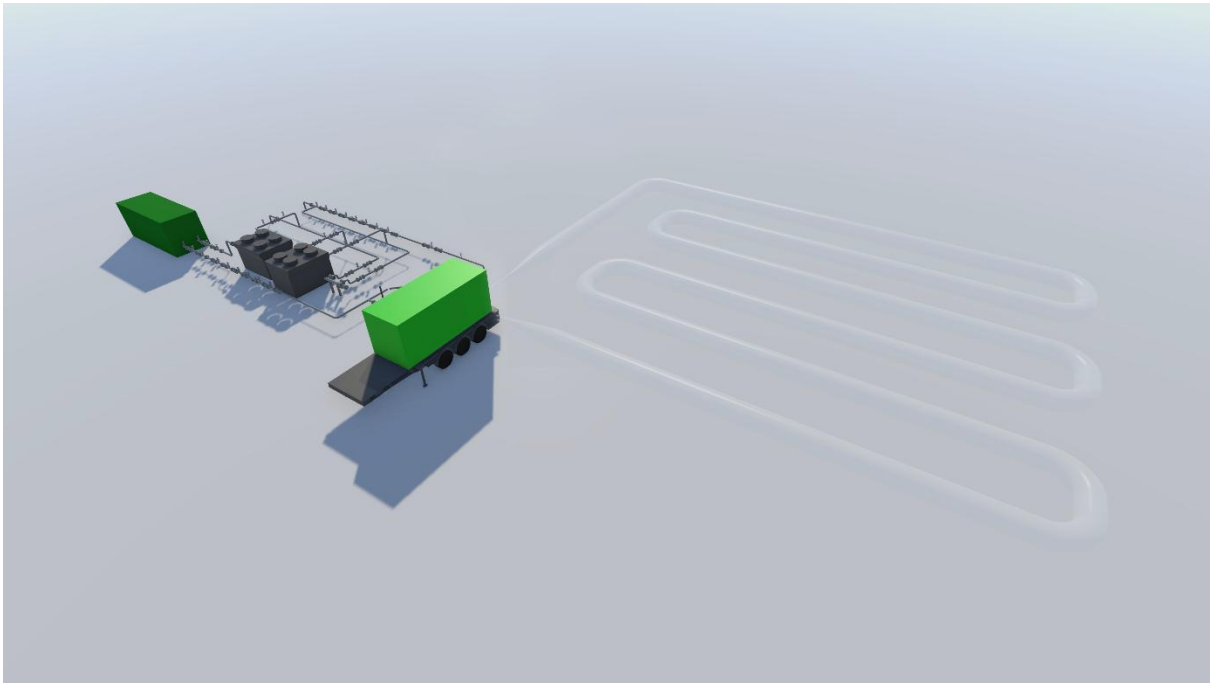
# Appendix D Proposed Site Renders











National Gas Transmission

# STRATEGIC INNOVATION FUND (SIF) ALPHA B- LINEPACK HYDROGEN STORAGE INNOVATION PROJECT

## Environment and Planning Site Options Appraisal

UK0042588.3685
OCTOBER 2025

CONFIDENTIAL

National Gas Transmission

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**TYPE OF DOCUMENT (1) CONFIDENTIAL**

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## Environment and Planning Site Options Appraisal

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# QUALITY CONTROL

| Issue/revision | Revision 1 | Revision 2 | Revision 3 |
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QUALITY CONTROL I

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# 1. INTRODUCTION

## 1.1. BACKGROUND

1.1.1. WSP UK Ltd. (WSP) has been commissioned by National Gas Transmission plc (NGT) (the 'Client') to prepare an Environmental and Planning Site Options Appraisal to support the selection of appropriate sites for hydrogen storage facilities (hereafter referred to as the 'Proposed Development'). A description of the Proposed Development is provided within Section 2 of this report.

1.1.2. There are fourteen potential hydrogen storage facility site options (hereafter known as 'Site Options), which are described within Section 4 of this report.

1.1.3. A Site Locations Plan is also attached at **Appendix A**.

## 1.2. PURPOSE OF THIS DOCUMENT

1.2.1. The purpose of this report is to identify environmental and planning constraints and opportunities at each of the fourteen Site Options to inform the selection of five commercial sites and one demonstrator site for the Proposed Development.

1.2.2. The demonstrator site will serve as a pilot installation of the Proposed Development while the commercial sites will be developed as full-scale operational facilities considering scalability to meet future requirements. NGT is now working in collaboration with WSP, Premtech and Gravitricity to identify one site location for a demonstrator site for the Proposed Development and five potential locations for commercial sites for the Proposed Development.

1.2.3. This report collates existing information from desktop sources to identify environmental risks or features relevant to development, and to determine where further information, specialist studies or surveys may be required to further understand and manage those risks. The findings are summarised within the main body of this Report, and presented in full in the Options Appraisal Summary Tables at **Appendix B.**

## 1.3. SCOPE

### ENVIRONMENT

1.3.1. The environmental elements of this report comprise of a desk-based study using readily available data from a variety of online sources covering the following environmental topics:

- Air Quality;
- Cultural Heritage and Archaeology;
- Ecology and Arboriculture;
- Landscape and Visual;
- Geology and Soils;
- Noise and Vibration;
- People and Communities (Socio-economic); and
- Water, Drainage and Flood Risk.

## PLANNING

1.3.2. The planning elements of this report are based on the desk-top analysis study available from online planning sources including the respective Local Planning Authorities (LPA), Magic Maps, and Planning system sources[1]. For the purposes of this report, the planning appraisal is based on the following parameters:

- Planning Policy Provisions;
- Site Allocations;
- Article 4 Directions;
- Planning History Searches; and
- Hazardous Substances Consent.

[1] https://www.gov.uk/

# 2. PROJECT DESCRIPTION

## 2.1. PROJECT BACKGROUND

2.1.1. The Office of Gas and Electricity Markets (OFGEM) Strategic Innovation Fund (SIF) is a £450 million initiative launched in 2021 by the UK's energy regulator, Ofgem, in partnership with Innovate UK. The SIF aims to help transform gas and electricity networks for a low-carbon future. It funds projects that could speed up the transition to net zero at the lowest cost to the consumer as part of the RIIO-2 price controls[2].

2.1.2. National Gas Transmission has identified a minimum capacity requirement of 1.74TWh for distributed “Linepack+” hydrogen supplementation by 2040 for Project Union (~2000km), which is the planned 100% hydrogen pipeline for the UK. National Gas has investigated the feasibility of intermediate scale geological hydrogen storage solutions to be deployed to supplement Linepack in a hydrogen transmission system. Due to lower volumetric energy density of hydrogen, the energy content in 1km of Linepack is only 1/3 of that of natural gas. The amount of energy able to be stored by Linepacking in the future may potentially decrease with the addition of blended or 100% hydrogen[3]. As part of the feasibility investigations, OFGEM SIF with National Gas Transmission and Scottish Gas Networks plc (SGN) have identified $H_2$FlexiStore as the preferred technology to achieve requirements for switching to $H_2$ and supplement the loss in linepack capacity we will see with Hydrogen transmission in future.

2.1.3. National Gas are now undertaking an optioneering study for smaller, intermediate scale storage sites for purpose built geological storage solutions to supplement linepack capacity and provide system flexibility and network optimisation (‘Proposed Development’).

2.1.4. The opportunity to utilise existing pipelines for renewable energy storage through hydrogen is invaluable in supporting the 2050 Net Zero Target. Linepack increases the volume of storage that in turn reduces our dependency on fossil fuels and emissions from underground storage are greatly decreased in comparison to above ground options.

## 2.2. TECHNICAL DESCRIPTION OF $H_2$FLEXISTORE

2.2.1. $H_2$FlexiStore, developed by UK based Gravitricity, is developing lined rock shafts for storage of gaseous hydrogen. This is state-of-the-art technology for hydrogen storage, with the potential to be deployed rapidly and at scale, depending on land and geological suitability, across the entire repurposed transmission system for hydrogen. $H_2$FlexiStore aims to be the world’s first in demonstrating lined rock shaft storage of hydrogen for Linepack supplementation in a 100% hydrogen transmission network to improve system resilience and enable energy ecosystem optimisation opportunities across both electricity and gas networks.

[2] Ofgem (2025). *Strategic Innovation Fund (SIF)*. Ofgem. Available at: https://www.ofgem.gov.uk/strategic-innovation-fund-sif

[3] Energy Networks Association (2024). *B-Linepack+ (project reference 10102109)*. Smarter Networks Portal. Available at: https://smarter.energynetworks.org/projects/10102109/

2.2.2. $H_2$FlexiStore is a modular hydrogen storage system, engineered to deliver a reliable and flexible hydrogen supply for the hydrogen economy. Each system is installed in a new subsurface shaft. The storage vessel is composed of a multi-layered liner which interacts with the surrounding geology to securely store large quantities of hydrogen within the subsurface shaft. It is engineered to be installed across a range of geologies and is rapidly deployable and enables customers to accelerate their decarbonisation timelines.

2.2.3. Some of the significant advantages of $H_2$FlexiStore are as follows:

- Provides a significant reduction in storage costs compared to conventional above-ground hydrogen storage methods for equivalent storage capacities;
- Achieves a substantial reduction in system footprint, which may serve as a key factor in project viability and site selection;
- The system architecture supports scalable deployment to meet a broad range of hydrogen storage demands;
- Geologically versatile, as it is not constrained by the presence of hard rock formations;
- Below-ground placement inherently shields the system from surface fire, explosion risks, and accidental plant collisions;
- Design reduces the number of potential leak sources and provides inherent containment to mitigate the impact of minor leaks;
- Operationally simple;
- Standard installation procedures can be adapted for LRS installation; and
- Compatible with conventional topside equipment, facilitating seamless integration.

## 2.3. PROPOSED DEVELOPMENT DESCRIPTION

### OPERATION OF THE PROPOSED DEVELOPMENT

2.3.1. The Proposed Development would involve the underground storage of hydrogen within a lining system, as shown on **Figures 2-1** and **2-2** below. The stored hydrogen would be connected to the existing pipeline to constrain and store hydrogen.

**Figure 2-1− Hydrogen Storage System- $H_2$Flexistore**

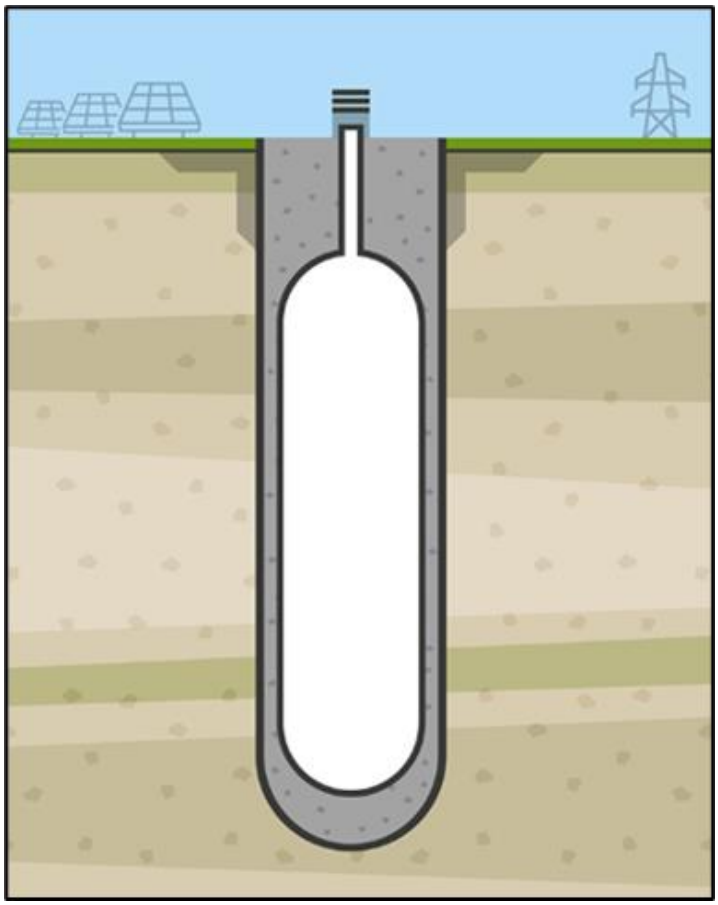
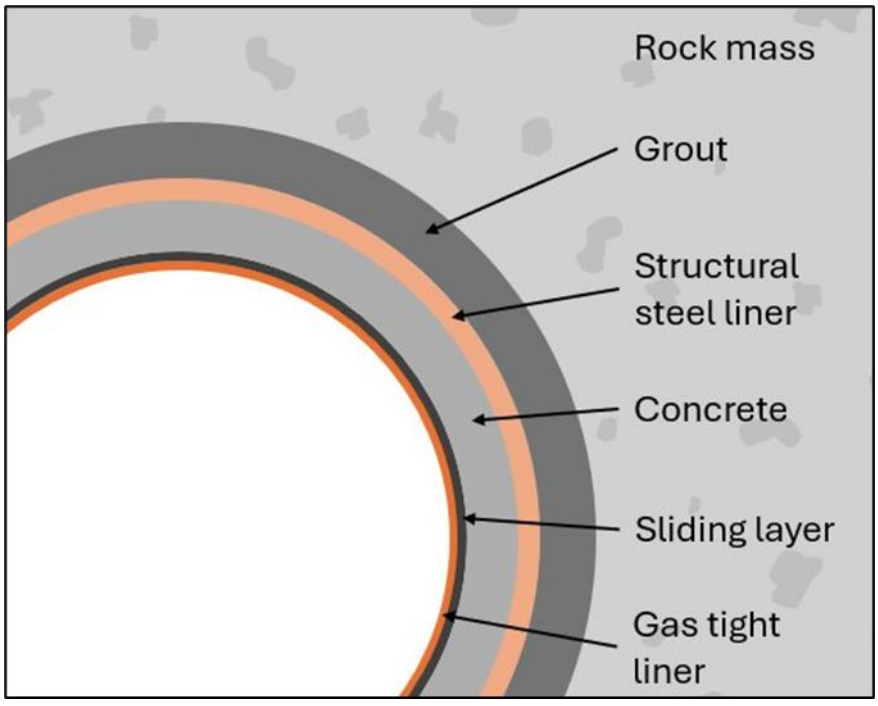


**Figure 2-2− Hydrogen-lined Rock Shafts**



2.3.2. The Proposed Development would include one Above Ground Installation (AGI), which is expected to include process equipment such as compressors, heaters, coolers, and piping, alongside welfare and office facilities housed in portacabins or similar structures. The AGI will be situated on a concrete slab above the shaft, with access roads surrounding the site to facilitate vehicle movement between different areas. The proposed layout currently requires a footprint of approximately 60.0m x 60.0m.

2.3.3. Eleven commercial sites, two Site Options that could be a commercial site or demonstrator site, and one demonstrator site have been identified by National Gas Transmission for appraisal, which are described within **Section 5** of this report. The demonstrator site will serve as a pilot installation of the hydrogen storage facility while the commercial sites will be developed as a full-scale operational facility considering scalability to meet future requirements. NGT is now working in collaboration with WSP, Premtech and Gravitricity to identify one site location for a demonstrator site for the Proposed Development and five potential locations for commercial sites for the Proposed Development.

2.3.4. The demonstrator site will be installed at first, where testing will be commenced before construction and operation of the commercial sites. The approximate parameters for the demonstrator site and commercial site are provided in **Table 2-1** below.

**Table 2.1: Parameters of Demonstrator and Commercial Sites**

| Parameters | Sites | |
|---|---|---|
| | Demonstrator Site | Commercial Site |
| Storage Capacity (in Tonnes) | 1 | 65 |
| Diameter of Shaft (in m) | 2-3 | 6.5 |
| Depth of Shaft (in m) | 100 | 300 |

## TEMPORARY CONSTRUCTION

2.3.5. The hydrogen storage facility would require approximately 11 hectares for construction laydown including drilling rigs, and associated equipment to be installed within the land during construction activity. It would be constructed via shaft sinking wherein each system will be installed in a subsurface shaft. A vertical shaft/vessel will be constructed to attain underground access. The vessel is composed of a multi-layered liner which interacts with the surrounding geology to securely store large quantities of hydrogen. The process of repurposing existing pipelines would likely to involve the removal and replacement of defective sections of pipeline.

# 3. DEVELOPMENT LOCATIONS

## 3.1. PROPOSED DEVELOPMENT AND SURROUNDS

3.1.1. The Site Options are located in Aberdeen in Scotland, and in the north and eastern region of England. The locations of each of the fourteen Site Options for the Proposed Development are described below in **Table 3-1** and are shown on the Site Locations Plan in **Appendix A**.

**Table 3-1: Description of the Storage Facility Site Options**

| Site Options | Site Type | Description and Location |
|---|---|---|
| 1 | Commercial and/or Demonstrator | Site Option 1 is located on land lying to the north of Wolviston Back Lane, Billingham, within an industrial (gas compression) facility. Site Option 1 is a small parcel surrounded by Cowpen Bewley Woodland Country Park. |
| 2 | Commercial | Site Option 2 is located on land lying to the west of Sandy Leas Lane, Stockton-on-Tees, within an industrial (gas compression) facility. Site Option 2 is located adjacent to deciduous woodland parcels to the south. |
| 3 | Commercial | Site Option 3 is located within BP CATS Gas Terminal, Seal Sands, North Yorkshire. Site Option 3 sits within an existing industrial facility and the River Tees is located approximately 1.9km east of Site Option 3. |
| 4 | Commercial | Site Option 4 is located on land on the east side of East Marsh Road, Goxhill within an industrial (gas compression) facility. Site Option 4 is surrounded by agricultural fields and is located approximately 1km east from the River Humber. |
| 5 | Commercial | Site Option 5 is located on land to the west of Caistor Lane, Walesby, Lincolnshire within an industrial (gas compression) facility. |
| 6 | Commercial | Site Option 6 is located on land on the west side of Melton Road, Shangton, Leicestershire within an industrial (gas compression) facility. |
| 7 | Commercial | Site Option 7 is located on land within an industrial (gas compression) facility south of the A64, east of Tadcaster, North Yorkshire. Site Option 7 is bordered by mature trees and is surrounded by agricultural land. |

| | | |
|---|---|---|
| 8 | Commercial | Site Option 8 is located within an industrial (gas compression) facility surrounded by agricultural areas within a rural setting adjacent to Mablethorpe, Lincolnshire. The North Sea is located approximately 470m to the east of Site Option 8. |
| 9 | Commercial | Site Option 9 is located on land within Hatton Compressor Station, within Hatton, Lincolnshire. Site Option 9 is adjacent to the north of the A158 and is surrounded by agricultural fields. |
| 10 | Commercial | Site Option 10 is located on land within Burley Bank gas offtake site, Burley Bank Road, Harrogate, North Yorkshire. A drain located adjacent to Site Option 10 flows into the Saltergate Beck river/watercourse. |
| 11 | Commercial | Site Option 11 is located on land within Thrintoft Gas Offtake Site, Myers Lane, Northallerton, North Yorkshire. Site Option 11 is bordered by mature trees and is surrounded by agricultural fields. |
| 12 | Demonstrator | Site Option 12 is located on land near to the Coast Road, in Altens, Aberdeen. The North Sea is located to the southeast of Site Option 12 with the Alterns Industrial Estate located to the west and south. |
| 13 | Commercial | Site Option 13 is located on land at the former Shell Tullos Complex in Altens in southeast Aberden. A parcel of Ancient Woodland, Ness Farm Landfill and the Tullos Hill Local Nature Conservation Site are located adjacent to Site Option 13 to the east. |
| 14 | Commercial and/or Demonstrator | Site Option 14 is located on land lying to the south of B1275 Belasis Ave, Billingham. Site Option 14 is located in the Haverton Hill industrial area, and bordered by fields to the north and the Tees and Weardale Railway to the south. |

# 4. PLANNING

## 4.1. INTRODUCTION

The purpose of this section is to undertake a desk study review to identify applicable planning policy and existing site allocations, article 4 directions, planning history and potential Hazardous Substances Consents (HSC) requirements (the 'constraints'). Analysis has been undertaken with regard to these constraints and suggests potential mitigation measures.

## 4.2. METHODOLOGY

4.2.1. A Red / Amber / Green (RAG) system has been used to assist with comparison of potential planning and consenting impacts for each proposed Site Option.

4.2.2. **Table 4-1** shows the three categories and methodology used to determine the risk rating for each subtopic, which was used within the Options Appraisal Summary Tables (OASTs) for each of the proposed Site Options, within **Appendix B** of this report.

**Table 4-1: RAG Rating Methodology**

| RAG Rating | |
|---|---|
| High Risk (Red) | Significant features that could severely impact project feasibility. |
| Moderate Risk (Amber) | Moderate features that require careful consideration and mitigation. |
| Low Risk (Green) | Minor or negligible features with little to no impact on project feasibility. |

4.2.3. Professional judgement was used to determine the potential impacts from the Proposed Development on each constraint. Consideration was given to the risks, nature, and opportunities, and from here, the likely outcomes were noted and applicable mitigation outlined.

4.2.4. For example, important areas for cultural heritage or landscape are considered a high consenting risk as planning policy states that such development proposals are generally unacceptable and will not achieve planning permission. In order to achieve consent any development would need to either demonstrate that mitigation can be implemented that addresses the negative effect or make a planning argument justifying the deviation from policy.

## 4.3. SUMMARY OF PLANNING APPRAISAL

4.3.1. The following section summarises the key planning and consenting elements of the initial desktop study for each Site Option which has been presented in the individual OASTs. The OASTs contain a detailed discussion of all planning risks and opportunities and are located at **Appendix B**.

### DEMONSTRATOR SITES

#### Site Option 1

4.3.2. An analysis of planning policy for Site Option 1 indicates that whilst there is strong policy support for low carbon energy development at a national, strategic and local level there are significant consenting challenges due to the presence of the Cowpen Belwey Woodland Country Park LNR

that surrounds Site Option 1 which conflicts with Stockon-on-Tees Local Plan (2019) policies SD5, ENV5, ENV6 and ENV7. The presence of the existing NGT gas site does indicate that industrial development in this otherwise rural and forested location can be supported. The Proposed Development would necessitate a laydown area for construction that would require felling of deciduous trees within the LNR and would be extremely challenging to mitigate in consenting terms.

4.3.3. On that basis the overall planning risk is considered to be **high**. Further details are provided in Table 2 of the Site Option 1 OAST within **Appendix B**.

**Site Option 12**

4.3.4. Site Option 12 is specifically allocated by Aberdeen City Council (ACC) for energy related development under local plan allocation OP61. Allocation OP61 supports innovative solutions that align with the wider Aberdeen Energy Transition Zone (ETZ) strategy. Furthermore, the site benefits from an existing planning permission in principle (PPP) – re: **231371/PPP** which establishes the principle of energy/industrial development on site. Whilst there are issues around consenting in relation to the nearby road and rail it is anticipated that these issues can be mitigated via stakeholder engagement with the relevant parties, namely the local authority and Network Rail.

4.3.5. On that basis the overall planning impact is considered to be **low**. Further details are provided in Table 2 of the Site Option 12 OAST within **Appendix B**.

**Site Option 14**

4.3.6. Hydrogen-related development at Site Option 14 is supported by national and local planning policies. Due to the wider planning history supporting low carbon energy development in the wider industrial area, including several Development Consent Orders (DCOs) relating to hydrogen and CO2, it is clear that the local authority are likely to view Site Option 14 favourably. The development area is itself located on an area of open green space with some demolished hardstanding, within a wider industrial area used for both heavy and light industrial uses such as food processing and waste recycling, indicating the suitability of the site.

4.3.7. There is a minor consenting risk regarding the location of Site Option 14 adjacent to an operational railway. Stakeholder engagement with Network Rail will be required to ascertain what geological safeguarding is necessary for railway safety but this is not considered a major concern as this can be dealt with via engineering design.

4.3.8. On that basis the overall planning risk is considered to be **low**. Further details are provided in Table 2 of the Site Option 14 OAST within **Appendix B**.

**COMMERCIAL SITES**

**Site Option 1**

4.3.9. The summary for Site Option 1 is included above.

**Site Option 2**

4.3.10. Site Option 2 is located in a rural location on land that may meet the threshold for Best and Most Versatile (BMV) agricultural land which is a risk in planning terms for which further assessment would be required. In addition, there is no history of similar industrial development in the vicinity that would support the principle of this form of development of Site Option 2. Furthermore, there are potential ecological and heritage impacts present in the form of the Sandy Leas Road Verge

Local Wildlife Site (LWS) and the Larberry Pastures Settlement Site Scheduled Monument, both located in close proximity to Site Option 2.

4.3.11. Whilst national and local policy in general does support the development, the issues of woodland heritage and potential BMV agricultural land mean there are consenting risks present at Site Option 2. Based on the above the consenting risk is considered to be moderate until engagement with the local authority is undertaken to ascertain their views on BMV agricultural land, ecology and heritage issues.

4.3.12. On the above basis the overall planning impact is considered to be **moderate**. Further details are provided in Table 2 of the Site Option 2 OAST within **Appendix B**.

**Site Option 3**

4.3.13. Site Option 3 is located adjacent to the 'Specialist Employment' land allocation in the Stockton-on-Tees Local Plan. Whilst Site Option 3 itself is not designated for specialist employment use it is clear that there is policy support for hazardous installations such as liquid and gas processing, carbon capture and storage (CCS) and biofuel manufacturing within the wider 'existing' industrial area. This pattern of heavy industry use is further supported by numerous planning applications, including DCOs for hydrogen, CCS and aviation fuel type projects. It should be noted that due to these numerous developments the cumulative risk for Hazardous Substances Consent is higher at Site Option 3 than elsewhere, but this is not deemed a major risk provided appropriate safety mitigation is implemented.

4.3.14. On the above basis the overall planning impact is considered to be **low**. Further details are provided in Table 2 of the Site Option 3 OAST within **Appendix B**.

**Site Option 4**

4.3.15. Site Option 4 is broadly supported at national, strategic, and local levels, particularly for renewable energy objectives. However, the location of Site Option 4 within an area designated as a Flood Zone 2/3 (a) tidal requires that a sequential flood test be undertaken as part of any planning application. Justifying the selection of Site Option 4 through the sequential flood test may be challenging when the Site Options Appraisal exercise has revealed that there are other site options which are more suitable from a flood risk perspective. Furthermore, it is notable that the surrounding land use is primarily agricultural with no history of similar development being identified in the planning application search, indicating that industrial uses may be unlikely to be supported at a local level.

4.3.16. On the basis of the above, particularly the flood risk sequential test requirement, the overall planning risk is deemed to be **high**. Further details are provided in Table 2 of the Site Option 4 OAST within **Appendix B**.

**Site Option 5**

4.3.17. Site Option 5 has strong 'in principle' support from both national and local planning policies. However, the site is located within the Lincolnshire Wolds National Landscape which creates a degree of consenting risk. The associated risks would likely be reduced by ensuring that the relevant specialist surveys, stakeholder engagement, and adequate mitigation measures are proposed as a part of any forthcoming planning application.

4.3.18. On the basis of the above the overall planning risk is considered to be **moderate**. Further details are provided in Table 2 of the Site Option 5 OAST within **Appendix B**.

**Site Option 6**

4.3.19. Site Option 6 aligns well with national and strategic policy objectives, particularly those relating to supporting renewable energy and climate resilience. While generally consistent with the National Planning and Policy Framework (NPPF) and Harborough District Local Plan Policy CC2 – Renewable Energy Generation, site-specific constraints linked to Local Plan policy GI5 – Biodiversity and Geodiversity and the location of the Proposed Development within the Kilby Foxton Canal SSSI Impact Risk Zone highlight the need for additional assessments to ensure policy compliance but such assessments are not expected to be unduly onerous. However, Site Option 6 is located in a rural location on land that classed as BMV agricultural land which is a risk in planning terms, and as such further assessment and consultation is required with the agricultural/lands section of the LPA

4.3.20. On that basis the overall planning risk is considered to be **low**. Further details are provided in Table 2 of the Site Option 6 OAST within **Appendix B**.

**Site Option 7**

4.3.21. Site Option 7 is supported by policies promoting renewable energy, climate change and low carbon policies but faces a moderate consenting risk due to conflicts with Green Belt, Mineral, Agricultural Land and Groundwater Safeguarding policies.

4.3.22. It is important that Site Option 7 provides sufficient supporting information to demonstrate that the Proposed Development would be appropriate within the Green Belt and not impact its openness in order to comply with Policies B2 and GB4 of the 2006 Selby Local Plan and 2013 Selby Core Strategy. As such further green belt assessments and mitigation will be essential to ensure compliance and reduce risk.

4.3.23. Given that Site Option 7 is located on Grade 2 Agricultural land, the Proposed Development would also be required to set out why steering the development to areas of a lower agricultural land value is not possible in line with Policy SP18 – Protecting and Enhancing the Natural Environment of the Core Strategy.

4.3.24. As Site Option 7 is in the Limestone Safeguard area and Building Stone Safeguard Area, -within the Shallow Safeguard Area the Proposed Development would be required to address the requirements of Policy SO2: Developments Proposed within-Safeguarded Surface Mineral Resource areas of the North Yorkshire Minerals and Waste Joint Plan.

4.3.25. Finally, due to the proximity of the Battle of Townton Historic Battlefield 1.7km to the south west of the site there are historic environment consenting challenges to consider.

4.3.26. Based on the above the overall planning risk is considered to be **moderate**. Further details are provided in Table 2 of the Site Option 7 OAST within **Appendix B**.

**Site Option 8**

4.3.27. Site Option 8 is supported at an overarching level both within the NPPF and the East Lindsey District Local Plan: Core Strategy (2018). However, significant consenting challenges exist due to the location of the site within Flood Zone 3a which requires the sequential flood test to be undertaken as part of any planning application. Justifying the selection of Site Option 8 through the

sequential flood test may be challenging when the Site Options Appraisal exercise has revealed that there are other site options which are more suitable. In addition, Site Option 8 is located adjacent to the Saltfleetby-Theddlethorpe Dunes and Gibraltar Point SAC, Humber Estuary SPA and Ramsar resulting in ecological consenting challenges.

4.3.28. On that basis the planning risk is considered to be **high**. Further details are provided in Table 8 of the Site Option 1 OAST within **Appendix B**.

**Site Option 9**

4.3.29. Site Option 9 is broadly supported in planning terms at both the national and local level. Whilst there are some minor policy conflicts with the East Lindsey District Local Plan: Core Strategy (2018) relating to the historic environment and ecology these are seen as low risk provided sufficient environmental mitigation can be provided.

4.3.30. There is no applicable planning history or allocations on the site but the location of the existing compressor station immediately adjacent to the Proposed Development area indicates that the principal of gas related industrial development has previously been supported in this otherwise agricultural area.

4.3.31. On the basis of the above the overall planning risk to Site Option 9 is considered to be **low**. Further details are provided in Table 2 of the Site Option 9 OAST within **Appendix B**.

**Site Option 10**

4.3.32. Site Option 10 is broadly supported by national and local planning policies. Whilst development in rural areas can typically be more challenging than in urban areas due to planning policy, at this location it is anticipated that the existing Gas Offtake site sets a precedent for such industrial development being acceptable. The low agricultural land value of Grade 5further supports this approach, as it is unlikely that any policy conflicts would arise regarding the loss of agricultural land.

4.3.33. It should be noted that Site Option 10 is located in land that forms part of the “Safeguarded Surface Mineral Resource Area” designation under Policy S02 of the Minerals and Waste Joint Plan and therefore there is a potential policy compliance issue. However, it is considered that this can be mitigated through further assessment, provision of a Mineral Resource Assessment with any future planning application and early engagement with the local authority.

4.3.34. Overall, the planning risk for Site Option 10 is considered to be l**ow**. Further details are provided in Table 2 of the Site Option 10 OAST within **Appendix B**.

**Site Option 11**

4.3.35. Option 11 is located in open countryside adjacent to the existing Thrintoff gas compressor site. Whilst the Site Option 11 is located on high value agricultural land it is unlikely that this will be a major issue in planning terms as the development site could be justified based on the need to be located adjacent to the

4.3.1. It should also be noted that Site Option 11 is located within a pipeline consultation zone. However, this may in fact be beneficial, rather than a constraint, as it is likely the existing pipeline will be connected to the Proposed Development and repurposed to convey hydrogen. Other policies are deemed to be either supportive of the Proposed Development or minor deviations from the relevant national and local plans. Note that there is a live planning application (**ZB24/01955/FUL**) for

extension to the existing compressor site by NGT which may cause cumulative impacts in planning terms, but this is not seen as a major concern.

4.3.2. On the basis of the above the planning risk is considered to be **low**. Further details are provided in Table 2 of the Site Option 11 OAST within **Appendix B**.

**Site Option 13**

4.3.3. Site Option 13 is specifically allocated within the ACC Local Development Plan for business and industrial development and aligns well with national and local policies relating to the re-use of brownfield land and creation of innovative low carbon energy development.

4.3.4. The site benefits from extant planning history in the vicinity which demonstrates that industrial development will be supported on site, and that hydrogen projects of a similar nature are encouraged in the area. Whilst there are possible issues around consenting in relation to green spaces nearby (including Kincorth Hill LNR, Tullos Hill LNCS, Kincorth Hill LNCS and Ancient Woodland), these can be mitigated via stakeholder engagement with the relevant parties and a robust set of mitigation measures.

4.3.5. On that basis the overall planning impact is considered to be **low**. Further details are provided in Table 2 of the Site Option 13 OAST within **Appendix B.**

**Site Option 14**

4.3.6. The summary for Site Option 14 is included above.

## SUMMARY OF RAG RATINGS (PLANNING)

4.3.7. **Table 4-2** and **4-3** presents the summary of RAG Ratings from the desktop study.

**Table 4-2 – Summary of RAG Ratings (Commercial Sites)**

| Planning Parameters | Site Option 1 | Site Option 2 | Site Option 3 | Site Option 4 | Site Option 5 | Site Option 6 | Site Option 7 | Site Option 8 | Site Option 9 | Site Option 10 | Site Option 11 | Site Option 13 | Site Option 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Planning Policy Provision | | | | | | | | | | | | | |
| Site Allocation | | | | | | | | | | | | | |
| Article 4 Directions | | | | | | | | | | | | | |
| Planning History Searches | | | | | | | | | | | | | |
| Hazardous Substances Consent | | | | | | | | | | | | | |
| **Score** | **1 High 4 Low** | **1 Moderate 4 Low** | **1 Moderate 4 Low** | **1 High 4 Low** | **1 Moderate 4 Low** | **5 Low** | **1 Moderate 4 Low** | **1 High 4 Low** | **5 Low** | **5 Low** | **5 Low** | **5 Low** | **5 Low** |
| **Conclusion** | **High** | **Moderate** | **Low** | **High** | **Moderate** | **Low** | **Moderate** | **High** | **Low** | **Low** | **Low** | **Low** | **Low** |

**Table 4-3 – Summary of RAG Ratings (Demonstrator Sites)**

| Planning Parameters | Site Option 1 | Site Option 12 | Site Option 14 |
|---|---|---|---|
| Planning Policy Provision | | | |
| Site Allocation | | | |
| Article 4 Directions | | | |
| Planning History Searches | | | |
| Hazardous Substances Consent | | | |
| Score | **1 High**<br>**4 Low** | **5 Low** | **5 Low** |
| Conclusion | **High** | **Low** | **Low** |

# 5. ENVIRONMENTAL FEATURES

## 5.1. INTRODUCTION

5.1.1. The purpose of this section is to undertake a desk study review to identify baseline conditions, potential environmental impacts and features, opportunities and potential mitigation measures which may have implications for the design, construction and operation of the Proposed Development.

5.1.2. The environmental topics and features which were explored in the desk-based study for each Site Option (within each OAST in **Appendix B**) are presented in **Table 5-1**. These include the appraisal of eleven Site Options located within England, and three Site Options located within Scotland. These topics were chosen based on the disciplines Study Area, respective consenting requirements and guidance. The 11ha temporary Construction/Laydown Area has been represented by an indicative 350m around each Site Option to identify constraints that could significantly account for selection of Preferred Site Option.

**Table 5-1: Environmental Topics and Feature Types**

| Topic | Feature Type (England) | Feature Type (Scotland) |
|---|---|---|
| Air Quality | • Air Quality Management Areas (AQMAs); and<br>• Sensitive Receptors. | • Air Quality Management Areas; and<br>• Sensitive Receptors. |
| Cultural Heritage and Archaeology | • Designated Heritage Assets:<br>- Scheduled Monuments;<br>- World Heritage Sites;<br>- Listed Buildings;<br>- Registered Battlefields;<br>- Registered Parks and Gardens; and<br>- Conservation Areas.<br>• Non-Designated Heritage Assets:<br>- Archaeology; and<br>- Cemeteries. | • Designated Heritage Assets:<br>- Scheduled Monuments;<br>- World Heritage Sites;<br>- Listed Buildings;<br>- Canmore Points;<br>- Historic Battlefields;<br>- Gardens and Designed Landscapes; and<br>- Conservation Areas.<br>• Non-Designated Heritage Assets:<br>- Archaeology; and<br>- Cemetery. |
| Ecology and Arboriculture | • EU/International Statutory Designated Sites:<br>- Special Areas of Conservation (SAC) and candidate SAC (c.SAC);<br>- Special Protected Areas (SPA) and potential SPA (pSPA); and<br>- Ramsar and potential Ramsar sites. | • EU/International Statutory Designated Sites:<br>- Special Areas of Conservation (SAC);<br>- Special Protected Areas (SPA);<br>- RAMSAR Sites.<br>• National Statutory Designated Sites: |

| Topic | Feature Type (England) | Feature Type (Scotland) |
|---|---|---|
| | • National Statutory Designated Sites:<br>- Sites of Special Scientific Interest (SSSI) and SSSI Impact Zones; and<br>- National Nature Reserves (NNR).<br>• Non-Statutory Designated Sites:<br>- Local Nature Reserves (LNR);<br>- Local Wildlife Sites (LWS); and<br>- Royal Society for the Protection of Birds (RSPB) Reserves.<br>• Habitats and Species:<br>- International statutory sites (SAC) designated for bats;<br>- Habitats of Principle Importance (HPI);<br>- National Forest Inventory Woodland Parcels;<br>- Countryside Stewardship Species;<br>- Protected and priority species (Great Crested Newts etc.);<br>- Important Bird Areas (IBAs); and<br>- Ancient Woodlands (Semi-natural ancient woodland and ancient replanted woodland).<br>• Arboriculture:<br>- Ancient, Veteran, and Notable Trees. | - Sites of Special Scientific Interest (SSSI) and SSSI Impact Zones;<br>- National Nature Reserves (NNR); and<br>- Scotland Wildlife Trust Reserve (SWTR);<br>• Non-Statutory Designated Sites:<br>- Local Nature Reserves (LNR);<br>- Local Nature Conservation Sites (LNCS);<br>- Sites of Importance for Nature Conservation (SINCs)/Local Wildlife Sites (LWS);<br>- Royal Society for the Protection of Birds (RSPB) Reserves; and<br>- Tree Preservation Orders (TPOs).<br>• Habitats and Species:<br>- International statutory sites (SAC) designated for bats;<br>- Habitats of Principle Importance (HPI);<br>- National Forest Inventory Woodland Parcels;<br>- Countryside Stewardship Species;<br>- Protected and priority species (Great Crested Newts etc.);<br>- Important Bird and Biodiversity Areas (IBA); and<br>- Ancient Woodlands (Semi-natural ancient woodland and ancient replanted woodland); and<br>- Priority Peatland Habitats. |
| Landscape and Visual | • National Character Areas (NCA);<br>• Landscape Designations:<br>- National Landscapes;<br>- Urban Areas;<br>- National Parks; and<br>- National Historic Landscape.<br>• Green Belt<br>• Sensitive Receptors | • Local Character Areas (LCA);<br>• Gardens and Designed Landscapes;<br>• National Scenic Areas;<br>• National Parks;<br>• Scottish Green Belt; and<br>• Sensitive Receptors. |
| Geology and Soils | • Bedrock and Superficial Geology;<br>• Soil Quality, type, land use;<br>• Current Landfill Sites; | • Bedrock and Superficial Geology;<br>• Soil Quality, type, land use;<br>• Current Landfill Sites;<br>• Historic Landfill Sites; |

| Topic | Feature Type (England) | Feature Type (Scotland) |
|---|---|---|
| | • Historic Landfill Sites;<br>• Regional Unexploded (UXO) Bomb Risk;<br>• Active Quarries;<br>• Agricultural Land Classification; and<br>• Aquifer Designation | • Regional Unexploded (UXO) Bomb Risk;<br>• Active Quarries;<br>• Land Capability Classification for Agriculture; and<br>• Aquifer Designation; |
| Noise/Acoustics | • Noise Important Areas (NIAs);<br>• Major Sources of Noise; and<br>• Sensitive Receptors. | • Noise Important Areas (NIAs);<br>• Major Sources of Noise; and<br>• Sensitive Receptors. |
| People and Communities (Socio-economic) | • Towns, Villages, Collections of Dwellings and Farms;<br>• Established Tourist and Visitor Locations;<br>• Businesses;<br>• Playing Fields and Sports Grounds;<br>• Features of Community Interest (e.g. Memorials);<br>• Public Rights of Way (PRoW);<br>• National Cycle Network (NCN) Routes;<br>• National Trails/Coastal Paths<br>• Highways and Access; and<br>• Amenity. | • Towns, Villages, Collections of Dwellings and Farms;<br>• Established Tourist and Visitor Locations;<br>• Businesses;<br>• Playing Fields and Sports Grounds;<br>• Features of Community Interest (e.g. Memorials);<br>• Core Paths;<br>• National Cycle Network (NCN) Routes;<br>• National Trails/Coastal Paths<br>• Highways and Access; and<br>• Amenity. |
| Water, Drainage and Flood Risk | • Water bodies/Watercourses;<br>• Flood Risk<br>- Fluvial<br>- Groundwater; and<br>- Reservoirs.<br>• Groundwater Protection Zone | • Water bodies/Watercourses;<br>• Flood Risk<br>- Fluvial<br>- Groundwater; and<br>- Reservoirs.<br>• Drinking Water Protection Area |

## 5.2. METHODOLOGY

5.2.1. A Red / Amber / Green (RAG) system has been used to assist with comparison of potential environmental impacts for each proposed Site Option.

5.2.2. **Table 5-2** shows the three categories and methodology used to determine the risk rating for each topic, which was used within the OASTs for each of the proposed Site Options within **Appendix B** of this report.

**Table 5-2: RAG Rating Methodology**

| RAG Rating | |
|---|---|
| High Risk (Red) | Significant features that could severely impact project feasibility. |

| RAG Rating | |
|---|---|
| Moderate Risk (Amber) | Moderate features that require careful consideration and mitigation. |
| Low Risk (Green) | Minor or negligible features with little to no impact on project feasibility. |

5.2.3. Professional judgement was used to determine the potential impacts from the Proposed Development for each topic. Consideration was given to the risks, features, and opportunities, and from here, the likely impacts were noted and applicable mitigation outlined.

5.2.4. For example, ecologically important areas are considered a high consenting risk, as any development on a SSSI should not have an adverse effect. To achieve planning permission, any development that is deemed likely to adversely affect an SSSI (either directly or indirectly) would need to demonstrate that the benefits of the proposal clearly outweigh the adverse impacts.

5.2.5. Permitted development works also require permission from relevant stakeholders, and this also applies to development on land that directly or indirectly causes significant adverse effects on the designated land.

## 5.3. SUMMARY OF ENVIRONMENTAL APPRAISAL

5.3.1. The following section summarises the key elements of the desktop study, which have been presented in the OASTs (**Appendix B)**, that differentiate each Site Option. The OASTs contain the full list of environmental features identified. The summary below highlights the environmental topics at each proposed Site Option that presents a consenting constraint or opportunity.

5.3.2. The figures in **Appendix C** show the location and extent of the environmental features for each Site Option.

### DEMONSTRATOR SITES

#### Site Option 1

5.3.3. Potential adverse effects on ecological receptors are anticipated during both the construction and operational phase, particularly Cowpen Bewley Woodland Country Park Local Nature Reserve (LNR) and Local Wildlife Site (LWS) and associated habitats that could support protected species. These features represent a major consenting constraint as they are directly adjacent to Site Option 1. There is likely to be insufficient space available to establish the 11ha construction compound and laydown areas without risk of significant adverse effects to the LNR and LWS. A Preliminary Ecological Appraisal (PEA) informed by field surveys and a Habitat Regulations Assessment (HRA) would be required.

5.3.4. Site Option 1 sits within an existing industrial facility and is surrounded by several mature trees. There is potential for adverse effects on landscape character and visual receptors (i.e., residents of Billingham, users of PRoW Billingham 30 and Billingham 31). Further assessment and consultation, for example with Natural England and the LPA, would be required to understand the full potential impacts. Further details are provided in Table 1 of the Site Option 1 OAST within **Appendix B**.

#### Site Option 12

5.3.5. Site Option 12 presents major cultural heritage constraints during both the construction and operation phase, due to its proximity to Crab's Cairn Scheduled Monument. The 11ha temporary construction and laydown area would likely be situated directly adjacent to Crab's Cairn Scheduled Monument. A Historic Environment Desk Based Assessment (HEDBA) would therefore be required, with mitigation to be agreed with the LPA if impacts are identified. The Balnagask to Cove LNCS and areas of National Forest Inventory Woodland may also be impacted adversely; a PEA informed by field surveys, and a HRA would be required. Located within the Green Belt and near sensitive receptors (e.g., Doonies Farm, Cove Coastal Path), development of Site Option 12 may cause adverse effects on landscape character and visual amenity.

5.3.6. Due to the proximity to Ness Farm Historic Landfill and Grade 3 agricultural land, that has the potential to be Best and Most Versatile (BMV), there would be potential impacts from contamination and loss of agricultural land. A Preliminary Risk Assessment (PRA) has identified localised contamination. A Remediation Strategy and Verification Report will be required as well as an Agricultural Land Assessment (ALA). Further assessment and consultation, for example with the LPA, would be required to understand the full potential impacts. Further details are provided in **Table 1** of the Site Option 12 OAST within **Appendix B**.

**Site Option 14**

5.3.7. Site Option 14 presents ecological constraints during construction and operation phases due to the presence of Teesmouth and Cleveland Coast Ramsar/SPA/SSSI/IBA, 'Salthome' RSPB Reserve along with associated habitats that could support protected species within the Study Areas. Since potential adverse effects on ecological receptors are anticipated, a Preliminary Ecological Appraisal (PEA) informed by field surveys and a Habitat Regulations Assessment (HRA) would be required.

5.3.8. Further details are provided in **Table 1** of the Site Option 14 OAST within **Appendix B.**

**COMMERCIAL SITES**

**Site Option 1**

5.3.9. The summary for Site Option 1 is included above.

**Site Option 2**

5.3.10. Potential adverse effects on cultural and heritage receptors are anticipated during both the construction and operation phase, particularly to Larberry Pastures Scheduled Monument and Grade II listed buildings. These features represent a major consenting constraint as the 11ha temporary construction and laydown area would likely be situated directly adjacent to the Scheduled Monument.

5.3.11. Located on land that has the potential to be BMV agricultural land, Site Option 2 risks permanent loss of this land; an ALA would be required to understand the full potential impact. There is the potential for noise impacts on Elton Home Park and the nearby Noise Important Area (NIA). Further noise assessments and consultation with the LPA and Environmental Health Officer (EHO) would therefore be required. The 11ha construction compound and laydown area lies within Flood Zones 2 and 3, near Coatham Creek tributary and waterbodies. There is therefore the potential for of contamination, flood risk and drainage impacts that would require a Flood Risk Assessment (FRA) and consultation with the Environment Agency. Further assessment and consultation, for example

with the LPA and the Environment Agency, would be required to understand the full potential impacts. Further details are provided in Table 1 of the Site Option 2 OAST within **Appendix B**.

**Site Option 3**

5.3.12. Site Option 3 presents several ecological constraints due to its proximity to designated conservation sites, such as the Teesmouth and Cleveland Coast SSSI, Ramsar and IBA, National Forest Inventory Woodland Parcels, Teesmouth NNR, and Salthome RSPB Reserve. These sites may restrict the development of construction compounds and laydown areas and pose risks to Habitats of Principal Importance (HPIs) during the construction phase. A PEA supported by field surveys would be conducted to assess site-specific ecological impacts and guide mitigation strategies as well as consultation with Natural England. If protected species such as Great Crested Newts are identified, a European Protected Species Licence (EPSL) from Natural England may be required. Additionally, a HRA would evaluate the SSSI/Ramsar site's protected features, and opportunities for biodiversity enhancement through collaboration with Local Nature Partnership Strategies (LNPS) would be explored.

5.3.13. Further risks stem from Site Option 3's proximity to the Seal Sands Road Historic Landfill Site, which could lead to contamination during construction. To evaluate this, a PRA and GI would be undertaken, including a review of historical records and contaminated land assessments. These risks necessitate additional assessments and consultation with the Environment Agency to determine the extent of potential impacts and inform appropriate mitigation measures. Further assessment and consultation, for example with the LPA and the Environment Agency, would be required to understand the full potential impacts. Further details are provided in Table 1 of the Site Option 3 OAST within **Appendix B**.

**Site Option 4**

5.3.14. Site Option 4 is located within Flood Zone 3 and therefore has the potential to cause adverse effects in relation to drainage and flood risk, an FRA would be required to be undertaken.

5.3.15. Further risks are anticipated due to the close proximity of Site Option 4 to the Second World War QF bombing decoy Scheduled Monument, that potentially could be impacted by the construction and laydown area. Ecological constraints include Humber Estuary SAC/SPA/Ramsar/SSSI/IBA, HPIs, National Forest Inventory woodland parcels, and a Lapwing stewardship area. These may also limit the construction and laydown areas. A PEA, field surveys, HRA, and EPSL (if protected species are present) will guide mitigation. Biodiversity Net Gain opportunities exist via LNPS. Further assessment and consultation, for example with Natural England and the Environment Agency, would be required to understand the full potential impacts. Further details are provided in Table 1 of the Site Option 4 OAST within **Appendix B**.

**Site Option 5**

5.3.16. Potential adverse effects to landscape and visual receptors are anticipated during both construction and operation phases, as the Site is located within Lincolnshire Wolds National Landscape. To address the potential impacts, a Landscape and Visual Impact Assessment (LVIA) would be undertaken.

5.3.17. Due to proximity of Walesby Top Historic Landfill Site, potential impacts from contamination on geological and soil receptors are likely during construction phase, requiring PRA, GI, and

chemical studies. Ecological constraints include nearby National Forest Inventory Woodland and the Linwood Warren SSSI Impact Zone. A PEA, field surveys, and consultation with Natural England will guide mitigation, with BNG opportunities via LNPS. NCN Route No.1 is located within the potential construction compound and laydown area and mitigation measures would need to be considered to avoid adverse impacts on the users of this route. Further assessment and consultation, for example with the LPA and Natural England, would be required to understand the full potential impacts. Further details are provided in Table 1 of the Site Option 5 OAST within **Appendix B**.

**Site Option 6**

5.3.18. Potential adverse effects are anticipated on ecological receptors, particularly, HPIs, National Forest Inventory Woodland Parcels and protected species during the construction and operation phases of the Proposed Development. The construction compound and laydown area should be carefully sited to avoid impacts to the deciduous woodland. A PEA along with other relevant Phase 2 ecology surveys would be undertaken to advise on specific species and habitat mitigation. Where protected species are confirmed (e.g. Lapwings and bats), it may be necessary to apply for a wildlife licence or EPSL from Natural England. Consultation may also be required with Natural England due to the location within a SSSI Impact Zone.

5.3.19. Further risks are anticipated on cultural heritage assets due to close proximity of listed buildings to Site Option 6; a HEDBA would be required to assess the potential impacts to these assets. Site Option 6 lies on Grade 2 agricultural land, which is characterised as BMV land. There is therefore the potential for significant adverse effects to agricultural land, and as such an ALA is required to be undertaken, as well as careful siting of the construction compound and laydown areas to reduce the potential impacts. Further assessment and consultation, for example with the LPA and Natural England, would be required to understand the full potential impacts, further details are provided in Table 1 of the Site Option 6 OAST within **Appendix B**.

**Site Option 7**

5.3.20. Site Option 7 is located within the Liverpool, Manchester and West Yorkshire Greenbelt, Grade 2 agricultural land, which is characterised as BMV land, and Ground Water Protection Zone (Zone 1: Inner Protection Zone). These features are considered major constraints for landscape and visual, agricultural land, and groundwater considerations. There is likely to be insufficient space available to establish the 11ha constriction compound and laydown areas without risk of significant effects to the landscape and visual receptors, geological receptors, and groundwater. To understand the full potential impacts a PRA, GI, ALA, Hydrogeological Risk Assessment, and Groundwater Risk Assessment (GRA) would be required to be undertaken.

5.3.21. Further risks are anticipated on ecological receptors due to the close proximity of deciduous woodlands, National Forest Inventory Woodlands and Stutton Ings SSSI (Site Option 7 lies within a SSSI Impact Zone). A PEA, field surveys, and EPSL may be required, with BNG opportunities via LNPS. Whilst not within the Study Area, due to the proximity of Site Option 7 to the Battle of Townton Historic Battlefield, a HEDBA would be required to understand the full potential impacts to this asset. Further assessment and consultation, for example with the Environment Agency and the LPA, would be required to understand the full potential impacts. Further details are provided in Table 1 of the Site Option 7 OAST within **Appendix B**.

**Site Option 8**

5.3.22. Potential adverse effects on ecological receptors are anticipated during the construction and operation phase, particularly to Gibraltar Point SAC/SSSI; Humber Estuary SPA/Ramsar/SSSI/IBA; Greater Wash SAC; Lincolnshire Coronation Coast NNR, HPIs; National Forest Inventory Woodland; and Countryside Stewardship designated areas for Lapwings; due to the close proximity (adjacent) of Site Option 8 to these receptors. A PEA along with Phase 2 Surveys would be undertaken to advise on specific species and habitat mitigation measures that would be carried out. Where protected species are confirmed, it may be necessary to apply for a EPSL from Natural England. To understand the potential impacts to protected features of habitats within the Ramsar located within 2km of Site Option 8, a HRA would be undertaken..

5.3.23. Water, drainage and flood risk are considered a major constraint to Site Option 8 as there are approximately 16 to 17 drains located within the site; and the site is located within Flood Zone 3. As a result, an FRA would be required to understand the full potential impacts on flood risk. Further assessment and consultation, for example with Natural England and the Environment Agency, would be required to understand the full potential impacts. Further details are provided in Table 1 of the Site Option 8 OAST within **Appendix B**.

**Site Option 9**

5.3.24. As Site Option 9 is located within Grade 3 agricultural land, which has the potential to be BMV land, impacts to this agricultural land are therefore likely during construction. An ALA is required to fully understand the potential impacts and to inform the identification of mitigation measures would be required. To address concerns regarding potential impacts to the ditch and tributary of Hatton Beck located within Site Option 9, further assessment would be undertaken.

5.3.25. Risks are associated with potential impacts on ecological receptors located in close proximity to Site Option 9, particularly, Bardney Limewoods, Lincolnshire SSSI and NNR; HPIs; and National Forest Inventory Woodland. Careful siting of the construction and laydown area would therefore be required to avoid/reduce impacts to the National Forest Inventory Woodland, as well as users of the PRoW located in close proximity to Site Option 9. A PEA followed by Phase 2 surveys, and consultation with Natural England are recommended. Further assessment and consultation, for example with the Environment Agency, would be required to assess understand the full potential impacts. Additional details are provided in Table 1 of the Site Option 9 OAST within **Appendix B**.

**Site Option 10**

5.3.26. Potential adverse effects are anticipated on ecological receptors, particularly HPIs; National Forest Inventory Woodland; Protected Species; Countryside Stewardship designated areas for lapwings and curlew; and SSSIs (as Site Option 10 is located within a SSSI Impact Zone). Site Option 10 is constrained by the presence of deciduous woodland and National Forest Inventory Woodland to the northeast. This should be considered along with other constraints prior to locating the temporary construction compound and laydown area. To fully understand the potential impacts to ecological receptors, a PEA followed by Phase 2 surveys would be undertaken.

5.3.27. There is potential for adverse effects on landscape character and visual receptors in close proximity to Site Option 10, including Burley Park Farm, Heather House Farm and the users of Footpath 15.65 14/1, Footpath 15.53 19/1, and Footpath 15.65 15/1 during construction and operation.. Proximity to NIAs, residential and commercial areas, tourist sites, and amenities may result in air

quality, noise, and traffic disruption. Engagement with the LPA and EHO will determine mitigation requirements, including the requirement for noise barriers during and a communication plan for affected residents during construction. Further assessment and consultation, for example with Natural England, the EHO and LPA, would be required to understand the full potential impacts. Further details are provided in Table 1 of the Site Option 10 OAST within **Appendix B**.

**Site Option 11**

5.3.28. Site Option 11 has risks associated with potential adverse impacts on heritage, ecology, and landscape. The Grade II listed Ladyfield Farmhouse may be affected by construction and operation activities. Careful siting of construction laydown areas and completion of a HEDBA would be required to understand the full potential impact on this asset. Ecological impacts are anticipated due to the proximity of Site Option 11 to Swale Lakes SSSI and HPIs. A PEA, field surveys, and stakeholder engagement will guide mitigation, with possible licensing for protected species and BNG opportunities via LNPS. Where protected species are confirmed, it may be necessary to apply for a European Protected Species Licence from Natural England. Visual impacts may affect residents of Thrintoft and PRoW users, necessitating further landscape assessment.

5.3.29. Site Option 11 is located on Grade 2 agricultural land which is characterised as BMV land, there is potential for significant adverse effects to agricultural land. As such, an ALA is required to be undertaken as well as careful siting of the construction compound and laydown areas to reduce the potential impacts . Site Option 11's proximity to watercourses, and its location within Zone II (Outer Protection Zone) pose risks to water quality during construction. Further assessment and consultation, for example with the Environment Agency and LPA, would be required to understand the full potential impacts. Further details are provided in Table 1 of the Site Option 11 OAST within **Appendix B**.

**Site Option 13**

5.3.30. The development of Site Option 13 may result in adverse effects on nearby AQMAs (Wellington Road AQMA, and Aberdeen City Centre AQMA), residential areas along Nigg Kirk Road, Little Clouds Nursery, and local amenities due to air quality, noise, visual and traffic impacts during construction and operation. Ecological receptors including Kincorth Hill LNR, Tullos Hill LNCS, Ancient Woodland, and National Forest Inventory Woodland may also be adversely impacted due to their close proximity to Site Option 13. Due to Site Option 13's proximity to Green Belt areas and Core Paths there are potential impacts to landscape and visual receptors. A PEA, informed by field surveys would be undertaken, with opportunities for biodiversity enhancement through collaboration with LNPS.

5.3.31. A PRA has identified potential impacts from potentially contaminated land due to the nearby Ness Farm landfill, necessitating further ground investigations and a Remediation Strategy if required. Given the site's proximity to watercourses and its location within a Drinking Water Protection Area, further assessment is essential to address potential risks to water quality, drainage, and flood resilience. Further assessment and consultation, for example with the LPA, would be required to understand the full potential impacts. Further details are provided in Table 1 of the Site Option 13 OAST within **Appendix B**.

**Site Option 14**

The summary for Site Option 14 is included above.

## SUMMARY OF RAG RATINGS (ENVIRONMENT)

5.3.32. **Table 5-3** and **5-4** presents the summary of RAG Ratings from the desktop study.

**Table 5-3: Summary of RAG Ratings (Commercial Sites)**

| Environmental Topic | Site Option 1 | Site Option 2 | Site Option 3 | Site Option 4 | Site Option 5 | Site Option 6 | Site Option 7 | Site Option 8 | Site Option 9 | Site Option 10 | Site Option 11 | Site Option 13 | Site Option 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Air Quality | | | | | | | | | | | | | |
| Cultural Heritage and Archaeology | | | | | | | | | | | | | |
| Ecology | | | | | | | | | | | | | |
| Landscape and Visual | | | | | | | | | | | | | |
| Geology and Soils | | | | | | | | | | | | | |
| Noise | | | | | | | | | | | | | |
| People and Communities | | | | | | | | | | | | | |
| Water, Drainage and Flood Risk | | | | | | | | | | | | | |
| Score | 2 High<br>4 Moderate<br>2 Low | 2 High<br>4 Moderate<br>2 Low | 2 High<br>1 Moderate<br>5 Low | 1 High<br>4 Moderate<br>3 Low | 2 High<br>3 Moderate<br>3 Low | 1 High<br>5 Moderate<br>2 Low | 3 High<br>1 Moderate<br>4 Low | 2 High<br>5 Moderate<br>1 Low | 0 High<br>5 Moderate<br>3 Low | 0 High<br>4 Moderate<br>4 Low | 1 High<br>5 Moderate<br>2 Low | 2 High<br>5 Moderate<br>1 Low | 0 High<br>1 Moderate<br>7 Low |
| **Conclusion** | **High** | **High** | **High** | **Moderate** | **Moderate** | **Moderate** | **High** | **High** | **Moderate** | **Moderate** | **Moderate** | **High** | **Low** |

**Table 5-4: Summary of RAG Ratings (Demonstrator Sites)**

| Environmental Topic | Site Option 1 | Site Option 12 | Site Option 14 |
|---|---|---|---|
| Air Quality | | | |
| Cultural Heritage and Archaeology | | | |
| Ecology | | | |
| Landscape and Visual | | | |
| Geology and Soils | | | |
| Noise | | | |
| People and Communities | | | |
| Water, Drainage and Flood Risk | | | |
| Score | 2 High<br>4 Moderate | 1 High<br>5 Moderate | 0 High<br>1 moderate |

| Environmental Topic | Site Option 1 | Site Option 12 | Site Option 14 |
|---|---|---|---|
| | 2 Low | 2 Low | 7 low |
| **Conclusion** | **High** | **High** | **Low** |

# 6. PREFERRED OPTION AND CONCLUSION

## 6.1. DEMONSTRATOR SITE

**6.2.** All of the demonstrator site options have some environmental and planning risks. However, Site Option 14 is recommended as the preferred option due to it having the fewest potential environmental features that may be impacted. Furthermore, there is more opportunity and space within the wider 350m temporary construction and laydown areas for mitigation measures to be put in place. While Site Option 14 does have constraints, namely those relating to ecology, it is located within an industrial facility and on the edge of a wider industrial estate, where there is more opportunity land for construction and laydown areas. The wider area is also subject multiple low carbon planning applications, including DCOs for $CO_2$ and hydrogen facilities, indicating that such development is viewed favourably by the LPA.

6.2.1. The least preferred option is Site Option 1 as development of this site could lead to significant impacts to the Cowpen Bewley Woodland Country Park LNR and LWS, and associated habitats, which are located adjacent to the site boundary. There is likely to be insufficient space available to establish the 11ha construction compound and laydown areas without risk of significant effects to the LNR and LWS.

6.2.2. Further assessments would be carried out potentially to reduce impacts through avoidance or mitigation measures, once site-based surveys and consultation has been undertaken, and more detailed design information is available.

## 6.3. COMMERCIAL SITES

6.3.1. All eleven potential commercial sites present potential environmental impacts and planning risks; however, the following five Site Options would be the most preferred options for the Proposed Development:

- Site Option 3;
- Site Option 6;
- Site Option 9;
- Site Option 10; and
- Site Option 11.

6.3.2. While Site Option 3 could potentially adversely impact one identified ecological receptor, it is still considered a preferred commercial site option from both an environmental and planning perspective due to the cumulative assessment of overall impacts/risks. Site Option 3 is only constrained by Teesmouth and Cleveland Coast SSSI; National Forest Inventory Woodland Parcels and Seal Sands Road Historic Landfill Site. Site Option 3 is located within the wider industrialised Teeside area which is the location of multiple DCO applications for energy infrastructure such as hydrogen, carbon capture and storage and aviation biofuel. This has helped to establish the principal of innovative energy development being an acceptable land use in the wider vicinity. On this basis, Site Option 3 is considered as a preferred commercial site for Proposed Development.

6.3.3. Site Option 6 poses potential impacts to cultural and heritage assets (listed buildings), ecological receptors (HPIs, National Forest Inventory Woodland Parcels, a SSSI Impact Zone and Protected Species), BMV agricultural land agricultural land, and watercourses that could be addressed by further assessments and consultation. With the application of suitable mitigation measures informed by further assessments, Site Option 6 is considered preferable for development.

6.3.4. Site Option 9 presents potential consenting constraints due to its proximity to sensitive ecological receptors including Bardney Limewoods SSSI and NNR, HPIs, and National Forest Inventory Woodland. The potential impacts are considered manageable through targeted assessments such as a PEA, PRA, GI, and ecological surveys, alongside consultation for example with Natural England and careful siting of the construction and laydown. With the application of suitable mitigation measures informed by further assessments, Site Option 9 is considered preferable for development.

6.3.5. Site Option 10's location is environmentally constrained primarily due to its location within SSSI Impact Zones and its proximity to designated ecological receptors, including National Forest Inventory Woodland, HPIs, protected species, and Countryside Stewardship areas supporting lapwing and curlew. The presence of deciduous and National Forest Inventory Woodland, potential impacts on landscape character and visual receptors can all be managed through undertaking appropriate technical assessments to identify suitable mitigation measures, including a PEA, protected species surveys and engagement for example with Natural England and the LPA to understand the full potential impacts. With the application of suitable mitigation measures informed by further assessments, Site Option 10 is considered preferable for development.

6.3.6. Site Option 11 poses potential risks to heritage, ecology, geology and soils and water quality, particularly to the Grade II listed Ladyfield Farmhouse, BMV agricultural land and groundwater which may be affected by construction and operation activities, and will require careful siting of laydown areas. The associated risks are considered manageable through undertaking appropriate technical assessments to identify suitable mitigation measures and careful siting of the construction compound and laydown areas. With the application of suitable mitigation measures informed by further assessments, Site Option 11 is considered preferable for development.

6.3.7. As outlined in **Table 3-1,** Site Option 14 could be progressed as either a Demonstrator or Commercial Site. While it is currently identified as the Preferred Demonstrator Site Option, Site Option 14 may therefore also be considered as a preferred Commercial Site Option, subject to further evaluation, and the Client's preferred approach.

## 6.4. ENVIRONMENTAL SURVEY SUGGESTIONS

6.4.1. Site-based surveys and assessments are recommended to further understand the environmental and planning risks of the preferred Site Options for the Proposed Development.

6.4.2. Site-based surveys and assessments should include (but not limited to):

- Preliminary Ecological Appraisal and specialist ecology surveys where necessary;
- Habitats Regulations Assessment;
- Historic Environment Desk Based Assessment;
- Agricultural Land Assessment;
- Preliminary Risk Assessment;

- Geotechnical Investigations;
- Landscape and Visual Impact Assessment; and
- Flood Risk Assessment.

6.4.3. Stakeholder consultation, and consultation with the LPAs would also be undertaken.

## 6.5. NEXT STEPS

6.5.1. A Consenting Strategy including Environmental Impact Assessment strategy is to be prepared for the Proposed Development once the final demonstrator and commercial sites are chosen. Early engagement with stakeholders is recommended, for example the relevant LPA, Natural England and the Environment Agency, as detailed where relevant within this report.

# 7. ASSUMPTIONS AND LIMITATIONS

7.1.1. The findings presented above are based on a high-level environmental features desktop study review using publicly available data. It is recommended that further quantitative assessment, valuation, monitoring, and surveys are scoped and commissioned to provide a greater understanding of potential impacts of the Proposed Development on sensitive receptors and help inform the option development process. This would bring more certainty over Site Option suitability, and full conclusions should not be drawn without visits to the Site Options in question.

7.1.2. Access arrangements have not been considered during or post-construction, or any associated utilities connections required for the Proposed Development.

7.1.3. The footprint of each assessment varies for each potential Site Option. It is assumed that during further optioneering, specified locations would be available for a more in-depth assessment.

7.1.4. At the time of assessment, the AGI locations or design parameters were not available, and therefore not included within this stage of assessment.

7.1.5. An assessment has not yet been conducted on any additional connections or utilities necessary to make the hydrogen storage facility sites operational.

# Appendix A

## SITE OPTIONS LOCATION PLAN

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# Appendix B

## ENVIRONMENTAL AND PLANNING OPTION APPRAISAL SUMMARY TABLES

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# Appendix C

## ENVIRONMENTAL FEATURES MAPS

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Guildford, Surrey
GU1 1UN

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National Gas Transmission

# STRATEGIC INNOVATION FUND (SIF) ALPHA B - LINEPACK HYDROGEN STORAGE INNOVATION PROJECT

## Consenting Strategy – Site Option 14

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# 1. INTRODUCTION

1.1.1. This consenting strategy considers the potential routes for securing planning consent to facilitate the construction, operation and decommissioning of the Proposed Development as described in **Section 2.1** of this report, at Site Option 14 in Billingham, Stockton on Tees alongside the regulatory rules around stakeholder engagement and Environmental Impact Assessment (EIA). It sets out the recommended route to securing consent alongside the likely views of the Local Planning Authority (LPA).

1.1.2. The consenting strategy has considered the potential route towards obtaining planning permission as set out in **Section 2.3** of this report. Note that this consenting strategy is *specific to the demonstrator site only* and that Site Option 14 was chosen as the preferred demonstrator site in our Environmental and Planning Site Options Appraisal (hereafter referred to as the 'Site').

# 2. PLANNING AND CONSENTING

## 2.1. DESCRIPTION OF PROPOSED DEVELOPMENT

### PROJECT BACKGROUND

2.1.1. The Office of Gas and Electricity Markets (OFGEM) Strategic Innovation Fund (SIF) is a £450 million initiative launched in 2021 by the UK's energy regulator, OFGEM, in partnership with Innovate UK. The SIF aims to help transform gas and electricity networks for a low-carbon future. It funds projects that could speed up the transition to net zero at the lowest cost to the consumer as part of the RIIO-2 price controls[1].

2.1.2. National Gas Transmission (hereon referred to as the 'Applicant') has identified a minimum capacity requirement of 1.74TWh for distributed "Linepack+" hydrogen supplementation by 2040 for Project Union (~2000km), which is the planned 100% hydrogen pipeline for the UK. National Gas has investigated the feasibility of intermediate scale geological hydrogen storage solutions to be deployed to supplement Linepack in a hydrogen transmission system. Due to lower volumetric energy density of hydrogen, the energy content in 1km of Linepack is only 1/3 of that of natural gas. The amount of energy able to be stored by Linepacking in the future may potentially decrease with the addition of blended or 100% hydrogen2. As part of the feasibility investigations, OFGEM SIF with National Gas Transmission and Scottish Gas Networks plc (SGN) have identified H2FlexiStore as the preferred technology to achieve requirements for switching to H2 and supplement the loss in linepack capacity we will see with Hydrogen transmission in future.

2.1.3. The Applicant is now undertaking an optioneering study for the construction and operation of smaller, intermediate scale storage sites for purpose built geological storage solutions to supplement linepack capacity and provide system flexibility and network optimisation ('Proposed Development').

2.1.4. The opportunity to utilise existing pipelines for renewable energy storage through hydrogen is invaluable in supporting the 2050 Net Zero Target. Linepack increases the volume of storage that in turn reduces our dependency on fossil fuels and emissions from underground storage are greatly decreased in comparison to above ground options.

### TECHNICAL DESCRIPTION OF $H_2$FLEXISTORE

2.1.5. H2FlexiStore, developed by UK based Gravitricity, is developing lined rock shafts for storage of gaseous hydrogen. This is state-of-the-art technology for hydrogen storage, with the potential to be deployed rapidly and at scale, depending on land and geological suitability, across the entire repurposed transmission system for hydrogen. H2FlexiStore aims to be the world's first in

[1] Ofgem (2025). *Strategic Innovation Fund (SIF)*. Ofgem. Available at: https://www.ofgem.gov.uk/strategic-innovation-fund-sif

[2] Energy Networks Association (2024). *B-Linepack+ (project reference 10102109)*. Smarter Networks Portal. Available at: https://smarter.energynetworks.org/projects/10102109/

demonstrating lined rock shaft storage of hydrogen for Linepack supplementation in a 100% hydrogen transmission network to improve system resilience and enable energy ecosystem optimisation opportunities across both electricity and gas networks.

2.1.6. H2FlexiStore is a modular hydrogen storage system, engineered to deliver a reliable and flexible hydrogen supply for the hydrogen economy. Each system is installed in a new subsurface shaft. The storage vessel is composed of a multi-layered liner which interacts with the surrounding geology to securely store large quantities of hydrogen within the subsurface shaft. It is engineered to be installed across a range of geologies and is rapidly deployable and enables customers to accelerate their decarbonisation timelines.

## PROPOSED DEVELOPMENT DESCRIPTION

### Operation of the Proposed Development

2.1.7. The Proposed Development would consist of the $H_2$Flexistore demonstrator storage and AGI, associated above-ground infrastructure and construction area that includes permanent works as shown in **Figures 2-1** and **2-2** below. The stored hydrogen would be connected to the existing pipeline to constrain and store hydrogen.

**Figure 2-1− Hydrogen Storage System- $H_2$Flexistore**

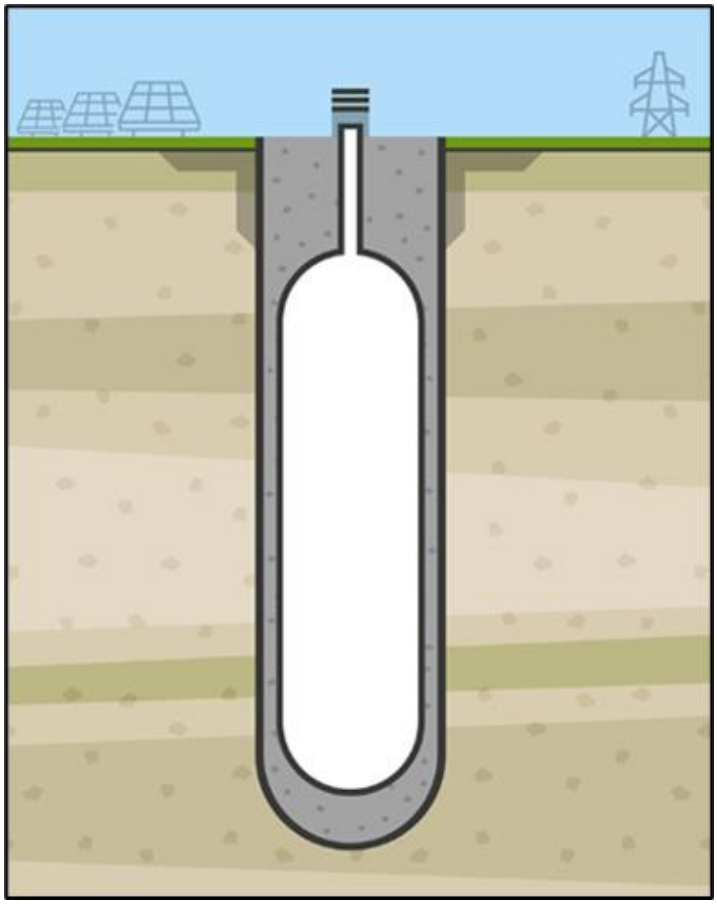
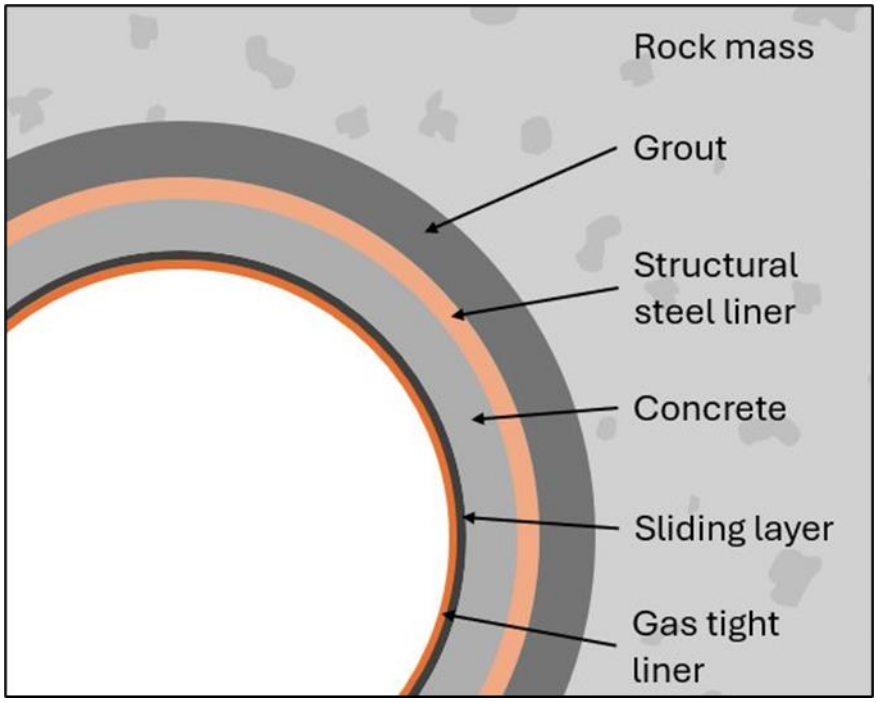


**Figure 2-2− Hydrogen-lined Rock Shafts**




2.1.8. The Proposed Development would include one Above Ground Installation (AGI), which is expected to include process equipment such as compressors, heaters, coolers, and piping, alongside welfare and office facilities housed in portacabins or similar structures. The AGI will be situated on a concrete slab above the shaft, with access roads surrounding the site to facilitate vehicle movement between different areas. The proposed layout currently requires a footprint of approximately **60.0m x 60.0m (3,600sq.m.)**

2.1.9. The Demonstrator site will serve as a pilot installation of the hydrogen storage facility while the commercial sites will be developed as a full-scale operational facility considering scalability to meet future requirements. NGT is now working in collaboration with WSP, Premtech and Gravitricity to identify one site location for a demonstrator site for the Proposed Development and five (5) potential locations for commercial sites for the Proposed Development.

2.1.10. The demonstrator site will be installed at first, where testing will be commenced before construction and operation of a commercial site at a later date. The approximate parameters for both the demonstrator and commercial sites are provided in **Table 2-1** below. As outlined above note that the commercial site is not considered further in this consenting strategy.

**Table 2.1: Parameters of Demonstrator and Commercial Site**

| Parameters | Demonstrator Site (Site 14) | Commercial Site (Site 14) |
|---|---|---|
| Storage Capacity (in Tonnes) | 1.0 | 65.0 |
| Diameter of Shaft (in m) | 2-3 | 6.5 |
| Depth of Shaft (in m) | 100 | 300 |

### TEMPORARY CONSTRUCTION

2.1.11. The Proposed Development would require approximately **11 hectares** for construction laydown including drilling rigs, and associated equipment to be installed within the land during construction activity. It would be constructed via shaft sinking wherein each system will be installed in a subsurface shaft. A vertical shaft/vessel will be constructed to attain underground access. The vessel is composed of a multi-layered liner which interacts with the surrounding geology to securely store large quantities of hydrogen. The process of repurposing existing pipelines would likely to involve the removal and replacement of defective sections of pipeline.

### DEVELOPMENT ASSUMPTIONS

2.1.12. As outlined in **paragraph 2.2.3** below on Permitted Development Rights, it is likely that temporary surface construction activity can be undertaken via permitted development and the only aspects of the Proposed Development requiring planning permission are the following (hereafter referred to as $H_2$ Storage Infrastructure):

- the construction and operation of the AGI and any other permanent above ground infrastructure such as access roads, landscaping or fencing and
- the construction and operation of the permanent underground shaft and storage itself below ground.

## 2.2. PLANNING BASELINE

### PLANNING HISTORY

2.2.1. A review of the planning application history within a 5km radius reveals no indication of consenting risk, suggesting a favourable outlook for approval. Regionally, several Development Consent Order (DCO) projects involving hydrogen and carbon capture demonstrate strong support for energy infrastructure, reinforcing the likelihood of approval for the Proposed Development. Locally, the approval of application **23/1634/FUL** highlights a spatial development trend in the Billingham area toward energy-related projects, indicating that the LPA is likely to view the Proposed Development positively. The conditions attached to **23/1634/FUL** suggest similar requirements may apply to Site Option 14, including environmental management measures such as surface water discharge controls, ecological surveys, a Construction Environmental Management Plan (CEMP), Arboricultural Impact Assessment, and restoration for agricultural use post-demolition. Additionally, local impact considerations—such as traffic management (CTMP), noise mitigation, and coordination with nearby railway infrastructure regarding lighting, drainage, and construction access—are expected to be addressed.

2.2.2. This suggests that while the Proposed Development is likely to be viewed positively — given the supportive planning history for energy infrastructure in the Billingham area at both local and DCO levels — approval will not be unconditional. It is expected that consent will be subject to specific planning conditions.

**PERMITTED DEVELOPMENT**

2.2.3. Some development types are classed as permitted development and are exempt from the requirement of the planning permission. This may be relevant for the temporary construction laydown site surrounding the AGI on the surface.

2.2.4. The Town and Country Planning (General Permitted Development) (England) Order 2015 – Part 4: Temporary Buildings and Uses[3], Class A – temporary buildings and structures states:

*A. The provision on land of buildings, moveable structures, works, plant or machinery required temporarily in connection with and for the duration of operations being or to be carried out on, in, under or over that land or on land adjoining that land.*

*A.1 Development is not permitted by Class A if—*

*(a) the operations referred to are mining operations, or*

*(b) planning permission is required for those operations but is not granted or deemed to be granted.*

*A.2 Development is permitted by Class A subject to the conditions that, when the operations have been carried out—*

*(a) any building, structure, works, plant or machinery permitted by Class A is removed, and*

*(b) any adjoining land on which development permitted by Class A has been carried out is, as soon as reasonably practicable, reinstated to its condition before that development was carried out.*

## 2.3. CONSENTING STRATEGY FOR PLANNING APPROVAL

2.3.1. The proposed H2FlexiStore hydrogen storage facility is categorised as a Major Development under the Town and Country Planning (Development Management Procedure) (England) Order 2015, rather than a project of Nationally Significant Infrastructure (NSIP) under the Planning Act 2008. While national policy, including the National Planning Policy Framework (NPPF) and the Government's Hydrogen Strategy, supports hydrogen production, storage, and distribution, there is currently no explicit designation of lined rock shaft hydrogen storage as NSIP.

2.3.2. However, due to its scale and nature, H2FlexiStore falls within the major development category, as underground gas storage is listed under Schedule 2 of the Town and Country Planning (Environmental

[3] The Town and Country Planning (General Permitted Development) (England) Order 2015

Impact Assessment) Regulations 2017[4], and is therefore likely to require EIA screening. The demonstrator site includes a 100m deep shaft with associated Above Ground Infrastructure.. This classification triggers statutory requirement including early engagement with Stockton-on-Tees Borough Council, consultation with statutory consultees, preparation of a Design and Access Statement, and the completion of an Environmental Statement (ES), if required. Together, these ensure that the Proposed Development is considered under the enhanced consenting regime for major projects in England.

2.3.3. In England, development of the scale and type proposed for the H2 Storage Infrastructure would normally proceed via a full planning application under the Town and Country Planning Act 1990 (TCPA), as applied to Stockton-on-Tees Borough Council. The Council's Validation Checklist requires all applications to be accompanied by mandatory national requirements including: the application form, fee, site/location plans, ownership certificates, design and access statement if required) together with local validation requirements set out by the Council, which typically also include flood risk assessment, ecological reports, noise/air quality assessments, heritage/archaeology reports, and a transport statement or assessment.

2.3.4. A key procedural consideration is whether the H2 Storage Infrastructure constitutes EIA development under the Town and Country Planning (Environmental Impact Assessment) Regulations 2017[5] (as amended). This is discussed in **Section 2.5** of this report. For energy-related industrial facilities exceeding 0.5 hectares or involving storage of chemical products, the project may fall within Schedule 2 development, meaning a screening opinion from Council should be sought to determine whether significant environmental effects are likely. If so, an EIA scoping request may then be submitted to define the content of the Environmental Statement (ES).

2.3.5. The application process is structured as follows:

**Pre-application Phase (Optional but recommended)**

- Engage with Council planning officers to confirm applicable local validation requirements and scope of assessments (transport, noise, ecology, drainage, etc.).
- Request an EIA Screening Opinion (and Scoping Opinion if required) to clarify environmental documentation needs.
- Early engagement with statutory consultees (Environment Agency, Natural England, Highways Authority) and informal community consultation is strongly advised.

**Submission and Validation**

- A full planning application is submitted with all supporting documents required by the Council Validation Checklist.
- The application is validated once all mandatory documents and correct fee are provided. If the application is incomplete, validation will be delayed.

**Determination Period**

[4] The Town and Country Planning (Environmental Impact Assessment) Regulations 2017

- For major developments (defined as sites over 1 hectare, buildings over 1,000 m², or significant infrastructure), the statutory determination period is 13 weeks from validation (or 16 weeks where an EIA is required).
- A planning performance agreement (PPA) can extend this period by agreement.
- The application will be subject to statutory consultation (minimum 21 days), site notices, and possible referral to Council's Planning Committee.

**Post-decision Phase**

- If permission is granted, conditions will be attached (e.g., landscaping, biodiversity net gain, surface/foul drainage, construction management, noise, transport, archaeology).
- The applicant must submit applications to discharge conditions prior to commencing development. Council generally seeks to determine condition discharge applications within 8 weeks, though this can vary.

2.3.6. The advantage of this route is that it provides the Applicant with full control over the application documents and ability to directly address the Validation Checklist and EIA requirements from the outset. However, the process is front-loaded: significant baseline surveys and technical assessments must be completed before submission to avoid invalidation or refusal. All detailed design, layouts and environmental considerations must be addressed upfront at application stage.

## 2.4. HAZARDOUS SUBSTANCES CONSENT

2.4.1. The Planning (Hazardous Substances) Regulations 20155 state that to store or use hazardous substances at or above defined limits at a site, Hazardous Substances Consent (HSC) must be secured in addition to standard planning permission. This is a legal requirement. Application for consent for the H2 Storage Infrastructure is made to the hazardous substances authority (HSA), which is usually the local planning authority. Health and Safety Executive (HSE) and the Environment Agency (EA) would likely be statutory consultees).

2.4.2. HSE guidance states that applicants should build in a timeframe of 6 to 12 months to get a decision on HSC from the hazardous substances authority. The demonstrator site has a capacity of 1.0 tonne of hydrogen which is below the control limit and therefore would not require HSC[5].

## 2.5. ENVIRONMENTAL IMPACT ASSESSMENT

2.5.1. Many planning applications require at least some level of environmental assessment and reporting, for example, a noise assessment. Larger scale planning proposals however may trigger the requirement for a full Environmental Impact Assessment (EIA) under The Town and Country Planning (Environmental Impact Assessment) Regulations 2017[6]. Where this is the case, a planning application

[5] The Planning (Hazardous Substances) Regulations 2015

[6] The Town and Country Planning (Environmental Impact Assessment) Regulations 2017

needs to be accompanied by an ES. The EIA process could still apply for the selected consented route.

### EIA SCREENING

2.5.2. The TCPA EIA Regulations 2017[6] distinguish between:

- Schedule 1 give the Descriptions of development for the purposes of the definition of "schedule 1 development, the developments listed in this schedule would require EIA.
- Schedule 2 gives the Descriptions of development and applicable thresholds and criteria for the purposes of the definition of "schedule 2 development.
- Schedule 3 states the Selection criteria for screening schedule 2 development.

2.5.3. In order to identify whether the development is EIA the applicant can request what is known as an 'EIA screening' opinion from the LPA.

2.5.4. This request must include a plan identifying the land, a description of the development detailing its physical characteristics and any demolition works, and the location with attention to environmentally sensitive areas. It should also describe environmental aspects likely to be significantly affected, and where available outline potential significant effects from residues, emissions, waste production, and use of natural resources such as soil, land, water, and biodiversity. Additionally, the requester may provide any other relevant information or measures designed to prevent or mitigate adverse environmental impacts.

2.5.5. Under the TCPA EIA Regulations 2017[5], the LPA has five (5) weeks to adopt an EIA screening opinion.

### EIA SCOPING

2.5.6. Following EIA Screening, if it is determined that an EIA Report is required, a formal 'Request for an EIA Scoping Opinion Report' would be prepared and submitted to the LPA. The Request for an EIA Scoping Opinion Report will set out the matters that the applicant believes should be 'scoped in' or 'scoped out' of the onward assessment within the EIA Report. The LPA will consult with key statutory consultees such as the Environment Protection Agency and feed their responses regarding these matters into the Scoping Opinion. The authorities aim to respond within five (5) weeks of receiving a valid Request for an EIA Scoping Opinion Report, depending on the complexity of the proposal and the consultation required.

### ENVIRONMENTAL STATEMENT

2.5.7. Following receipt of the Scoping Opinion, an ES would then be prepared to support the planning application. The ES would take into account the conclusions of the Scoping Opinion, in particular the matters to be scoped in or out of the assessment. Undertaking an ES can be a lengthy process, especially where environmental surveys, monitoring and / or modelling are required. Some types of surveys, such as ecology surveys, have seasonal restrictions and can only be carried out at certain times of the year. This can mean that data collection alone can take a year or longer. This should be factored into any programme.

### EIA RECOMMENDATIONS

2.5.8. The Proposed Development is likely to be classified under category Energy industry 3(d) of Schedule 2, which are *underground storage of combustible gases*. For such developments, EIA is triggered when either:

- The area of any new building, deposit or structure exceeds 500 square metres; or
- a new building, deposit or structure is to be sited within 100 metres of any controlled waters.

2.5.9. Since the permanent footprint of the AGI is anticipated to be 60 m by 60 m (3,600 $m^2$), EIA would likely be required for the Proposed Development given the Proposed Development exceeds the threshold of category 3(d) of Schedule 2 of the EIA Regulations.

2.5.10. Early engagement with the LPA is recommended regarding the screening and scoping process for the EIA.

**Habitats Regulations Assessment (HRA)**

2.5.11. Some developments also require an HRA under the Conservation of Habitats and Species Regulations 20177 (hereafter referred to as the 'Habitat Regulations') to be undertaken by a 'competent authority' before they can be consented. This Consenting Strategy does not provide advice on HRA but briefly summarises the steps of the HRA process.

2.5.12. The Habitats Regulations aim to ensure the long-term conservation of certain species and habitats by protecting them from adverse effects of projects by providing for the designation of sites for the protection of habitats and species of international importance. These protected sites include Special Areas of Conservation (SACs); Special Protection Areas (SPAs); and Ramsar Sites.

2.5.13. Teesmouth and Cleveland Coast Ramsar/SPA is located within 2km of Site Option 14. An HRA screening for likely significant effects would therefore likely be required.

2.5.14. A HRA screening request is the initial test required to determine if a proposed development, on its own or in combination with other proposals, risks having a significant effect on the protected site. If this screening confirms no likely significant effect, then no further work is required.

2.5.15. Where a proposed development is likely to have a significant effect on any protected site, alone or in-combination with other plans and projects, an appropriate assessment (AA) is carried out to determine whether or not the project will have an adverse effect on the integrity of the site in view of that site's conservation objectives.

2.5.16. Should the AA confirm that the protected site will be adversely affected, and no mitigation strategies can prevent this, then the next test would be to determine whether the project qualifies for any exceptions via a process called derogation. To see if a proposal qualifies for derogation, it must pass three legal tests which are:

2.5.17. Confirm there is no alternative solution that would be less damaging to the protected site;

- Consider if there are imperative reasons of overriding public interest (referred to as IROPI);
- Secure compensatory measures.

[7] The Conservation of Habitats and Species Regulations 2017

2.5.18. If a proposal passes all three legal tests, then it can proceed under HRA derogation, if not then the development cannot proceed.

2.5.19. The HRA process is separate to the planning process and needs to be completed before planning permission can be granted. To avoid delays to the planning process, consideration should be given to the location of protected sites and screening undertaken at an early stage in the consents process.

**Biodiversity Net Gain Assessment (BNG)**

2.5.20. In England, Biodiversity Net Gain (BNG) is a statutory requirement under the Environment Act 2021, which mandates that all major developments must achieve a minimum 10% net gain in biodiversity. This requirement is enforced through the planning system and applies to most planning applications, with developers required to submit a biodiversity gain plan demonstrating how this will be achieved.

2.5.21. Therefore, in the context of the Proposed Development, the applicant must not only explore but formally integrate biodiversity enhancements into the EIA and planning submission. This includes baseline ecological surveys, habitat creation or enhancement strategies, and long-term management plans to ensure measurable biodiversity improvements. Compliance with statutory BNG requirements will be essential for securing planning consent.

## 2.6. PLANNING POLICY COMPLIANCE

2.6.1. Any future planning submission will need to ensure compliance with National and Local planning policies. An assessment of the Proposed Development against relevant policies is undertaken below.

### NATIONAL PLANNING POLICY FRAMEWORK (NPPF) 2024

2.6.2. The NPPF sets out the Government's planning policies for England and how they should be applied. The following section highlights sections of the NPPF which are of relevance to the Proposed Development.

2.6.3. Chapter 2 *(Achieving sustainable development):*

- Paragraph 7 states that the "purpose of the planning system is to contribute to the achievement of sustainable development, including the provision of homes, commercial development and supporting infrastructure in a sustainable manner".

- Paragraph 8 identifies three overarching objectives of the planning system:

  a) ***an economic objective*** – to build a strong, responsive and competitive economy.

  b) ***a social objective*** – to support strong, vibrant, and healthy communities, through delivery of sufficient homes, fostering a safe and well-designed built environment, and supporting health, social and cultural well-being.

  c) ***an environmental objective*** – to protect and enhance the natural, built and historic environment, including improving biodiversity and mitigating/adapting to climate change through a low-carbon economy.

2.6.4. Chapter 4 *(Decision-making):*

- Paragraph 39 requires local planning authorities to "*work proactively with applicants to secure sustainable development that improves economic, social, and environmental conditions*."

2.6.5. Chapter 6 (*Building a strong, competitive economy) places significant weight on supporting economic growth and productivity, tailored to local strengths and opportunities.*

2.6.6. Chapter 12 *(Achieving well-designed places)*:

- Paragraph 131 states "*The creation of high quality, beautiful and sustainable buildings and places is fundamental to what the planning and development process should achieve. Good design is a key aspect of sustainable development, creates better places in which to live and work and helps make development acceptable to communities*."

- Paragraph 132 states *"Plans should set out a clear design vision and expectations, developed with local communities so they reflect local aspirations and are grounded in the area's defining characteristics."*Paragraph 133 states *"All local planning authorities should prepare design guides or codes consistent with the National Design Guide and National Model Design Code, providing a local framework for creating beautiful and distinctive places."*

- Paragraph 134 states *"Design guides and codes may be prepared at area-wide, neighbourhood or site-specific scale, and should be based on effective community engagement and reflect local aspirations for the development of their area."*

- Paragraph 135 states *"Planning policies and decisions should ensure that developments function well, are visually attractive, sympathetic to local character, establish a strong sense of place, optimise site potential, and create safe, inclusive and accessible places."*

- Paragraph 137 states *"Design quality should be considered throughout the evolution and assessment of proposals, with early engagement between applicants, authorities and communities encouraged."*

- Paragraph 138 states *"Design quality should be considered throughout the evolution and assessment of proposals, with early engagement between applicants, authorities and communities encouraged."*

- Paragraph 139 states *"Development that is not well designed should be refused, while significant weight should be given to schemes that reflect local policies and guidance, or demonstrate outstanding or innovative design that raises sustainability standards."*

- Paragraph 140 states *"Planning conditions should refer to clear and accurate plans and drawings to provide certainty, and authorities should ensure that the quality of approved development is not materially diminished between permission and completion."*

2.6.7. Chapter 14 *(Meeting the challenge of climate change, flooding and coastal change)*:

- Paragraph 161 confirms "*planning system should support the UK's transition to net zero by 2050."*

- Paragraph 163 requires that the "*need to mitigate and adapt to climate change is considered when preparing and assessing planning applications, taking into account the full range of potential climate change impacts."*

- Paragraph 164 requires "developments to avoid increased climate vulnerability and integrate mitigation measures such as green infrastructure and SuDS."

- Paragraph 166 confirms that, "*in determining planning applications, local planning authorities should expect new development to comply with decentralised energy policies where feasible and to minimise energy consumption through landform, layout, orientation, massing and landscaping."*

- Paragraph 168 gives "*significant weight to renewable and low-carbon energy developments and their contribution to net zero."*
- Paragraph 170 directs that "*inappropriate development in high flood risk areas should be avoided."*

- Paragraphs 172 - 178 require "*the application of the sequential and, where necessary, exception test for flood risk."*

2.6.8. The Proposed Development aligns with the overarching objectives of the NPPF 2024. It advances the economic objective by supporting growth and productivity *(Chapter 2, Paragraph 8)*, the environmental

objective through measures consistent with the UK's net zero target *(Chapter 14, Paragraphs 161–168*), and the social objective by contributing to well-being through sustainable infrastructure delivery *(Paragraph 8).*

## SPATIAL DEVELOPMENT STRATEGY

### Tees Valley Combined Authority Strategic Plans (Tees Valley Net Zero/Cluster Plan)

2.6.9. The Tees Valley Net Zero Cluster Plan sets out to reach UK to be Net Zero by 2040, driving hydrogen, Carbon Capture, Utilisation and Storage (CCUS) and industrial decarbonisation as core strategies.

2.6.10. *"In the Climate Change Act (2008) the UK has set into law that the country as a whole must reach **Net Zero by 2050**. Industrial clusters around the UK are relatively easy to abate … the Tees Valley is set to become a low-carbon industrial cluster by 2030 and potentially the world's first Net Zero cluster by 2040.*

2.6.11. *The principal aim of the Cluster Plan are to demonstrate how the Tees Valley industrial cluster can become a low-Carbon cluster by 2030 and the UK's first Net Zero industrial Cluster by 2040."*

2.6.12. The ***Hydrogen Vision*** is to create a Tees Valley hydrogen economy capable of supporting low carbon growth, energy security and industrial decarbonisation. Hydrogen is a key enabler in the transition to a low carbon economy and can support energy-intensive industries in achieving Net Zero.

2.6.13. *"The Tees Valley has the ambition to become a **Hydrogen SuperPlace**, producing low carbon hydrogen that will provide fuel and feedstocks for industry, power transport and heat buildings and homes regionally and across the UK. The ambition is for the Tees Valley to be part of the UK's net zero energy engine room, powering a transformation in the country's industrial economy**."***

2.6.14. *"In the journey to Net Zero, decarbonising industry is key to decarbonising the Tees Valley as a whole. Across the UK, 24% of total CO2 emissions are due to industry – locally in the Tees Valley industry accounts for a much greater proportion of the total - 64% of the total CO2 emissions. In the Tees Valley there are 6.40 tCO2/yr emitted per person compared with the national average of 1.24 tCO2/yr. This demonstrates the importance of **Industrial Decarbonisation** to the Tees Valley."*

2.6.15. The Proposed Development at Site Option 14 site fully aligns with the Tees Valley Net Zero Cluster Plan. The Proposed Development supports the Hydrogen Vision, the ambition for Tees Valley as a Hydrogen SuperPlace, and the infrastructure requirements for hydrogen distribution. It complements the region's $CO_2$ reduction strategies and industrial decarbonisation objectives.

## LOCAL DEVELOPMENT PLAN

### Stockton-on-Tees Borough Council Local Plan 2019*:*

2.6.16. The Stockton-on-Tees Local Plan (2019) sets out the Council's policies and proposals to guide planning decisions and establishes the framework for the sustainable economic growth and development of the Borough up to 2032.

2.6.17. **Policy SD4 (Economic Growth Strategy)** indicates the policies related to economic development within the Borough. The Policy states:

*"1. Economic development needs will be directed to appropriate locations within the Borough to ensure the delivery of sustainable economic growth.*

*2. Proposals for the redevelopment of previously developed land, in particular prominent sites which have been derelict for a significant period of time, will be supported.*

*5. Economic growth proposals which attract significant numbers of people will be permitted in the vicinity of a hazardous installation only where there is no significant threat to public safety.*

*7. The following sites are identified as principal office locations where new office development will be directed:*

*a. Stockton Town Centre and the District Centres.*

*b. North Shore.*

*c. Teesdale and Thornaby Place.*

*19. Support will be given to the creation of employment and training opportunities for residents. Major development proposals will demonstrate how opportunities arising from the proposal will be made accessible to the Borough's residents, particularly those in the most deprived areas and priority groups.*

2.6.18. Policy SD5 (Natural, Built and Historic Environment) states that:

*"1. Conserve and enhance the natural, built and historic environment through a variety of methods including:*

*a. Ensuring that development proposals adhere to the sustainable design principles identified within Policy SD8.*

*b. Protecting and enhancing designated sites (including the Teesmouth and Cleveland Coast Special Protection Area and Ramsar) and other existing resources alongside the provision of new resources.*

*c. Protecting and enhancing green infrastructure networks and assets, alongside the preservation, restoration and re-creation of priority habitats, ecological networks and the protection and recovery of priority species.*

*d. Enhancing woodlands and supporting the increase of tree cover where appropriate.*

*[…]*

*l. Preventing both new and existing development from contributing to or being put at unacceptable risk from, or being adversely affected by unacceptable levels of ground, air, water, light or noise pollution or land instability. Wherever possible proposals should seek to improve ground, air and water quality.*

*2. Meet the challenge of climate change, flooding and coastal change through a variety of methods including:*

*a. Directing development in accordance with Policies SD3 and SD4.*

*e. Ensuring development takes into account the risks and opportunities associated with future changes to the climate and are adaptable to changing social, technological and economic conditions such as incorporating suitable and effective climate change adaptation principles.*

*f. Ensuring development minimises the effects of climate change and encourage new development to meet the highest feasible environmental standards.*

*g. Supporting and encouraging sensitive energy efficiency improvements to existing buildings.*

*h. Supporting proposals for renewable and low carbon energy schemes including the generation and supply of decentralised energy."*

2.6.19. Local Plan Policy **SD3 – SD5** requires the Proposed Development to show compliance to integrate sensitive landscape features and demonstrate the benefit of the Proposed Development over housing provision as stated under **SD3(1)(2)(3)(5)**.

2.6.20. **Policy SD4(1)(2)(5)(7)(19)**: The Proposed Development is required to demonstrate compliance to support sustainable economic growth.

2.6.21. **Policy ENV5 (Preserve, Protect and Enhance Ecological Networks, Biodiversity and Geodiversity)** talks about protecting and enhancing the biodiversity and geological resources. The Policy states:

*"1. The Council will protect and enhance the biodiversity and geological resources within the Borough. Development proposals will be supported where they enhance nature conservation and management, preserve the character of the natural environment and maximise opportunities for biodiversity and geological conservation particularly in or adjacent to Biodiversity Opportunity Areas in the River Tees Corridor, Teesmouth and Central Farmland Landscape Areas.*

*2. The Council will preserve, restore and re-create priority habitats alongside the protection and recovery of priority species.*

*3. Ecological networks and wildlife corridors will be protected, enhanced and extended. A principal aim will be to link sites of biodiversity importance by avoiding or repairing the fragmentation and isolation of natural habitats."*

2.6.22. **ENV6 (Green Infrastructure, Open Space, Green Wedges and Agricultural Land)** states that:

*"5. Development proposals will be expected to demonstrate that they avoid the 'best and most versatile' agricultural land unless the benefits of the proposal outweigh the need to protect such land for agricultural purposes. Where significant development of agricultural land is demonstrated to be necessary, proposals will be expected to demonstrate that they have sought to use areas of lower quality land in preference to that of a higher quality."*

2.6.23. **ENV7 (Ground, Air, Water, Noise and Light Pollution)** states that:

*"1. All development proposals that may cause groundwater, surface water, air (including odour), noise or light pollution either individually or cumulatively will be required to incorporate measures as appropriate to prevent or reduce their pollution so as not to cause unacceptable impacts on the living conditions of all existing and potential future occupants of land and buildings, the character and appearance of the surrounding area and the environment.*

*2. Development that may be sensitive to existing or potentially polluting sources will not be sited in proximity to such sources. Potentially polluting development will not be sited near to sensitive developments or areas unless satisfactory mitigation measures can be demonstrated."*

2.6.24. Potential adverse effects are anticipated in relation to compliance with the Stockton-on-Tees Local Plan (2019), particularly with Policies SD3 - SD5, ENV5, ENV6, and ENV7. While the Proposed Development could deliver economic growth benefits in line with Policy SD4, there are some constraints relating to ecology and biodiversity. The proximity of sensitive features such as Teesmouth

and Cleveland Coast Ramsar/SPA and associated habitats that could support priority and protected species present a minor consenting risk which can likely be dealt with via mitigation measures.

2.6.25. The Proposed Development is strongly supported in broad terms by policy at a national, strategic, and local level. There are policy conflicts with some elements of both the NPPF and the Local Plan with regards to sustainable design. Additionally, pre-application consultation is required to ensure the Proposed Development mitigates potential impacts on ecological assets and neighbouring land uses. Any potential issues associated with unstable and/or contaminated land can be mitigated via engagement with the relevant parties around the scheme.

## 2.7. NETWORK RAIL CONSENT

2.7.1. The location of the site adjacent to an operational railway will likely require permission from Network Rail for any interaction with railway land. The Proposed Development will therefore likely be subject to several planning conditions serving to protect the line during construction and operational life of the Proposed Development. These conditions will be informed by Network Rail asset protection standards, namely around any geological works interacting with the structure of the existing tracks. This is not seen as a major risk due to the low usage (one train per day) of the line.

# 3. CONCLUSION AND CONSENTING OPTION

3.1.1. The Proposed Development does not meet the criteria for classification as an NSIP under the Planning Act 2008. However, it qualifies as a Major Development under Part 1 of the Town and Country Planning (Development Management Procedure) (England) Order 2015. The TCPA route is therefore considered to be appropriate.

3.1.2. A review of planning history indicates that energy-related development proposals within the Billingham area have generally received favourable responses at both LPA and DCO level. It is therefore anticipated that the Proposed Development will be positively received. Nonetheless, planning consent is likely to be subject to conditions addressing localised impacts, proximity to the railway line, and environmental management obligations.

3.1.3. Site Option 14 and its surrounding area are not subject to any designated site allocations. Additionally, the local planning authority has not issued any Article 4 Directions affecting this location.

3.1.4. While there is no statutory requirement for public consultation with the local community, undertaking such engagement is considered best practice. It is therefore recommended that NGT incorporates a proportionate consultation strategy to support transparency and stakeholder confidence.

3.1.5. Major developments require early and proactive consideration of environmental obligations to avoid delays and ensure regulatory compliance. An EIA screening and scoping request should be submitted to the LPA to determine the need for and scope of any EIA. Given that the thresholds under Schedule 2 of the EIA Regulations are exceeded, the requirement for a full EIA is highly probable. Early engagement with the LPA is strongly advised. Additionally, an HRA may be triggered if internationally designated sites are potentially affected. Projects can only proceed if stringent legal tests are satisfied. Furthermore, developers must demonstrate a minimum 10% BNG embedding ecological enhancements into the design and delivery of the scheme. These processes collectively ensure environmental protection is integral to decision-making and provide greater certainty for project progression.

In conclusion, the recommended consenting route is via the TCPA, in full compliance with the Council's validation requirements. A formal pre-application submission is strongly advised prior to lodging the full application. Implementing the above recommendations will enhance certainty around programme timelines, resource allocation, and budget planning for the consenting phase of the Proposed Development.

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# B-Linepack+ Stakeholder Interviews Report

Daniel Curry, Rosie Madge, and Grant Tuff

28 November 2025

CATAPULT Energy Systems

Accelerate Net Zero energy innovation

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# Introduction and background

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# Background

Linepack is a volume of gas that is stored in gas pipelines that can change pressure and therefore volume to provide flexibility in the system. It is used for daily balancing between supply and demand, providing operational flexibility. The B-linepack+ project has been designed to identify a way to provide the UK with the same amount of resilience on hydrogen networks as on the current natural gas network.

$H_2$FlexiStore is a modular hydrogen storage system originally developed by Gravitricity, that can deliver a reliable and flexible hydrogen supply for the hydrogen economy. Each system is installed into a new subsurface shaft and can provide storage of up to 100 tonnes of hydrogen.

During the Discovery Phase project, the research team found that limiting storage volume to 65 tonnes rather than maximum capacity increases the number of suitable geological locations for system installation.
$H_2$FlexiStore has the potential to:

- Deliver lower costs than above ground compressed hydrogen storage vessels.
- Provide locational flexibility as the concrete lined shaft allows construction in a wide range of different geologies. Unlike a salt cavern which requires a specific geology.
- Offer safe subsurface installation and multi-layer design.
- Provide flexible scale of storage to deliver hydrogen where it is needed

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# Introduction

We interviewed stakeholders with an interest in hydrogen across the wider energy sector. Our goal was to interview stakeholders from different categories to reflect the full range of perspectives across the sector (Table 1).

We interviewed six stakeholders to understand their insights on the following topics:

- How linepack is currently used in the natural gas network.
- How they see linepack being used in the future.
- The potential role of linepack with hydrogen.
- Perspectives on how costs for linepack should be allocated and possible payment mechanisms for linepack services.

The aim of this part of the project is to use stakeholder engagement to:

- Discuss with industrial stakeholders of their views around hydrogen linepack.
- Assess the potential value of using $H_2$FlexiStore technology to replace linepack for security of supply and resilience
- Consider likely impacts to consumers

This report provides the consortium with an overview of consumer understanding and response to the need to replace or substitute the gas networks linepacking for hydrogen linepacking.

| Stakeholder |
| --- |
| Academic |
| Geotechnical specialist |
| Hydrogen Producer |
| Hydrogen System Designer |
| Hydrogen End User |
| Policy |

Table 1: Stakeholder Categories

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# Methodology

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# Interview schedule

Each interview was conducted in three parts. The questions asked in each part are given below.

**Part 1: Understanding hydrogen use and storage needs**

- How do you see hydrogen being utilised now and in the future? Do you have any current examples?
- If you've done some modelling (for example: co-optimised electricity and gas system modelling incorporating hydrogen storage) what did it suggest about hydrogen usage and storage?
- How does the supply of hydrogen impact your modelling or operational needs?
- Will short term, readily accessible hydrogen storage become important? What scale do you think you'd need now and in the future?

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# Interview schedule

**Part 2: Linepack current use and requirements if hydrogen linepack was available**

- Do you currently use, or see a use/need for, hydrogen linepack* as the transition to Net Zero continues?
- If hydrogen gas usage increases, and is supplied through a network, do you feel linepack will be valuable to normal operation?
- What do you think the advantages and disadvantages of linepack are? Any challenges?

**Part 3: Understand perspectives of paying for Linepack**

Natural gas linepack has been an integral part of an energy system that utilises natural gas for many years. However, alternatives to natural gas will not provide this level of incidental storage within the system. This raises additional questions around how gas storage should be funded to ensure continued resilience and flexibility as we switch to net zero alternatives.

- Who should pay for linepack?
- How should it be funded?

**from this point in the report, "hydrogen linepack" is referred to as "linepack"*

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# Anonymised stakeholder comments and preferences

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# Part 1: Understanding hydrogen use and storage needs

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# Interview Results: Understanding hydrogen use and storage needs

The following tables give a summary of the key comments made, and views raised during part 1 of the interviews with each of the stakeholders.

| Stakeholder | Comments |
|---|---|
| Academic | • Hydrogen will be crucial for both seasonal and ultra long duration energy storage at large scales. Hydrogen is likely to be used in the following sectors: high temperature industrial processes, agriculture, fertiliser production and potentially for export. Hydrogen is likely to play a limited role in home heating; this will depend on whether homes are in areas where hydrogen infrastructure is already present.<br>• The government is currently using industrial clusters as an approach to develop hydrogen. Blending might be another way to help kick start a hydrogen sector in the UK.<br>• There is an emerging need for short term and linepack storage as electric vehicle fleets and demand profiles evolve. Economic competitiveness will factor in here. Gas system flexibility and balancing revenues currently lack clear frameworks for hydrogen. |
| Geotechnical Specialist | • There has recently been a rollback in predicted uses for hydrogen and policy supporting it. Therefore, it seems likely that hydrogen will act as a specific tool for industrialisation in some sectors and as a tool to cover the intermittency of renewables and provide long-term storage.<br>• A wide range of hydrogen storage remains crucial, which includes linepack, to provide flexibility across the system. Technology diversification is essential, as we will need storage with different response times and in different areas. |

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# Interview Results: Understanding hydrogen use and storage needs

The following tables give a summary of the key comments made, and views raised during part 1 of the interviews with each of the stakeholders.

| Stakeholder | Comments |
|---|---|
| Hydrogen Producer | • Industrial hydrogen will have clear end users.<br>• Currently, hydrogen users have a lack of confidence in the market. Hydrogen users are struggling to get a constant supply of hydrogen at a reasonable cost. Offtake agreements and storage could help to improve this.<br>• Energy is more secure with modular hydrogen production facilities rather than one large facility. Modular production facilities could also feed into the pipeline and therefore reduce the need for storage. |
| Hydrogen System Designer | • Hydrogen scale will depend on plant operations (continuous vs. batch). Hydrogen to power requirements need to be considered as they demand large storage capacity, but not enough to cover extreme events like Dunkelflaute*.<br>• Hydrogen storage needs to cover a variety of scenarios, such as industrial shut-downs when hydrogen production is still running and hydrogen consumption shuts-down.<br>• Small scale projects will likely need intra-day storage, while large scale producers or offtakers that shut down could lead to a large misbalance and therefore require larger storage. |

* *Dunkelflaute is a German term which refers to a period of low renewables (such as dark days and low wind in winter) which can cause increases in electricity prices.*

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# Interview Results: Understanding hydrogen use and storage needs

The following tables give a summary of the key comments made, and views raised during part 1 of the interviews with each of the stakeholders.

| Stakeholder | Comments |
|---|---|
| Hydrogen End User | • Hydrogen consumers need the right amount and quality of hydrogen at the right place and right time therefore linepack could be an option to provide this. If transportation is done to a timetable, then this can be predicted and modelled.<br>• A big factor is how to get the necessary hydrogen from the production location to where it is needed at a suitable cost. |
| Policy | • Industrial hydrogen will be focused initially on sectors like aviation and shipping, rather than large scale ammonia production. Early offtake opportunities may be available for refineries transitioning towards renewables or renewable hubs.<br>• Additional buffer storage options will be needed for hydrogen due to energy density compared to gas. However, alternative flexibility options must also be explored.<br>• The pace of deployment will be dependent on market development and conditions, government support, and the need for suitable policy frameworks to drive investment. |

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# Part 2: Linepack current use and requirements if hydrogen linepack was available

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# Interview Results: Linepack current use and requirements if hydrogen linepack was available

The following tables give a summary of the key comments made, and views raised during part 1 of the interviews with each of the stakeholders.

| Stakeholder | Comments |
|---|---|
| Academic | • Hydrogen linepack will act very differently to gas linepack due to pressure differences. Therefore, although hydrogen storage is required, the traditional linepack technology might not be the best method to provide it.<br>• Modular linepacking, like Gravitricity's technology, could provide more resilience than traditional linepacking. Modular linepack could provide flexibility whilst diversifying away from the reliance on a heavy weight energy system. However, modular systems will need suitable financial and market structures to exist to enable deployment. |
| Geotechnical Specialist | • Small scale modular systems have several advantages, such as lower CAPEX, reduced need for geotechnical assessments and reduced geotechnical risk, compared to large systems, such as salt caverns.<br>• The value of linepack increases as the number of supply and demand users on the network increases. The effectiveness also depends on its role in the broader storage mix and how it complements other technologies. |

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# Interview Results: Linepack current use and requirements if hydrogen linepack was available

The following tables give a summary of the key comments made, and views raised during part 1 of the interviews with each of the stakeholders.

| Stakeholder | Comments |
|---|---|
| Hydrogen Producer | • To maintain efficiency and supply, some regions will have 24/7 hydrogen production, despite potential stockpiling. Linepack is great at providing an extra storage option.<br>• There is a need for security of supply of hydrogen for end users. |
| Hydrogen System Designer | • Linepack should be able to manage hourly and daily balancing between supply and demand without oversizing the network.<br>• Even considering hydrogen's lower energy density, oversizing the network beyond what is required from the network seems unnecessary. Additional storage may be needed to provide higher flowrates at reduced capacities. |

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# Interview Results: Linepack current use and requirements if hydrogen linepack was available

The following tables give a summary of the key comments made, and views raised during part 1 of the interviews with each of the stakeholders.

| Stakeholder | Comments |
|---|---|
| Hydrogen End User | • Linepack could provide better security of supply and availability than other options, however it would need to be at the right pressure, quality and cost. For example, the pressure directly from the hydrogen line may not be suitable so linepack might be able to help with pressure changes. There is a query around whether linepack would be able to continually supply hydrogen at the required pressures and volumes. |
| Policy | • Linepack will depend on whether the need for hydrogen is centralised or decentralised. For shorter, more local uses, linepack may be unnecessary and alternatives like batteries may be better.<br>• A big factor will be the costs of expanding the electricity network versus the cost of repurposing the gas network. There could be a trade-off between hydrogen transport costs and direct electricity distribution.<br>• Linepack provides resilience and balancing benefits. However, it requires a national hydrogen network and without it, linepack's role in achieving net zero is limited. |

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# Part 3: Understand perspectives of paying for linepack

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# Interview Results: Understand perspectives of paying for Linepack

The following tables give a summary of the key comments made, and views raised during part 1 of the interviews with each of the stakeholders.

| Stakeholder | Comments |
|---|---|
| Academic | • There is no current mechanism to recover the cost of linepack, however it does provide an essential tool to manage system supply and demand. All compression costs are imbedded at the transmission level which makes it essentially “free”.<br>• A market-based framework is needed that includes mechanisms to recognise and value storage and flexibility services, rather than combining with other overall system costs.<br>• Hydrogen storage could be funded by each storage facility reserving a portion of hydrogen for resilience, funded by government, while the remaining storage could be traded on the market. This approach would mirror electricity, with a standing charge to cover the cost of maintaining resilient storage.<br>• Historically, linepack is paid for through consumer bills therefore hydrogen linepack might end up being paid for in a similar way. |
| Geotechnical Specialist | • Subsidies and allocation rounds are being introduced to fund storage technologies, however, they create a non-level playing field which may disadvantage other storage technologies. Broader support or funding mechanisms may be more beneficial towards smaller scale storage types like linepack.<br>• Private capital, clear payback mechanisms and trading systems are needed for linepack to be commercially viable. Price signals and nodal pricing will help this, but also integration of linepack into larger UK hydrogen markets will be critical for storage operators' revenue.<br>• Gas network operators could be an option to operate local storage. This would work in a similar way to linepack currently. As we move towards a blended system, there may need to be blurred lines between the electricity and gas sectors, especially if hydrogen is being used in the power sector. |

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# Interview Results: Understand perspectives of paying for Linepack

The following tables give a summary of the key comments made, and views raised during part 1 of the interviews with each of the stakeholders.

| Stakeholder | Comments |
|---|---|
| Hydrogen Producer | • Offtake agreements need a guarantor. Government might have to absorb the financial and market risks if industry are unwilling to take them in the initial phase or start up. Market signals will be key in reducing doubt and risk.<br>• Linepack could be funded using a circular economy approach. |
| Hydrogen System Designer | • Producers and users should be required to pay for storage they use to meet their needs, which includes demand spikes and variation.<br>• Any self-initiated oversizing of linepack must be funded by the operator. System should be designed to its use.<br>• Some operators may choose to link with a salt cavern for example, rather than linepack based on operational needs. |

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# Interview Results: Understand perspectives of paying for Linepack

The following tables give a summary of the key comments made, and views raised during part 1 of the interviews with each of the stakeholders.

| Stakeholder | Comments |
|---|---|
| Hydrogen End User | • Ideally, costs should not be on end users. The network operators may be better suited as they must balance the pressures and feed.<br>• "Hydrogen valleys" could act as a test case for demonstrating hydrogen linepacking and how it is costed. They would be locations that are supported by public funding with several local hydrogen beneficiaries. |
| Policy | • If industrial offtakers bear the full cost, then this will likely be passed on to the cost of commodities, such as SAF, and eventually to the end consumers.<br>• The feasibility of linepack without government funding is uncertain, interim public funding may be needed to show the viability of linepack. |

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# Interview summary

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# Interview Results Summary

A combined summary of each part of the interview is provided below.

## Part 1: Understanding hydrogen use and storage needs

- **Storage will be crucial to ensuring a constant supply of hydrogen.** The volume of hydrogen being produced may exceed what linepack can handle if demand fluctuates too dramatically. Therefore, the **system needs to be designed to cope with the intraday fluctuations and events**, such as shut-downs, so that the supply and demand is properly managed and doesn't compromise the network.

- Hydrogen is becoming a **tool for industrial decarbonisation and for seasonal and long duration energy storage to provide resilience and security.** Local short-term storage will be crucial for intraday balancing but given that the energy density is lower than natural gas, there may need to be more storage. Energy storage options outside of hydrogen may provide better flexibility such as batteries, but this will be on a case-by-case basis.

- **Predictable supply, demand, and distribution of hydrogen is needed**, especially in the transport sector. **Market confidence depends on a reliable supply, offtake agreements, certification, cost competitiveness, and network flexibility and reliability** for example in the deployment of a hydrogen network. Short term storage technologies (like linepack) are likely to play an important part in providing energy security and to help with supply chain growth.

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# Interview Results Summary

A combined summary of each part of the interview is provided below.

## Part 2: Linepack current use and requirements if hydrogen linepack was available

- Linepack can provide **clear benefits to operational flexibility through intra-day balancing between demand and supply.** However, there needs to be **clear tolerances** when it comes to pressure, for example to ensure consistent supply without having to do additional processing for end consumers if it fell below tolerances. The perceived value is dependent on a sufficiently sized network. **Smaller localised centres may not require flexibility from linepack** and exist on individual agreements, for example. How hydrogen linepacking is **delivered is also up for debate**, for example using small production facilities instead of storage facilities.

- In some situations, there may be a **trade-off between technologies and their respective flexibility.** Hydrogen can be generated in ways that work alongside the electricity network, whereas batteries rely solely on it. The decision to use **hydrogen vs. electricity will depend on several factors such as cost, scale, and security of supply.** However, **seasonal and long duration energy storage is a non-negotiable** and multiple smaller stores are likely to still be required to provide resilience and security.

- **Linepack requires careful management around operational parameters** such as quality and pressure, but also geological assessment to determine suitable locations for deployment. **Localised clusters with smaller networks may be less risky than national networks** which may have a greater intrinsic risk and associated costs. **Market mechanisms and support from government will further help deployment and demonstrate commitment.** The network should be sized correctly rather than just oversizing.

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# Interview Results Summary

A combined summary of each part of the interview is provided below.

## Part 3: Understand perspectives of paying for Linepack

- **There is not one definitive answer over who should pay for linepack.** Producers and users pay for the storage that meets their demands on the network side which includes linepack. If the network operator oversize's the system, then this cost should be borne by them. If this is the case, then this might be passed on to consumers in the form of increased prices for the end product. **Hydrogen valleys could be used to demonstrate technologies such as linepack at a larger scale** before scaling up further. This would help demonstrate the case for, and size of linepack required across a wide range of different end users and producers and help to develop potential business models.

- Current business models favour certain storage technologies which creates an uneven playing field and hinders the development and growth of other storage technologies. **Government guarantees, interim funding, and incentivised private investment will help deploy linepack, but the requirements for securing funding should include how the storage technology supports linepack.** The perception of risk will impact funding levels too, but with clear and consistent market and policy directions this risk can possibly be reduced.

- The cost of **using linepack may cause a shift in usage patterns towards other methods of providing flexibility that is cheaper and more established within market and policy frameworks. When developing the hydrogen network, considering how it could interact with the electricity network could support it economically rather than developing the hydrogen network in isolation**. If the cost of deploying a national hydrogen network is not as effective as spending the funding on strengthening the electricity network. Implementing things like standing charges or other mechanisms similar to the electricity market might be an option to ensure continuity without undermining market dynamics.

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# Opportunities and challenges identified

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# Opportunities and Challenges Identified

Recognition of the value of hydrogen linepack was broadly positive across the interviews, however there were key themes that kept emerging around key aspects:

- **Balancing, storage, and operation:**

**Understanding the supply and demand profiles, including off time, ramp rate, and line operational boundaries will impact who can join the network alongside what other interim storage may be needed to ensure consistent supply.**

The network needs to be **designed with a whole system approach to ensure operability and resilience** if an end user or producer comes offline for a period. Given the energy density difference between hydrogen and natural gas, this too needs to be considered given greater volumes and it is possible more storage may be needed to operate at the desired pressures for offtakers. This includes purity constraints particularly over longer distances.

Stakeholders implied that **linepack will need to play a part in supply demand balancing, especially during intermittent generation.** Other storage technologies will also play a role in ensuring system resilience and reliability by supplying hydrogen to the network and providing the volume and pressure required for hydrogen linepack when demand is greater than supply.

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# Opportunities and Challenges Identified

- **Local vs. National:**

Local hydrogen networks may operate differently to a national network. A national network will have greater numbers of producers and offtakers and could have a higher technical and financial risk. Other considerations such as geotechnical suitability, public perception, additional compressors, and safety pressures for example will influence the total cost of ownership.

Local hydrogen networks, such as in hydrogen hubs or valleys, may work better on other transportation mechanisms such as tube trailers, depending on their operational need. **Understanding the needs of various producers and end users will be crucial in defining operational parameters for linepack, as well as determining if it is feasible for them to be part of a network.**

- **System Integration and Market Challenges:**

**Hydrogen linepacking must be competitive with other flexibility technologies and services.** If it is too expensive or doesn't meet requirements, offtakers may decide to produce energy in some other form. Hydrogen may be integrated into the electricity network to provide electricity more competitively. **Exploring pricing structures, such as standing charges or flexibility tariffs, for hydrogen will help demonstrate the market, alongside policy direction.** These market signals will help to reduce the perceived investment risk

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# Opportunities and Challenges Identified

- **Economic uncertainty:**

Who should pay for linepack still remains a big challenge for deployment. **Addressing the market signals, government policies, and commitment will help to reduce the perceived risk of investment, but this doesn't answer who should pay for linepack.**

Short duration storage could play a crucial role in intra-day balancing and one way to reduce uncertainty may be a business model centred around linepack.

Alternatively, **undertaking a pilot study using a current hydrogen hub or valley would help demonstrate the business case for hydrogen linepacking**. One suggestion was that both the offtakers and producers pay for their required storage needs (including linepack all the way to salt caverns) from the system. If the system operators want to build more storage as a buffer then this proportion of linepacking (and other storage) would be borne by them.

**Understanding the operational parameters** of both the hydrogen network and linepack **will help to reduce stakeholders perceived risks** around security of supply and reliability. In some cases, linepack could become the preferred additional storage method if it is economically competitive and is reliable. **Ultimately, the cost of linepack may eventually be passed onto the consumers purchasing products, which could have further implications.**

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# Recommendations for next steps

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# Next Steps

- Wider stakeholder engagement – Speaking to more stakeholders provides a wider understanding around the perception of linepacking. This may help to identify a particular group of stakeholders with a particular interest in having access to hydrogen linepacking.

- Interview and reinterview participants with more detailed projected financial costs for linepacking and operational needs - doing so will help to understand the perceived value for money, alongside who may be more interested from a consumer angle.

- Consider wider stakeholder types – Working together alongside other projects, such as Project Union, would enable a wider understanding from stakeholders from other types of groups/bodies such as environmental groups and public perception groups.

- Given the responses, hydrogen linepack will likely play a role (alongside other hydrogen technologies supporting) in providing intraday supply demand balancing. However, understanding the availability and operational parameters of hydrogen linepack will factor into whether stakeholders will connect to a national network or source their hydrogen flexibility through other technologies or sources. When performing future stakeholder engagement, this information will help to understand what types of stakeholders will benefit from hydrogen linepacking.

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