Safe and Distributed Underground Storage of Green Hydrogen in Conjunction with Storage of Power and Inter-Seasonal Heat

Phase 1 Feasibility Report September 2022

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01	12/09/2022	Final Draft	SM/JLN/JW	MF	MF
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CHANGE DESCRIPTION

01	Final Draft
02	Addressed comments received from project monitoring officers and BEIS
03	Added Phase 2 information in executive summary, section 7 and appendix
04	CAPEX Breakdown, Cost reduction strategy, system architecture and some design results, and OPEX added

GLOSSARY OF TERMS

BEIS	Department for Business, Energy, and Industrial Strategy
MWh	Mega Watt Hour
TWh	Terra Watt Hour
GW	Giga Watt
CAPEX	Capital Expenditure
OPEX	Operating Expenses
WP	Work Package
GIS	Geographic Information System
LCOS	Levelised Cost of Storage
MPa	Megapascal
m	Meter
kg	Kilogram
RAG	Red, Amber, Green rating
IP	Intellectual Property
EPC	Engineering, Procurement, Construct
SPV	Special Purpose Vehicle
EPCM	Engineering, Procurement, Construct Management
COMAH	Control of Major Accident Hazards
IRR	Internal Rate of Return
NPV	Net Present Value
WACC	Weighted Average Cost of Capital
Te	Tonne

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1 EXECUTIVE SUMMARY

Gravitricity and partner Arup have conducted a study to explore the feasibility of storing compressed gaseous hydrogen at high pressures within a lined shaft, integrated with Gravity-based energy and inter-seasonal heat storage. Gravitricity's hydrogen storage concept will provide a novel hydrogen storage system to enable the hydrogen economy to grow and provide confidence to potential users that there will be a supply of sufficient volumes of low carbon hydrogen at a competitive price.

The first part of the study covered operational parameters to establish the hydrogen storage pressure, shaft dimensions, and required flow rates. This enabled the project to progress to system concept design. The shaft lining and capping design were the major technological concepts derived. Structural and geological modelling took place to assess the interaction of the shaft lining with the surrounding rock. Results indicate the liner can be designed to adequately transfer the load from the internal pressure to the surrounding geology in a safe manner, demonstrating that a lined rock shaft is a credible solution to store hydrogen within the subsurface at high pressures.

As part of the study, the integration of gravity-based and inter-seasonal heat storage was considered. Gravitricity have concluded that the integration of gravity-based storage is not desirable at present, due to the range of new technical challenges this would introduce such as modified dome geometry, on-surface (rather than below surface) cap design and hydrogen embrittlement of gravity energy equipment. Additionally, integrating a lifting system would increase the ignition risk within the shaft. The inter-seasonal heat stored within cylindrical pipes around the shaft would have capacity to store heat sufficient for a single building within proximity to the shaft and would thus be of limited commercial interest. As a result of these findings, Gravitricity will focus on the development of a hydrogen only storage system and do not intend to actively pursue the integration of hydrogen, heat & gravity combined storage technology variant further at present.

A commercial feasibility assessment was undertaken including a cost plan, roll out assessment and market assessment. Multiple capacity scenarios were assessed confirming that the more hydrogen that can be stored within the shafts the better the economic and commercial feasibility of the project.

The Phase 1 feasibility study has successfully shown that it is technically and commercially feasible to store large quantities of compressed gaseous hydrogen in a lined rock shaft. The project identified that Gravitricity's hydrogen storage system fills a gap within the market, by providing a medium level of storage potential with a high-level of geographical flexibility. The focus of this study was a 100-tonne capacity design, but the technology could be scaled up successfully for larger capacities, either using a larger shaft or multiple shafts on a single site. The project will continue to develop and will focus on a hydrogen-only storage system within a newly, purpose-sunk shaft.

Gravitricity has engaged with industry experts, research organisations and end-users to propose a demonstration program which involves a range of development activities which includes component, sub-system, and integration level validations. Research organisations, such as BGS, will characterise long-term rock mass behaviour under cyclic loading and validate effects of hydrogen embrittlement of shaft lining materials. The University of Leeds will validate lining long-term behaviour in their large-scale testing facility. Shaft Sinking expert (VSL-Bouygues) and pressure vessel design and manufacturer (Bendalls Engineering) will support the development of the lined rock shaft hydrogen storage system and work with Gravitricity to build an underground demonstrator.

Gravitricity have received letters of support from potential key energy network/infrastructure companies such as Scottish Power and SGN, expressing their support for the project and their belief that Gravitricity's hydrogen storage system has potential to accelerate the transition to a hydrogen economy in a cost-effective way.

2 INTRODUCTION

This work was completed as part of the Business, Energy, and Industrial Strategy (BEIS) Low Carbon Hydrogen Supply 2 competition – Phase 1, from which the project received £299,895 of funding to undertake a feasibility study. The study explored the storage of compressed gaseous hydrogen at high pressures in an underground lined shaft, integrated with gravity and inter-seasonal heat storage. To carry out this project, Gravitricity partnered with Arup to utilise their multi-disciplinary design capabilities.

3 THE PROJECT

The aim of the Low Carbon Hydrogen Supply 2 competition is to support the development of innovative solutions for the supply of hydrogen. Gravitricity and Arup have worked together to develop a safe, scalable, and commercially viable hydrogen storage system, which will accelerate the growth of the hydrogen economy. The system is flexible to be applicable for numerous end-use applications such as fuel gas for high-heat industry (e.g., steel, glass works), ammonia production and heavy transport. The storage system will be capable of responding to variable supply of hydrogen produced by electrolysis from renewable energy sources such as wind and solar, also known as green hydrogen.

Hydrogen gas will be stored at high pressures in an underground shaft. Gravitricity's underground hydrogen storage utilises the surrounding in-situ ground stresses, as well as the rock mass strength and stiffness, to resist internal gas pressure from the stored hydrogen. This reduces steel tonnage by a factor of 3-5 per unit mass of hydrogen stored compared to current above ground storage solutions, resulting in reduced material costs. The risk of leaks is low as the hydrogen is contained by a gas-tight liner and additionally the surrounding rock mass. With a reduced above ground footprint, and improved safety measures, the system has the potential to be employed on a large scale and can be deployed anywhere hydrogen storage is needed.

Hydrogen production and use will be essential if the UK is to achieve net zero target by 2050. An analysis by BEIS suggests that 250 to 460TWh of hydrogen may be needed by 2050[1]. Hydrogen can be produced through processes such as steam methane reformation from natural gas, known as blue or grey hydrogen and/or electrolysis using renewable energy to power electrolysers, known as green hydrogen. The UK's ambition is to provide up to 10GW of low-carbon hydrogen by 2030, with at least half of this being produced from electrolytic hydrogen[1]. The UK is already producing hydrogen for several industries and end users (ammonia production, fuel cells for vehicles e.g., buses). However, to achieve net zero targets this rate of production must increase and there will be a greater need to store hydrogen.

Hydrogen storage will need to provide storage flexibility over various timescales from daily use to periods of a month and upwards. At present, there are limited solutions to store hydrogen and salt caverns and above ground storage vessels are the main technologies available. Currently, salts caverns in Teesside provide half of the UK's hydrogen storage capacity of 30TWh with the rest being stored in above ground storage vessels. The UK's annual hydrogen demand is predicted to increase to 460TWh by 2050 and Gravitricity's hydrogen storage concept is envisaged to be an integral part of the UK's hydrogen storage solution.

3.1 Description of work packages

The project was divided into five work packages.

Work Package	Description
WP1 Operating Parameters	The aim of WP1 was to explore the operating parameters of the hydrogen storage system. These included shaft dimensions, input and output pressures, flow rates and storage pressure. Preliminary assessments of geology and types of lining was also completed. The work was carried forward into WP2 for a thorough evaluation. A high-level review of the hydrogen storage market, potential end-users and the broader role of hydrogen storage was compiled and fed into WP4.
WP2 System Design	WP2 progressed with the parameters identified in WP1 and provided the major technical output of the project together with a CAPEX (Capital Expenditure)/OPEX (Operating Expenses) assessment. The aims of WP2 were to: 1. identify the shaft sinking technique and construction sequence for developing underground shafts suitable for hydrogen storage 2. develop a shaft lining and capping technology concept for the safe storage of hydrogen (e.g., mechanical integrity for operation under high pressures, material compatibility with hydrogen) 3. assess feasibility of the integration of Gravity-based and inter-seasonal heat storage
WP3 Site Selection Criteria	Parameters identified in WP1 and WP2 helped to define site requirements e.g., operating and storage pressure etc. A list of potential sites was assessed by developing a Geographic Information System (GIS) model to assess parameters including accessibility to gas and electricity grid networks, proximity to hydrogen production, and proximity to existing hydrogen storage facilities. Based on the work carried out in WP3, areas have now been identified where Gravitricity's hydrogen storage system is best suited within the UK.
WP4 Commercial Feasibility	The aim of WP4 was to undertake a cost plan, revenue model and market assessment to assess whether Gravitricity's hydrogen storage concept is commercially feasible.
WP5 Project management	This work package ran for the length of the project and was responsible for ensuring outputs were delivered as planned. It included final reporting to BEIS and wider dissemination work. The partners met monthly to monitor progress. Quarterly BEIS meetings took place, where KPIs were reported, and deliverables assessed. The work package deliverables included draft and final feasibility reports as well as any additional reporting that has been requested by BEIS. A risk register was also maintained for the duration of the project.

Table 1: Project work packages

3.2 Assessment overview and benefits of the system

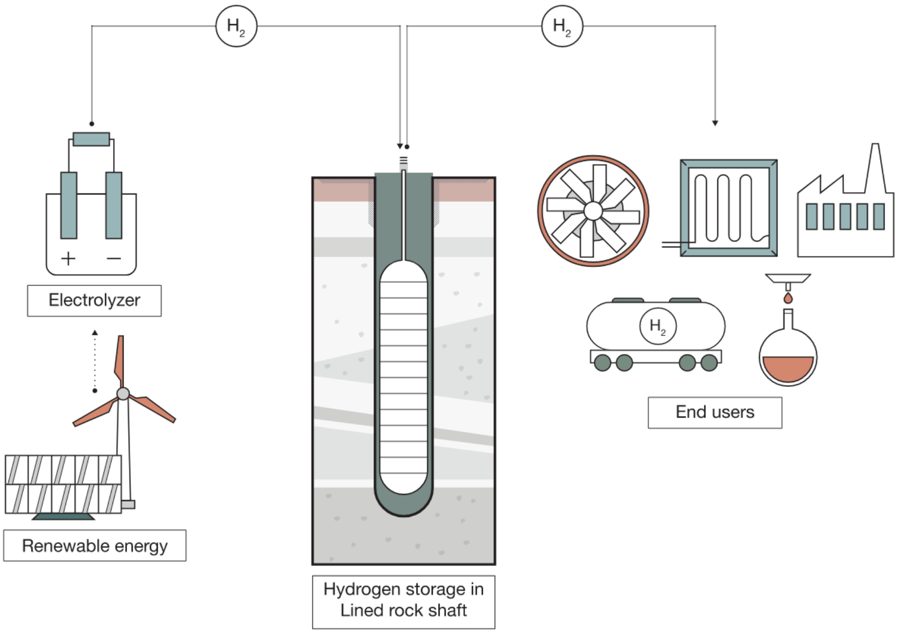

Figure 1: Schematic diagram of the Gravitricity hydrogen storage system linking to the hydrogen industry, producers, and end-users

As the part of the BEIS Low Carbon Hydrogen Supply 2 competition, BEIS have supported the UK hydrogen sector to develop novel hydrogen storage solutions to enable the hydrogen economy to grow and provide confidence to potential users that there will be a supply of sufficient volumes of low carbon hydrogen at a competitive price. This project has completed a feasibility study on an innovative hydrogen storage system that will be capable of storing compressed gaseous hydrogen within purpose-built, newly sunk shafts which would support the global effort toward more hydrogen storage infrastructure required to meet the UK's commitment to achieve net zero by 2050. A commercial feasibility study has also been carried out as part of the project to determine the levelised cost of storage (LCOS) for the storage system. Four scenarios were modelled, a single shaft scenario with varying capacities, to a multi-shaft scenario.

The study focussed on a commercial scale project consisting of a shaft diameter of 6m by 200m depth to store compressed hydrogen, however Gravitricity identified a range of shaft dimensions that is applicable. Hydrogen will be injected and withdrawn from the shaft daily, weekly, or monthly depending on the users' requirements. The maximum operating pressure within the shaft will be 20MPa when the shaft is at full capacity. As the pressure decreases during withdrawal of the hydrogen it may reduce to a minimum of 3MPa. Access may be required to allow for regular inspections of the system, and this could be carried out by withdrawing all hydrogen from the shaft and inspecting via remote monitoring and instrumentation. The storage system has ability to store up to 100 tonnes of hydrogen per shaft; however, the shaft dimensions and volumes are flexible depending on the end-users' requirements for a hydrogen-only storage system. Diameter and depth components of the shaft can be varied for a wide range of sizes and dependent on factors including uplift, shaft-sinking methodology and constructability. This will be explored further within the next stages of the project and in discussion with shaft sinking companies, pressure vessel manufacturing and design experts.

The study has included the basic parameters required for storing compressed hydrogen. Potential end-users including renewable energy generators, hydrogen consumers for industrial use, heavy-transport and ammonia production were investigated. Site requirements were listed, and a GIS model was constructed to be able to adjust the weighting of each requirement to short-list potential sites for the hydrogen storage system. Geotechnical and structural modelling was undertaken to assess interaction of the lining with the rock to understand how the rock behaves during unloading and reloading of the shaft when injecting and withdrawing hydrogen from the storage shaft.

The benefits of storing hydrogen within a shaft are:

- the internal gas pressure is distributed through the lining system to the surrounding rock mass, which provides confinement to the system therefore reducing material needs compared to above ground storage systems
- small site footprint
- reduced risk of leak as hydrogen will be, additionally to the liner, contained by the surrounding rock mass
- hydrogen purity maintained - the hydrogen will not be exposed to geology where impurities may enter the system and therefore will maintain purity when loaded in the shaft. The shaft is lined and gas-tight and therefore will prevent any contaminants from entering the shaft
- scalable – shaft dimensions can be adapted to fit end-user/producer capacity requirements
- multiple shafts may be sunk at a single site to provide greater capacity
- not restricted to certain geology
- fast speed of deployment of hydrogen, the system can be constructed within 2 years unlike salt caverns that take up to 6 years.

4 SYSTEM DESIGN

4.1 Functional requirements

For design purposes, the project defined the operational condition and geometrical requirement ranges of pressurised gaseous underground hydrogen storage in a lined rock shaft. Ultimately, end-user requirements, hydrogen production capabilities and site-specific ground characteristics will inform the optimum conditions for commercial design. The baseline parameters for this study were:

Parameter	Value
Shaft depth [m]	200
Shaft internal diameter [m]	4.5 to 10.0
Operating pressure range [bar]	30 to 200
Operating temperature range [°C]	0.0 to 38.0
Cyclicity [year^{-1}]	70 to 365
Design life [years]	25

Table 2 : System parameters

4.2 System architecture

For the purposes of considering the requirements, interfaces, and design, the system has been divided into ten sub-systems. The technological maturity at the start of the project and therefore the risk associated with each sub-system differs and Gravitricity focussed on de-risking and understanding the novel aspects of this technology. The integration of the lifting system and the heat exchanger are further explained in the Section 4.7. However, after carrying out design and cost analysis, the project has concluded the focus should be on a hydrogen-only storage system. A particular focus will be given on the novel aspects of this technology (i.e. shaft, lining and cap).

4.3 Shaft sinking

The suitability of different shaft sinking technologies was considered for the construction of a lined rock shaft for hydrogen. Due to safety restrictions for small diameter shaft construction, mechanised or caisson design will be required. Electing the most advantageous sinking technique to mitigate design and construction risk will be based upon the results of thorough ground investigation and characterisation for each specific site.

4.4 Liner and capping description

The lining design considers the functional requirements of the system and the construction sequence, and will consist of several components:

- gas tight liner – to provide gas tightness, for which material selection will consider hydrogen embrittlement and cyclic fatigue
- sliding layer – to surround the gas tight liner, reducing friction and minimising localised strains in the gas tight liner, as well as providing a level of corrosion resistance
- structural liner – to ensure a smooth base for the inner lining system and transfer the load from the internal gas pressure into the surrounding rock mass. The structural liner will also resist ground loading for cases where the ground loading is greater than the internal pressure
- depending on the shaft radius, depth, excavation technique, and ground conditions, additional temporary lining or a drainage system may be required

The lining system will require capping to provide a gas tight shaft. Hemispherical caps are the most efficient geometry. The bottom hemispherical cap will form a bulkhead at the shaft bottom. The top hemispherical cap will consider the required uplift resistance to the maximum operational pressure. The shaft will be connected to above ground plant by a production string with subsurface safety valve.

4.5 Shaft design and analysis

Four main aspects were considered for the system design:

- stability of the rock mass and lining system during excavation and construction
- gas-tight lining system with ability to distribute loads to the rock mass during operation
- resistance of the system to uplift pressures during operation
- stability of the rock mass and lining system during cyclic operational loading conditions

All of the aspects for the shaft lining design are dependent on the predominant ground behaviours. A range of rock masses were assessed for their potential suitability as host rocks. Rock mass characterisation was carried out for several intact rock properties, providing rock mass parameter inputs for analysis.

Analytical calculations using the convergence-confinement method were undertaken to determine the ground behaviour of each rock mass due to ground relaxation during excavation, as well as due to reloading from internal pressurisation. Additionally, finite difference method continuum numerical modelling was undertaken to validate analytical calculations (Figure 2), before undertaking modelling using more advanced constitutive models, and including the lining system, to further understand the ground behaviour. Analytical calculations and numerical modelling were also undertaken to assess the uplift resistance of the system (Figure 3).

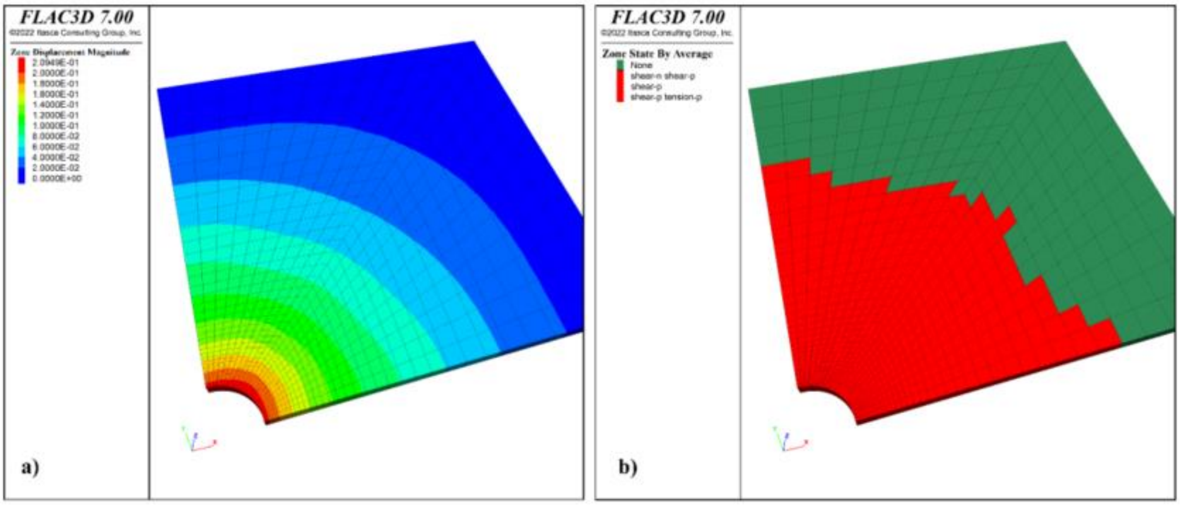

Figure 2: Unsupported numerical model for a given geological condition. A) displacement magnitudes due to reloading. B) yielding/plasticity due to reloading.

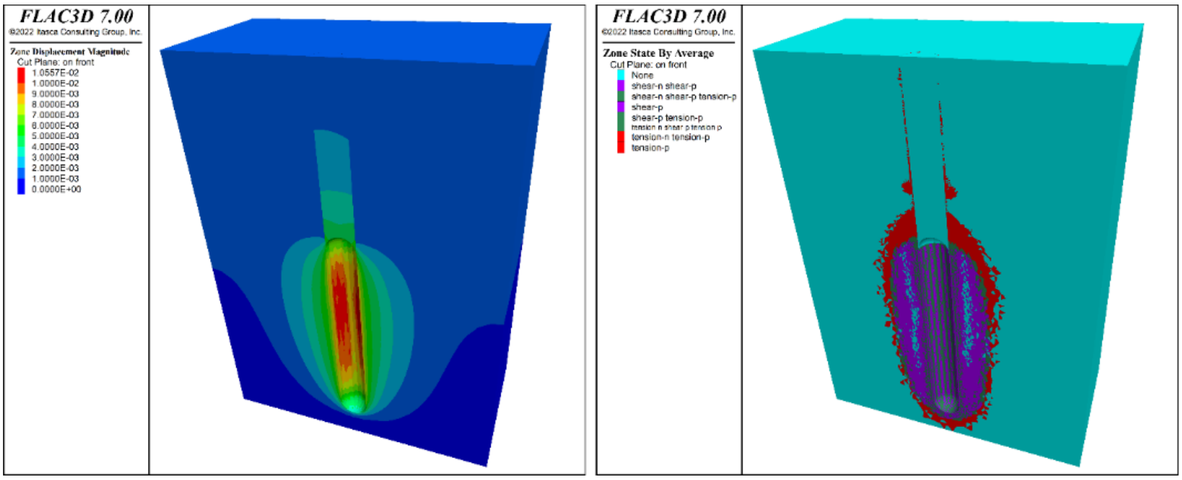

Figure 3: model of uplift resistance for plug with interface properties. a) Displacement magnitudes b) Zone yielding/tensile failure.

The behaviour of the structural lining system was assessed in greater detail using multi-physics simulations, capturing the non-linear behaviour of steel and concrete and the contact interfaces within the lining system (Figure 4). In addition to the mechanical load cases, a thermal load case was assessed. Additionally, analytical calculations were undertaken to assess the buckling stability and fatigue life of the lining system.

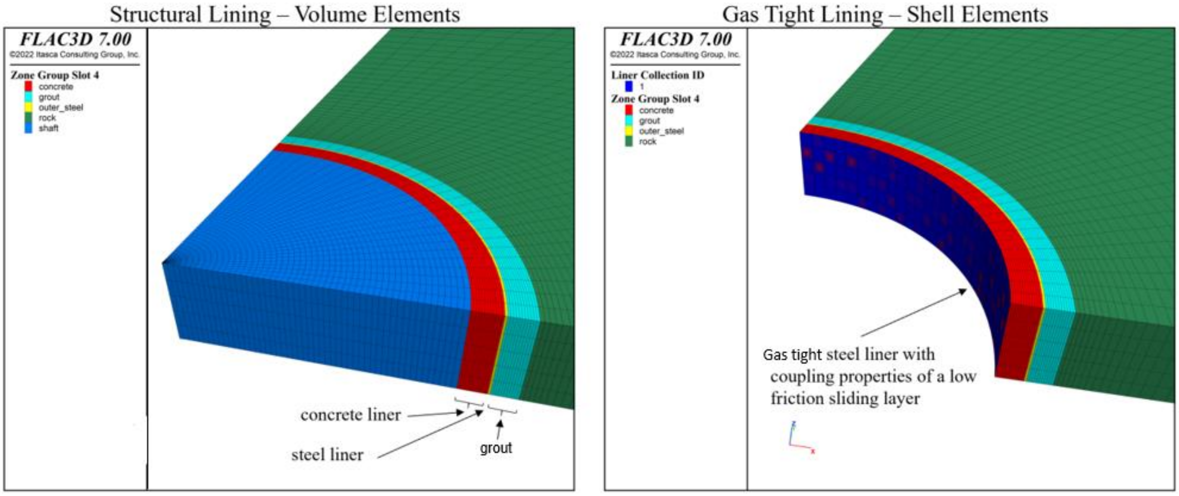

Figure 4: Supported model geometry.

Convergence-confinement analysis shows that the structural lining system would be suitable for all tested rock mass scenarios during initial ground relaxation due to excavation. Upon reloading when the system is pressurised, the rock mass strength and stiffness are key to the system performance, with low stiffness, weak rock masses being unsuitable for high internal pressures. However, the functional requirements, operating conditions and the design of the system may be tailored to suit specific geological conditions. These findings were validated by the numerical modelling results, and the key factor for the design life was determined to be the fatigue life of the lining. For the current assumptions, even the most onerous case (a single sided weld with daily cycle) is predicted to have a fatigue life over the 25-year design life. Analytical calculations and numerical modelling show that acceptable uplift resistance can be achieved with a below ground shaft plug system.

4.6 Injection/Withdrawal Model

The injection mechanism is a system of compressors and intercoolers. The energy consumption is reduced as the number of stages increases. The returns on increasing the number of stages decreases after 2 stages, therefore it is unlikely that a compressor system of more than two stages would be a cost-effective solution. There is a pay-off between system efficiency and the capital cost of the compressors, further work is required to optimise the ratio CAPEX/OPEX for the injection/withdrawal system and confirm this initial assumption.

4.7 Integration of Gravitricity's gravity-based storage and inter-seasonal heat storage

One of the aims of the project was to explore the option to integrate gravity-based and inter-seasonal heat storage within the same shaft used for storing compressed hydrogen gas.

The Gravitricity gravity energy storage system raises and lowers weights within a shaft. As the weights are lowered via a cable, the cable rotates the winch that is linked to a generator to produce electricity. The system can be configured to provide between 1-20MW of power with a response time of less than one second. The equipment required to raise and lower the weights would be kept within the pressurised hydrogen environment to minimise the risk of loss of containment of the hydrogen gas. Prior to the commencement of the feasibility project, it was initially thought that due to access being required to maintain the gravity system equipment an above-ground capping system could be constructed.

Thermal energy storage within the shaft was also previously considered a potential option for storing energy. A closed loop pipe would be placed around the shaft perimeter and be incorporated in the liner. Air would be circulated around the closed loop system. Inter-seasonal heat would be stored in the lining of the shaft utilising earth-air heat exchangers. During summer months heat would be stored for heating in winter, and cooler air would be produced in the summer.

As well as inter-seasonal heat storage options, waste heat will be generated from electrolysers and compressors. Research needs to be undertaken to see how waste heat from on-surface equipment could be captured, stored and utilised.

Risk workshops were held to identify hazards and to propose mitigations for the integrated system. Gravitricity have concluded that the integration of gravity-based and heat storage is not desirable at present, due to the range of new technical challenges this would introduce and the absence of a clear market for combined storage technologies. Work will continue on the technical development of these technologies separate to this project and if key risks are addressed the integration of the storage technologies within a hydrogen shaft may be reconsidered in the future. As a combined system will currently not be pursued further, this removes constraints on the shaft dimensions.

5 SITE SUITABILITY

5.1 Initial site identification

As part of the feasibility study, the suitability of a given site for hydrogen storage was defined for a full-scale commercial storage system. Site requirements for a proof-of-concept trial demonstrator were also considered. As part of this package of work a high-level assessment of end-user types was carried out, including hydrogen for industry, transport, heating/grid, and power generation, to assist with generating a list of potential sites. This helped to determine the capacity, purity, temperature, availability, and flow rate requirements. Site specific requirements would be identified once a potential site is located. This identified 42 locations where hydrogen is being produced and sites where hydrogen production is proposed and a further 135 sites where hydrogen could be used.

Following on from this list, targeted engagement proceeded with a small number of landowners and stakeholders of identified potential sites. There are several sites within Scotland that Gravitricity have had engagement with and the site owners are very positive and would like to be involved with the development of the project both at a proof-of-concept scale and at commercial scale. Engagement with all key stakeholders is ongoing.

To help prioritise and develop a short-list of sites, a GIS database was constructed to generate an interactive map which could be manipulated to identify potential sites. Geospatial data and code-based calculations were used to enhance the speed, automation, consistency, and versatility of analysing each site for suitability. The following sub-sections describe the methodology and results of this study.

5.2 Criteria

The attractiveness of a site, in relation to the installation of an underground hydrogen storage system, depends on many considerations and constraints. The key constraints and opportunities are summarised into the following themes:

- Commercial competitiveness (e.g. in relation to other hydrogen storage options such as salt caverns)
- Area attractiveness (e.g. expected hydrogen supply and demand type, capacity and proximity)
- Supporting infrastructure
- Land availability and constraints
- Likelihood of future hydrogen production

5.3 Methodology

It was determined that a geospatial approach would be most suited to identify the attributes that make a site attractive for underground hydrogen storage. The project followed the steps below to build the geospatial database:

- a dataset was created containing the sites to be assessed and their locations
- a human and computer readable list of scoring criteria was created. The criteria were assigned a weighting, and a total weighted score calculated to derive a priority list of sites
- all datasets required to test the criteria were created and compiled. These datasets contained published data on present and future demand of hydrogen and potential consumers. Locations of hydrogen production at present and future potential sites were also included

5.4 Results

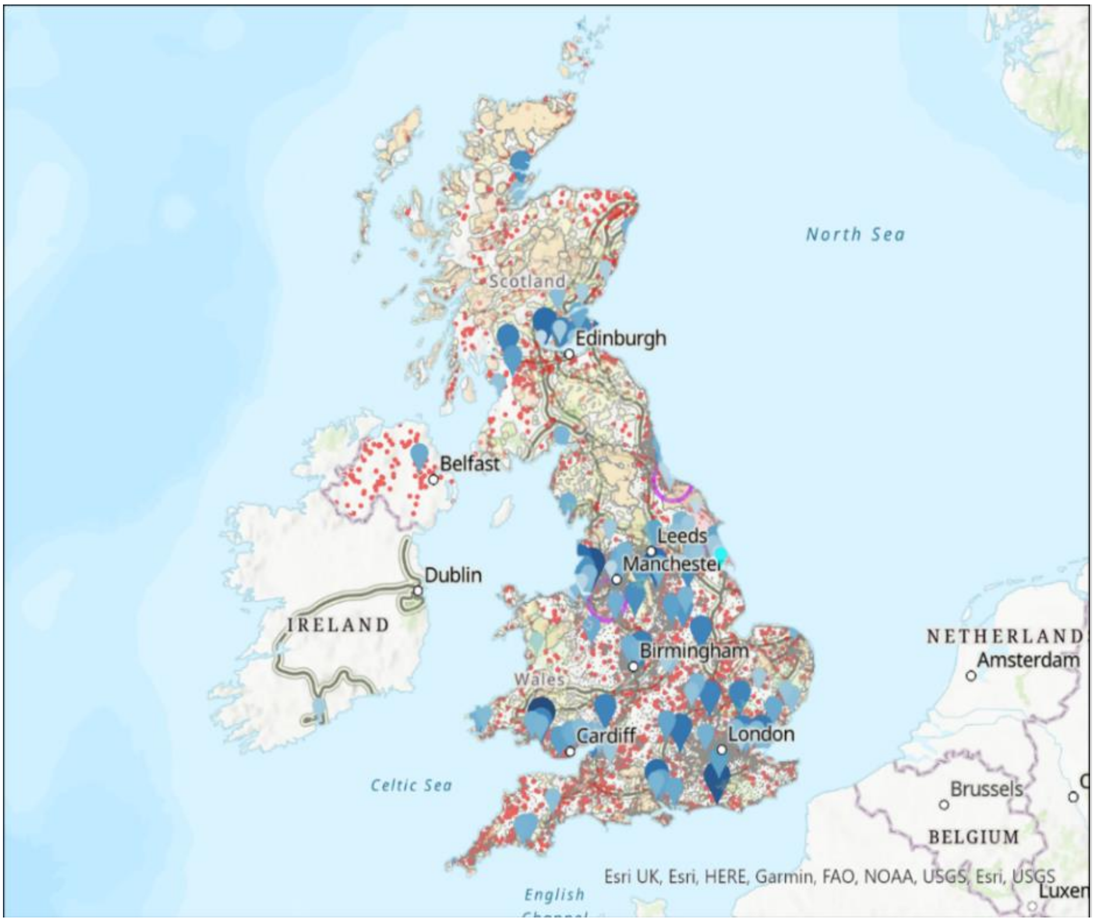

Figure 5: Map showing the location of the sites being tested (point markers) and the geometry used in the scoring criteria

Figure 5 shows a map produced using geospatial software with point markers indicating the location of the sites. Larger and darker blue point markers, indicate a more favourable site based on the scoring of the criteria.

The criteria inputted into the geospatial map can be adjusted depending on the priorities required for a site. For example, the hydrogen storage system needs to be in proximity to the hydrogen gas infrastructure to be able to receive hydrogen to store thus, this criterion can be more heavily weighted so that sites close to this infrastructure can be easily identified.

The weighting for criteria within the geospatial software were adjusted to test the sensitivities and to identify the areas of the UK with the most demand for hydrogen storage, in the range of capacities that Gravitricity's hydrogen system can provide. Site scoring considered proximity to future hydrogen demand and supply sources, distance from restricted areas for planning purposes, distance from salt caverns, and proximity to the proposed hydrogen backbone. Furthermore, the sites are near to renewable generation sources producing the required amounts of electricity for electrolysis.

The geospatial mapping tool will continue to be updated regularly as new data is released regarding hydrogen demand and hydrogen production. This will allow the project to keep updated on the best possible sites for the development of Gravitricity's hydrogen storage system. As Gravitricity and Arup develop relationships with companies either producing hydrogen and/or requiring storage this data will also be added and therefore will continue to be a vital tool for the development of projects.

6 COMMERCIAL FEASIBILITY

As part of the package of work to investigate the commercial feasibility of Gravitricity's hydrogen storage system, Gravitricity contracted Everoze to provide expertise and input. A rigorous cost plan, development plan (roll-out assessment) and market assessment were undertaken, making a strong case to go forward with phase 2 of the competition.

The required storage capacity for each scenario is derived from estimates of hydrogen production rates (in the case of storage located with a producer), hydrogen consumption rates (in the case of storage located with an off-taker) and cycling periods.

6.1 Cost plan

This section summarises the lifetime costs of the hydrogen storage system. It is intended to provide a summary of assumptions and inputs used to understand the key parameters that influence capital and operational costs for four different system designs of the Gravitricity storage system. The costs for project development works, shaft sinking (based on blind boring techniques), shaft lining, shaft capping, and the injection and withdrawal system were estimated by Gravitricity.

This cost plan considers the hydrogen storage system only, including the compression system to inject hydrogen. Facilities associated with hydrogen production and any facilities associated with the eventual use of the hydrogen, including transportation, sit outside of the project boundary.

The analysis suggests that there are important economies of scale expected for larger systems and some cost reductions are likely in the future.

Regarding OPEX, from the experience of salt caverns, compressors are expected to be replaced every 10 years throughout the design life of the system, but regular inspection and maintenance may prolong the life of the compressors. Shaft inspection will take place so far as is reasonably practicable. The shaft is designed for occasionally being emptied of hydrogen. However, it is expected that shaft inspections will take place using remote monitoring equipment, such as strain gauge and borehole seismic survey with no need for human access into the shaft. In the unlikely event that shaft remediation is required, Gravitricity have discussed the development of robotic means for access and maintenance with industrial experts. As the shaft is lined, no hydrogen gas losses (hydrogen egress) are expected from the storage vessel, but a small amount may be expected through the valves of the injection and withdrawal system. The round-trip efficiency, defined by the quantity of hydrogen injected divided by the quantity that can be extracted is estimated to be 99%, which is similar to overground storage tanks (IEA. 2019).

The cost assessment is based on levelised cost of storage (LCOS) specific to hydrogen storage and cost of delivered hydrogen. Levelised cost of storage is a metric that has been developed to understand the average cost of storing one unit of energy over the whole lifetime of a project. LCOS considers all capital and operational costs along with the quantity of energy stored to produce a simple single metric useful for comparing the costs of different technologies.

The shaft sinking cost is the main driver of the system capital cost. The basis of the economic assessment of the hydrogen storage system was a bottom-up cost estimate carried out by engaging discussion with shaft sinking companies. The input cost is based on budget figures, for a single shaft dimension and multiple shafts of that dimension, given by the sinking contractor within their current sinking capabilities. Gravitricity estimated, using an empirical cost scaling law, the relation between shaft sinking cost and volume of rock excavated. The design life of the system will impact the LCOS of the system. Future technological development, on long-term rock mass behaviour and lining interaction, will help refining the system design life.

Gravitricity and Arup engaged with several companies to provide costs to inform the CAPEX cost of the system. Shaft sinking companies provided costs for a number of shaft sinking scenarios, with a range of shaft sizes, diameter, and depth with several geological scenarios. These costs helped to build a parametrised cost model to be able to understand how costs can be scaled up or down.

As part of Gravitricity's gravity-based project, shaft sinking costs and techniques have also been explored and this knowledge has been advantageous to the Phase 1 hydrogen project. Both projects are working towards bringing shaft sinking costs down to enable energy storage underground to be more economical. Lining material costs were also explored and informed the CAPEX model.

At an early feasibility stage, the CAPEX costs were provided for a first-of-the-kind commercial system, the design costs are expected to decrease for some sub-systems such as the shaft, lining and cap for later projects down to recurring design cost. Moreover, as the shaft sized was optimum for the Gravitricity storage integrated solution, some analysis has since been carried out to find the optimum shaft parameters for gas storage only. At present, Gravitricity demonstrated that a 20% reduction of the cost per kg of H2 stored is achieved by optimising the shaft.
The work with shaft sinking contractors and the monitoring of latest shaft technological development enabled Gravitricity to understand cost drivers and identify further cost reductions which are expected after deploying a number of commercial systems in the near future:

- 40%-50% cost reduction is expected by ownership of the equipment, using local contractor for above ground works and gaining experience with drilling many holes or ordering multiple shafts (not necessarily at the same location). Cost would reduce even further maybe another 10-15% by sinking multiple shafts in one location.
- 30% overall cost reduction is expected by global experts on shaft sinking due to new technologies available and the emergence of new market needs.

All in all, after deploying multiple systems, the overall CAPEX would be reduced by 66% and will evolve as below:

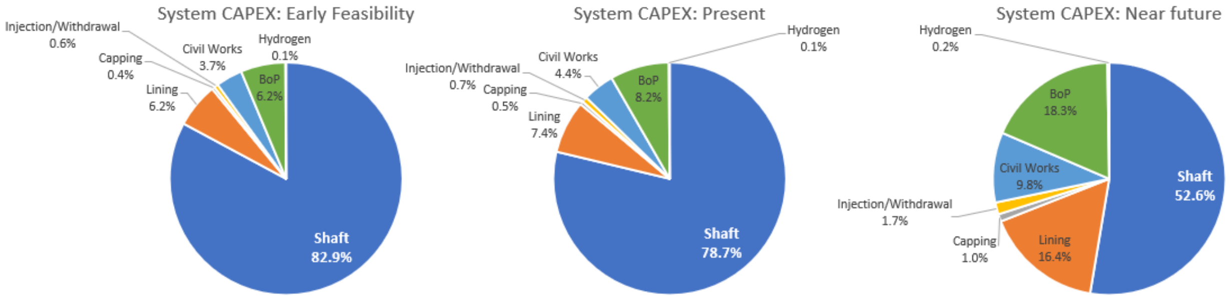

Figure 6: Cost breakdown per sub-system

6.2 Development plan - end-use scenarios

The development plan was designed to explore several potential routes to market for Gravitricity's lined rock shaft hydrogen storage system. The aim was to highlight the most suitable end-use scenarios along with their strengths and weaknesses. To achieve this the following methodology was developed, which comprises of three main steps:

1. Identify technical design constraints
2. Define and assess end-use project scenarios
3. Explore revenue business models

Technical design constraints were identified to understand what may limit and guide the commercial applications of the system. Important factors considered included the flow rate at which hydrogen can be withdrawn from the system, design life, and the storage capacity.

Several project scenarios for Gravitricity's storage system were identified using a long-list of electricity/hydrogen generators and hydrogen off-takers, and then down-selecting to a list more applicable to the type of hydrogen storage that Gravitricity's system offers.

The scenarios identified with requirement for either none or large-scale storage (capacity equivalent to salt caverns) were discounted from further review. The remaining scenarios were scored on a red-amber-green (RAG) basis against the key drivers determining hydrogen storage requirements. Four scenarios were identified where small-medium scale storage is most suited:

- isle/island grid where an electrolyser is used flexibly with a renewable asset to provide an off grid total energy system
- renewable power to heat where hydrogen is produced to supply hydrogen villages/towns. Independent need for hydrogen supply pipeline and storage
- industrial user (large user) where a firm hydrogen supply is required for a dedicated industrial use, replacing natural gas/fuel oil or grey hydrogen
- wind farm revenue diversification with hydrogen produced at the wind farm is transported for further use e.g. to a vehicle depot to refuel a fleet of hydrogen vehicles. Storage drivers could be multi-faceted depending on use case

6.3 Comparison to other hydrogen storage technologies

The LCOS of lined rock shaft storage is competitive when comparing against other hydrogen storage technologies such as liquid hydrogen and organic carriers. The lined rock shaft concept fits within the mid-scale storage requirement that other storage technologies cannot provide. Figure 7 plots the current hydrogen storage technologies against hydrogen mass stored and storage cost £/kg. It shows that the Gravitricity system fits an existing gap of medium-scale capacity in the current hydrogen storage market.

The lined rock shaft can be constructed and operational within 2 years, and therefore the speed of deployment will also be much faster than salt caverns which can take up to 6 years to construct: a further benefit for the end-users. When compared to above-ground storage, lined rock shafts have a much lower site footprint and as the hydrogen is stored below the surface, there is a reduced risk of leaks. The lined rock shaft storage is geographically less restrained than salt caverns.

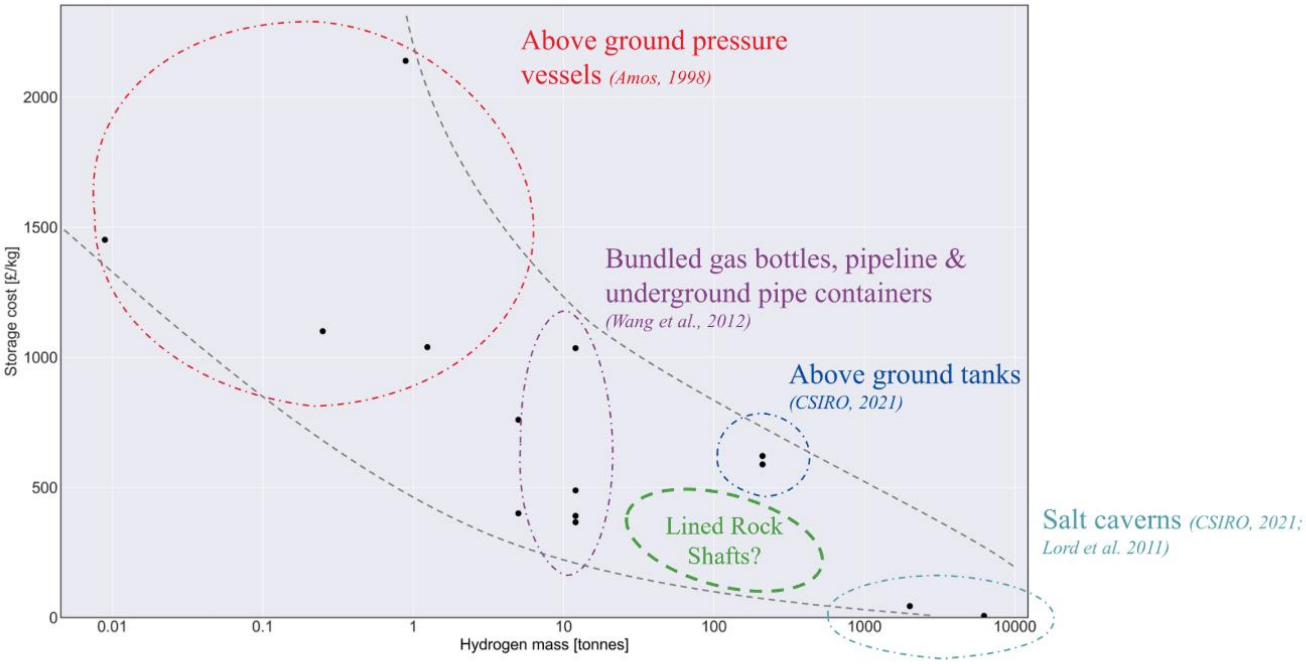

Figure 7: Comparison of Lined Rock Shafts with current hydrogen storage technologies

As the technology is proven and shaft sinking costs will decrease over time: the LCOS of lined rock shaft hydrogen storage will decrease and with the advantages of being located next to or close by producers and end-users, the costs to transport the hydrogen will be much lower. Salt caverns are restricted to areas of sufficient salt deposits and hydrogen will need to be transported either via vehicles or pipelines, adding to the cost of storing hydrogen in salt caverns.

6.4 Business development plan

A multitude of possible business models to deliver hydrogen storage to the market are possible. However, as part of this project Everoze and Gravitricity focussed on core variations around Intellectual Property (IP) licensing and Engineering, Procurement and Construction (EPC) packaged options. Although the preferred contract model for the Gravitricity board is the IP licensing only approach it was important to also consider the EPC packaged options, as these can unlock the reward/risk opportunity of developing such a hydrogen storage asset.

Four models were explored for commercial rollout of the Gravitricity hydrogen storage concept, with client or asset owner (where applicable) roles present in the table below:

Option	Business model	Gravitricity role	Client role	Revenue structure
1	IP licensing only (client finds turnkey EPC contractor) Ownership structure TBC ***"Tech Innovator"***	Licensing of Technology IP to meet design & construction standards/ requirements. Possible involvement during early project process to ensure progression with EPC contractor as expected.	Client pays for tech. IP to instruct EPC to build it.	Revenue upfront (from project developer or Special Purpose Vehicle (SPV)) with final payment likely to be tied to successfully commissioned asset.

2	Licensing + operation (requires EPC partner) Assume client ownership ***"Tech innovator + operator"***	As per option 1, with additional contract to be responsible for operation and maintenance of the asset	Investment, instruction of EPC provider	As per 1, plus operational revenue from fulfilment of operation &management contract
3A	Turnkey EPC (storage asset handed over built to client to run) Assume client ownership and operation ***"Builder"***	License technology IP to EPC provider or engineering procurement, construction management (EPCM) (services only contract) to deliver project	Client receives storage asset that they can 'turn key' to operate (e.g. fully commissioned and operational)	Revenue from sale of operational storage asset
3B		Design, build and commission asset then hand over to client to operate	As above, plus client benefits from single point of contact with Gravitricity and reduced risk (price, timescales etc.)	As for 3A, with possible ongoing fee to maintain warranties
4	EPC and operation; leasing model assumed. This includes SPV management, construction ownership, operation of storage asset ***"Builder + operator + owner"***	Full design, build and operation of asset. Value of storage sold as a service. May require partnership with EPC provider.	Buys storage asset as a service	Lease payments Price arbitrage of hydrogen bought and sold

Table 3: Business model options

The key findings of the rollout assessment work indicates where there is the strongest alignment between possible project scenarios and the business models under consideration. It is recommended that this work is developed further with specific case studies and input of stakeholder information to understand each in greater detail.

Business model	**Preferred project archetypes**
1: *Tech innovator*	Of the hydrogen off-takers considered, few were viewed to prefer this contracting approach due to the substantial risk exposure for both the EPC provider and project owner. Although this business model may work in the future it is unclear how it could be achieved before the technology is more proven and the market for hydrogen storage significantly more mature. Off-takers identified as the highest potential partners for this route were: Industrial user, hydrogen ring main, Isle grid, or grid constrained wind. It was assumed that these off-takers would have resources to deliver projects and would prefer a higher degree of control over the constructed asset.
2: *Tech innovator and operator*	This contract approach provides a bolt on to model 1, so many of the same off-taker types apply. The Scottish Island or Isle grid was considered a preferred business model for model 2 on the basis that these types of projects often have a community ownership or willingness to have funding control of all assets, but do not want responsibility of running an asset day to day.

3: *Builder*	This contract approach was viewed as preferable for the broadest range of project archetypes. Most clients/asset owners are expected to want access to the hydrogen storage asset, but without the associated construction and delivery risk. Only two archetypes were judged as unlikely to be suited to this option: the sustainable aeronautical fuel and private wires renewables developer. This was because these sectors are seen as unlikely to have sufficient competence or desire to own/operate this type of asset.
4: *Tech innovator + operator*	This approach is seen as particularly desirable for small/medium use cases or independent clients. It provides a low-risk entry point for these off-takers. It could also be attractive to medium users, like constrained or island wind, where achieving financing may stall progress of a required hydrogen store. It is considered an unlikely business model for locations where the lowest hydrogen market pricing could be achieved (e.g. hydrogen ring main or chemical processing). This was due to these sites having large-scale resources including the embedded engineering resource to deliver projects potentially within strict local site controls, e.g. Control of Major Accident Hazards (COMAH) status.

Table 4: Preferred project archetypes

6.5 Market assessment

The market assessment used the four down selected project scenarios from the potential rollout assessment to create four corresponding modelling scenarios and tests the commercial viability of investment in the Gravitricity storage system. The results show that the system can be a profitable investment in some scenarios, with internal rates of return (IRR) of over 13% suggested, but also serve to highlight the significant uncertainties in the modelling at this early feasibility stage. Modelling of several scenarios with a wide range of storage requirements displays the wide potential range of applicability of the technology.

6.6 Revenue, IRR and NPV results

For each scenario the internal rate of return (IRR) and net present value (NPV) was also calculated to give an indication of when each scenario will become profitable. The IRR can be used to estimate the profitability of the investment scenario. If IRR is greater than the weighted average cost of capital (WACC) then this indicates that the investment will be profitable.

The NPV is a metric related to IRR that is also used to estimate the profitability of an investment. It is understood as the difference between the present value of cash inflows and outflows over a period of time. A positive NPV indicates that IRR is greater than WACC and that the investment is likely to be profitable.

The results indicate that the more hydrogen that can be stored within the shafts the better the economic and commercial feasibility of the project.

7 TECHNOLOGICAL DEVELOPMENT

7.1 Phase 2 next steps

Future design considerations and research questions for Gravitricity's underground hydrogen storage concept have been highlighted during the feasibility study. These research questions will help Gravitricity understand and de-risk some critical areas of the design to reach concept design review for a commercial system at the end of Phase 2. The program for Phase 2 involves a range of development activities which includes component, sub-system, and integration level validations. Gravitricity is engaging with industrial experts and end-users including pressure vessel manufacturers Bendall's Engineering, who supply pressure vessels to the nuclear industry, shaft sinking experts VSL-Bouygues and end-users Ardersier Port Authority, SGN and Scottish Power.

The de-risking and validation process is explained below:

A. Site development and planning (~£218k): Gravitricity has received a written letter of support to use a port facility in the North of Scotland.
    - Secure a site for an underground demonstrator testing program including land agreement, planning application and relevant connection agreements

B. Identify constructability constraints on Gravitricity's lining design concept (~£313k)
    - Create a detailed construction plan with costing for an in-situ field test
    - Assess construction techniques effects on system performance and costs
    - Assess schedule and cost of the construction sequence, including quality control requirement

C. Advance the lining design commenced during Phase 1. (~£390k)
    - Develop a concept lining design for a full-scale system which can be deployed at any site.
    - Develop a detailed demonstrator lining design for site-specific in-situ testing

D. Component validation: gain a better understanding to progress design and validate material conformance to requirement. (~£1.1mi)
    - Assess long-term rock mass behaviour under cyclic loading
    - Test the sliding layer to determine the friction properties and life of the layer under cyclic loading
    - Test the gas tight layer (and welds) susceptibility and permeability to hydrogen for the system operational parameters

E. Sub-system validation (~£692k)
    - Develop discontinuum numerical analysis models to refine the lining design by modelling how rock mass behaves under loading and how the lining interacts with heterogenous geology
    - Test within large-scale laboratory setup to confirm integrity of the lining and provide insight to the long-term behaviour (e.g., concrete creep, steel strain and stress) with the possibility to replicate in controlled conditions the stress concentrations induced by heterogenous ground conditions

F. Integration validation: underground demonstration to validate modelled interactions of the shaft lining with the surrounding rock mass. (~£2.4mi)
    - Carry out site testing on a scaled demonstrator including in-situ pressure tests to understand rock mass behaviour
    - Test the effect of ground improvement technique on rock mass behaviour

  - Build an underground instrumented lining to test the mechanical integrity of the lining at operating pressure, to demonstrate the functionality of the system and to monitor mechanical behavior when subjected to cyclicity. In addition to overall proof of operation, this test will enable refinement of the analytical and numerical models, will help identify pathways for commercialisation and develop relationships with relevant industries.

G. Commercial feasibility (~£180k)
  - Complete targeted market research to determine the most suitable way to structure future commercial projects to cater for newly evolving hydrogen markets. Subsequent financial modelling will be completed to support decisions around preferred construction of a demonstrator.

By adding project management activities (knowledge dissemination, HSE, Risk management, grant administration, meetings, reporting), Gravitricity is proposing a £5.48mi project to build this consortium of industrials that will support the delivery of the demonstration program and will support the concept toward commercialisation.

7.2 Post-demonstration

Technical de-risking, initiated with the demonstrator, will be pursued to come to a mature, market-ready technology. Further constructability testing of the shaft excavation will be required for the selected full-scale system sinking method. Test results from the demonstrator will enable optimisation of the lining component thicknesses. Gravitricity will continue to work with multiple contractors to better understand the system costs, including the cost of sinking multiple shafts at a single site, operational costs and cost associated with injection and withdrawal systems for different off-takers and producers.

8 KNOWLEDGE DISSEMINATION

Project Manager Sally Molyneux and Arup Project Manager Tasos Stavrou, co-presented at the Hydrogen Storage in Caverns conference held at the Geological Society of London. Gravitricity's Managing Director, Charlie Blair presented Gravitricity's gravity-based and hydrogen storage concepts at the All Energy conference in Glasgow.

9 SUMMARY

The feasibility project has addressed several technical questions to assess whether combining gravity energy storage, inter-seasonal heat storage and compressed hydrogen gas within the same shaft were feasible. Basic operating parameters were defined, and an initial design concept established.

The integration of the three energy storage technologies within one shaft was assessed. Due to the technical challenges associated and the absence of a clear market path for the integrated system: it has been concluded that it will not be pursued at this time and the project will focus on a hydrogen-only storage system for Phase 2.

Geological and structural design work carried out during the feasibility phase have shown that the construction of a purpose-built shaft for hydrogen storage is feasible and commercially viable. Gravitricity's design utilises a multi-layer construction with a gas tight inner liner acting against a layered outer which enables gas tightness whilst allowing the surrounding rock mass stiffness to do 'most of the work' to counteract the outward movement of the liner when the hydrogen is stored at high pressure. This reduces steel tonnage by a factor of 3-5 per unit mass of hydrogen stored compared to current above ground storage solutions, resulting in reduced material costs.

A cost plan, market assessment and roll-out assessment determined that the storage concept becomes increasingly economically feasible with increased capacity. The flexibility of the design approach, outlined in this report, will allow capacity to be increased by designing a shaft with greater volume or by using multiple shafts at a single location.

Gravitricity have engaged with research organisations, industrials, and end-users to build a consortium that will support the delivery of the demonstration program and progress the concept toward commercialisation. Shaft sinking and pressure vessel contractors will help advancing the shaft and lining design by further considering constructability constrains and provide their high-standard quality management experience. Then, a series of de-risking activities, in collaboration with these parties, will be carried out. It includes a range of small and large scale lab testing and building an underground demonstrator to undertake component, sub-system, and integration level validations.

10 REFERENCES

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11 APPENDICES

11.1 Project risk register

This table presents the top 10 risks from all risk categories. It is an excerpt from a comprehensive risk register for the technology.

Risk Type	**Description**	**Severity**	**Likelihood**	**Current Risk level**	**Further actions**
Technical	Loss of containment due to lining failure	High	Very Unlikely	MEDIUM	Develop a lining and capping technology to achieve hydrogen containment and withstand load cases. Specify and design for operating conditions (pressure, temperature and humidity level) Means to detect and control gas leakage. Quality control and Quality assurance processes of the lining during construction and regular inspections to assess condition. Install a leakage detection system to detect and handle possible groundwater and gas leakage.
H&S	Serious incident during construction (e.g. Injury, fatality, accidents, falls and impact with machinery and equipment used).	Very High	Improbable	MEDIUM	Safety Management System fully implemented on project with contractors employed with strong safety culture
Technical	Shaft-sinking technology unable to achieve desired shaft dimensions. Change shaft dimensions or decision to sink several shafts - impacts on total system energy and difficulty to meet end-users requirement	Low	Unlikely	MEDIUM	Engage with shaft sinking contractor early and often. Review feasibility of shaft dimensions regularly and for each new project
Financial	Cost escalation on shaft sinking	Medium	Possible	HIGH	Initial design work will establish high-level costs in different geologies. Geological site characterisation to be undertaken as part of site selection, which will then inform design. Review feasibility of shaft dimensions early in the project

Financial	Consortium - Collaboration Agreements insufficient, or partners drop out for other reason.	Low	Unlikely	LOW	Relationship developed with several shaft sinking contractors. Collaboration agreement with relevant partners will be established.
Legislative/ Regulatory	Political Risk - revenue uncertainty due to policy mechanisms being underdefined at this stage. Hydrogen law and regulation may change in the UK prior to Project operation.	Medium	Possible	HIGH	Market is expected to improve given the crucial role that energy storage must play in decarbonisation transition. Project team have a good knowledge of existing regulations and is actively watching regulations.
Commercial	Local opposition - Project cannot proceed in preferred location or significantly slows progress	Medium	Unlikely	LOW	Gravitricity to engage with several site owners within the UK and to conduct satisfactory technical visits.
Commercial	Issues with planning permission or site not available for demonstration phase	Medium	Possible	HIGH	The consortium will begin engagement with shortlisted site options and engage with site owners to prepare for Phase 2. Including, time allocated to study the planning/environmental/ecology implications by planning consultants, as part of the site selection work package. Stakeholders will be engaged accordingly.
Project Management	Inadequate resourcing of project. Gravitricity fails to recruit new team members.	Medium	Unlikely	MEDIUM	Gravitricity intends to recruit eight new team members. Additional engineers and project developers will be required for the development of this technology. Gravitricity will also use contractor/partners and maintain relationship with them to continue the development.
Commercial	Phase 2 costs higher than expected	Medium	Possible	HIGH	CAPEX and OPEX costs estimation carried out during Phase 1. Continuous tracking of cost performance during phase 2 is required.

Table 5: Project Top 10 risks