



HYDROGEN UNDERGROUND

Final report
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Preface

The goal of the Hydrogen Underground (HUG) project was to analyse the systemic structure and feasibility of underground hydrogen storage constructed in bedrock. The project adopted a comprehensive approach, covering the entire hydrogen value chain - from production and storage system planning to construction, operation, and long-term maintenance. Emphasis was placed on understanding how technical solutions, business models, and regulatory frameworks interact across different phases of the storage lifecycle.

The HUG project focused specifically on lined rock cavern (LRC) storage solutions, which are particularly relevant in geological conditions such as those found in Finland. These storage systems offer the potential to store hydrogen safely and at scale, while supporting the integration of renewable energy into the broader energy system. During the project, also lined rock shafts (LRS) concept was considered, since it could allow to provide a compact, safe solution designed to handle high pressures, making them suitable for urban areas.

The project was coordinated by VTT Technical Research Centre of Finland, with the Geological Survey of Finland (GTK) as a key research partner. In addition, the consortium included 20 organizations, representing a wide range of expertise across the hydrogen value chain. The project was structured into six interconnected work packages, each addressing specific aspects such as system design, construction methods, operational models, safety, and techno-economic assessment. Close collaboration between work packages and participating companies ensured that the research remained aligned with practical industry needs.

This report presents the main results of the project, which started on 1 April 2024 and concluded on 30 June 2026.

Tampere, August 28th, 2026

Pasi Valkokari

Executive Summary

Why Underground Hydrogen Storage Matters

Large-scale underground hydrogen storage (UHS) is essential for Finland's emerging hydrogen economy. It decouples renewable hydrogen production from real-time demand, balancing multi-day electricity fluctuations and ensuring a reliable industrial hydrogen supply - something pipelines alone cannot do. UHS is therefore critical for energy security, system flexibility, and meeting national and EU climate targets. Finland lacks salt caverns, making excavated and lined storage in crystalline bedrock the only viable large-scale option. The HYBRIT pilot in Sweden, although at a very small scale, has demonstrated that lined rock caverns can store hydrogen safely under Nordic conditions.

The HUG Project

The Hydrogen Underground (HUG) project (April 2024–June 2026), funded by Business Finland and ~20 partners from industry, research, and public authorities, established the foundations for industrial-scale UHS in Finland. HUG adopted a system-level approach, covering technology, safety and social acceptance, business and governance models, regulation, lifecycle operations, and the role of storage in the wider energy system. Technically, HUG focused on two solutions: Lined Rock Caverns (LRC) for large-volume, long-duration storage, and Lined Rock Shafts (LRS) as a smaller, more mature option for early deployment or constrained sites.

Key Results

HUG confirmed the technical feasibility of LRCs in Finland's hard crystalline bedrock. Long-term safe operation requires a multi-layer liner system that is inspectable and which condition can be monitored—typically combination of steel, a sliding layer, and concrete—to ensure gas-tightness and durability over decades. UHS deployment requires early stakeholder engagement, organizational capabilities to manage risk and take responsibility for safety, and sustained attention to safety culture throughout the storage lifecycle. A medium-scale LRC of ~40,000 m³ was identified as a realistic pilot, requiring 4–5 years (including permitting) and an investment of about €30 million. Economies of scale are clear: larger volumes lower unit costs, while multiple caverns improve resilience with limited extra cost. LRS solutions are more mature and suitable for early pilots or local storage needs in the late 2020s. System analyses show that UHS enables hydrogen production during periods of low electricity prices and high renewable availability, improving utilization. Evidence from HYBRIT indicates 25–40% reductions in variable hydrogen production costs, while LRC storage typically contributes less than 10% to the levelized cost of hydrogen.

Strategic Implications for Finland

UHS is a strategic infrastructure asset that strengthens energy security and enables a reliable, fossil-free energy system at industrial scale. Buffered hydrogen supply is a prerequisite for continuous operation in hard-to-abate sectors such as steel, chemicals, refining, and synthetic fuels. HUG delivered Finland's first integrated UHS concepts, including preliminary business and governance models (e.g., storage-as-a-service; open vs. closed ownership), improving ecosystem readiness and clarifying value-chain roles and risks. Safety, responsibility, and social license were treated as core enablers through early risk management, transparent governance, and stakeholder engagement.

What Comes Next

Targeted follow-up R&D (e.g., HUG2) is needed to address remaining uncertainties and define research-based design requirements for an industrial-scale pilot. Early stakeholder engagement to ensure public–private support is crucial to de-risk first-of-a-kind projects and provide regulatory clarity. The next step is a medium-scale LRC pilot (~40,000 m³) to bridge concept development and operational experience ahead of larger deployments in the 2030s.

Bottom Line

Finland now has a credible technical and strategic basis for underground hydrogen storage. With continued R&D, coordinated public–private action, and focused piloting, lined rock caverns and shafts can become

cornerstones of Finland's hydrogen economy—supporting energy security, industrial competitiveness, and long-term decarbonization.

Contents

Preface	2
Executive Summary	3
Contents.....	5
List of abbreviations	8
1 Introduction	9
1.1 Market and export potential.....	9
1.2 Research and use cases.....	10
1.3 The project consortium.....	11
2 WP1: Ecosystem & Business models	13
2.1 Introduction	13
2.2 Methods	14
2.2.1 Qualitative methods	14
2.2.2 System dynamics modelling	14
2.3 Findings / Key results.....	15
2.3.1 Mapping of the UHS ecosystem and key bottlenecks	15
2.3.2 Future scenarios for underground hydrogen storage.....	16
2.3.3 Descriptions of potential business models in the underground hydrogen storage ecosystem	16
2.3.4 Leverage factors for viable business ecosystems.....	17
2.4 Future research directions	18
2.5 Conclusions	18
References	18
3 WP2: Safety, Sustainability and Responsibility	19
3.1 Introduction	19
3.2 Methods	20
3.3 Findings / Key results.....	21
3.3.1 Contamination of hydrogen.....	21
3.3.2 Leakage	22
3.3.3 Risks of common storage	22
3.3.4 Consequences of hydrogen releases.....	23
3.3.5 UHS ecosystem sociotechnical risks	23
3.4 Future research directions	25
3.5 Conclusions	26
References	27
4 WP3: Design and technology – Geological site criteria, key rock design parameters	28
4.1 Introduction	28
4.2 Methods	29
4.2.1 Site selection criteria.....	29
4.2.2 Site characterization	31
4.3 Findings / Key results.....	32
4.4 Future research directions	33

4.5	Conclusions	33
	References	33
5	WP3 Material technology solutions for H2 storages.....	35
5.1	Introduction	35
5.2	Methods	37
5.3	Findings / Key results.....	37
5.4	Future research directions	40
5.5	Conclusions	40
	References	40
6	WP4: Techno-economic feasibility of LRC operation and process concept options	42
6.1	Introduction	42
6.2	Methods	43
6.3	Results	44
6.3.1	State-of-the-art review	44
6.3.2	Dynamic process and CFD modelling.....	44
6.3.3	LRC storage investment costs and economies of scale.....	46
6.3.4	Large-scale H ₂ compressors for LRC storage	48
6.3.5	Optimization of renewable hydrogen production and the role of H ₂ storages	48
6.4	Future research directions	51
6.5	Conclusions	51
	References	52
7	WP5: Life-cycles and operations	53
7.1	Introduction	53
7.2	Methods	53
7.3	Findings / Key results.....	54
7.3.1	Literature review on UHS operations and human factors.....	54
7.3.2	Life-cycle perspective for UHS.....	55
7.3.3	Work domain analysis of UHS as a sociotechnical system.....	55
7.3.4	UHS monitoring concept.....	57
7.4	Future research directions	61
7.5	Conclusions	62
	References	62
8	HUG Roadmap.....	63
8.1	Introduction	63
8.2	Methods	63
8.3	Key results	64
8.4	Conclusions	65
	Acknowledgement	67
	References	67
9	Cookbook: Key takeaways for different stakeholders	68
	Acknowledgements.....	72

Appendix A: Table of HUG results and their expected utilization by different stakeholders	73
9.1 Investors	73
9.2 Designers, contractors, supplier network	75
9.3 Owners across the lifecycle	77
9.4 H ₂ Producers.....	79
9.5 Customers.....	80
9.6 Operators	82
9.7 Municipalities and public	83
9.8 Regulators and authorities	84
Appendix B: Policy Brief: Strategic Deployment of Underground Hydrogen	87

List of abbreviations

The list of abbreviations will be supplemented while finalizing the report

FOAK	First-of-a-kind
HFE	Human Factors Engineering
IoT solutions	Internet of Things. It refers to a vast network of physical objects—devices, vehicles, and appliances—embedded with sensors, software, and connectivity that allow them to collect, exchange, and act on data over the internet
LCOH	Levelised cost of hydrogen
LRC	Lined Rock Cavern
LRS	Lined Rock Shaft
PPA	Power purchase agreement
RAMS	Reliability, Availability, Maintainability, Safety
RFNBO	Renewable fuels of non-biological origin
UHS	Underground Hydrogen Storage

1 Introduction

Industrial-scale hydrogen storage is a key missing element in the Nordic energy transition. Growing renewable capacity and ambitious decarbonization targets require large-scale storage to balance variable power production and to ensure a reliable hydrogen supply for industrial off-takers, such as steel, chemicals, and refining.

In this context, hydrogen acts primarily as an industrial energy carrier and feedstock, not as a means of converting energy back into electricity. Excess renewable electricity can be converted into hydrogen, stored, and later supplied directly to industry when needed, enabling continuous fossil-free operation despite fluctuating power generation.

Despite its strategic importance, no large-scale hydrogen storage infrastructure currently exists in the Nordic region.

Background and drivers

Finland has strong potential for competitive green hydrogen production due to abundant low-carbon electricity, a well-developed power transmission network, and favorable system integration conditions. Synergies with district heating, strong grid reliability, and a stable, predictable business environment further strengthen Finland's position in the emerging global hydrogen economy.

Finland's government targets producing 10% of EU's clean hydrogen by 2030 (1 million tons or 33 TWh annually) and aims to match this share in consumption. Meeting these goals requires robust hydrogen transport and storage infrastructure. Large-scale storage is essential, particularly because hydrogen production from renewables is variable, while industrial demand e.g. in ammonia, chemicals, refining, and steel requires preferably constant supply.

Conventional underground storage options (salt caverns, depleted fields, aquifers) are not available in Finland. Instead, the country's stable granitic bedrock enables the use of lined rock cavern (LRC) storage, supported by strong national expertise in underground construction.

Large-scale hydrogen storage - especially lined rock caverns (LRCs) - is still an emerging field with limited global experience. Standardized design, construction, and operational practices are not yet fully established. Key technical challenges include ensuring long-term gas tightness due to hydrogen's small molecular size and managing its low volumetric energy density, which requires large storage volumes. In addition, LRC solutions are expected to be more capital-intensive than conventional underground gas storage alternatives.

To improve feasibility, strong collaboration and cross-sector integration are needed. Linking hydrogen systems with other sectors, such as district heating, can enhance efficiency, reduce costs, and support the development of a viable hydrogen economy.

1.1 Market and export potential

Recent high-ambition scenarios indicate ~USD 4 trillion in cumulative global investment across the green hydrogen value chain, which sits within the USD 6–12 trillion range projected by BCG & EDHECinfra (2023). This positions USD 4 trillion as a mid-range estimate for a fully decarbonized hydrogen pathway, higher than earlier IEA Net Zero projections based on slower uptake.

Europe's role by 2050: In a decarbonized European energy system, hydrogen could supply ~19–30% of final energy demand. Mid-range scenarios imply an annual market of ~€70 billion by 2050, between conservative EU baseline strategies (~10%) and high-adoption pathways (e.g., ~24% and ~€130 billion in the Hydrogen Roadmap Europe).

Europe is expected to account for ~47% of global hydrogen storage capacity additions by 2030, reflecting its early lead in hydrogen infrastructure development and climate policy ambition, as highlighted by industry analyses and corroborated by recent IEA assessments of announced projects.

In Finland, hydrogen technologies and services could generate annual revenues of €15–20 billion by 2035 and €31–39 billion by 2045 (Business Finland, 2024; Hydrogen Cluster Finland, 2023). National targets aim for 1 million tons (~33 TWh) of hydrogen production by 2030 (Ministry of Economic Affairs and Employment, 2023). Meanwhile, studies indicate Finland's hydrogen production potential could reach up to ~50 TWh by 2030 and ~150 TWh by 2050 (Gasgrid Finland, 2021), with domestic demand projected to be on the order of ~30 TWh by 2050 (Fingrid & Gasgrid, 2023). Hydrogen will primarily serve hard-to-abate sectors (e.g. heavy industry, shipping, and long-haul transport), which necessitates a stable supply and large-scale storage capacity to buffer variable renewable energy production (Ministry of Economic Affairs and Employment, 2023; Fingrid & Gasgrid, 2023).

The HUG project advanced lined rock cavern (LRC) storage design and construction, offering value across the hydrogen value chain—from developers to lifecycle service providers and research institutions. It supported business stability, competitiveness, and export potential in both technology and expertise. As global demand for hydrogen solutions grows, LRC innovation positions Finnish actors to capture market share while strengthening Finland's role in sustainable technology.

Collaboration and sector integration are critical to address high investment costs and scale storage solutions. HUG not only developed technical foundations but also identifies cooperative models and cross-sector synergies, extending export potential beyond storage technology.

1.2 Research and use cases

Several systemic challenges affect the development of underground hydrogen storage (UHS), spanning technology, infrastructure, and operational models, and influencing multiple planning phases. Practically these systemic challenges were the main research questions of the HUG project.

1. Planning, construction, and ownership

UHS development goes beyond geology and construction, requiring clear definition of system boundaries, business models, and actor roles. Key issues include identifying responsibilities, risks, and value-drivers across the hydrogen value chain. The HUG project aims to clarify these frameworks.

2. Techno-economic challenges

Both construction and operation face uncertainties. During operation, fluctuating supply and demand must be managed across multiple users. Key questions include pricing mechanisms, customer prioritization, and supply chain coordination. HUG explores alternative operational and business models to address these issues.

3. Implementation timeline

Developing lined rock cavern (LRC) storage requires a comprehensive roadmap covering design, construction, integration with hydrogen supply chains, operations, and environmental aspects. The lack of dedicated regulation for hydrogen storage remains a critical barrier and influences project timelines.

4. Hydrogen-specific properties

Hydrogen's small molecular size, combined with the mechanical sensitivity of storage structures to pressure and temperature variations, imposes strict technical requirements on LRC design and operation. A holistic approach is therefore required, integrating operating conditions, cavern and liner design, and site-specific geological characteristics. Safety aspects - including explosion risks and social acceptance - must be addressed from an early stage. In addition, the potential for hydrogen migration in bedrock needs to be assessed using geochemical and transport modelling to support environmental permitting and informed material selection.

The research conducted in HUG project was aligned with the selected use cases. Practically the research was steered by two technological solutions and five different business models.

The technological solution options were:

- Lined rock cavern (LRC), and
- Lined rock shaft (LRS)

The business models issued in the HUG project were:

- **Capacity-leasing model**, the owner(s) and/or operator builds and maintains the UHS. Hydrogen producers or traders lease storage capacity and pay capacity reservations and injection/withdrawal fees
- **Infrastructure-as-a-service (IaaS) model**, a consortium builds and owns UHS and sells infrastructure services (storage access, operations, digital services and decision support services) to hydrogen ecosystem participants
- **Market-driven model**, the operator buys hydrogen when the price is low, stores it to the UHS, and sells it when prices are high
- **One customer model**, a hydrogen producer (e.g. Power to X plant) or user builds storage to stabilize its own production and secure feedstock for downstream processes.
- **Public-private partnership model**, public sector actor pays for maintaining a minimum hydrogen reserve for energy security, similar to oil or gas business. Private actors design, build, operate and maintain UHS.

1.3 The project consortium

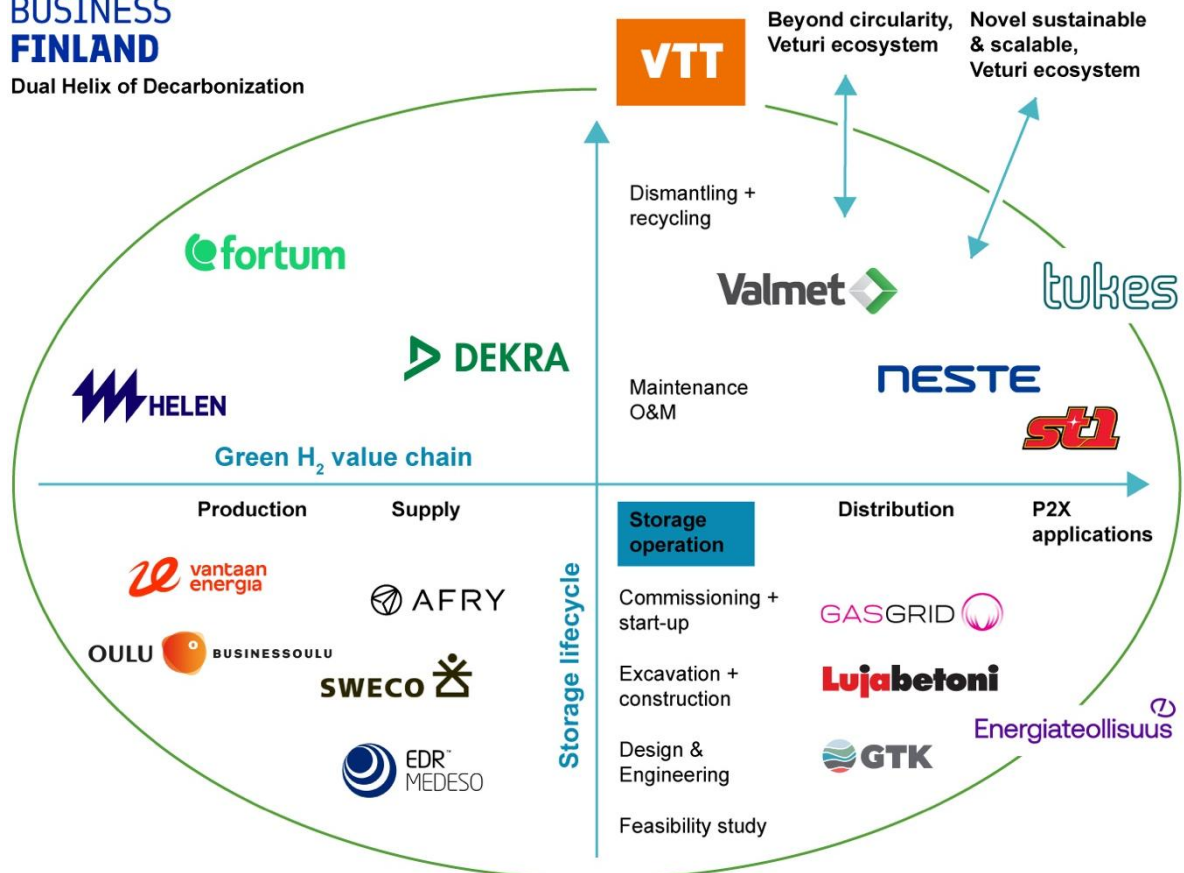
The Hydrogen UnderGround (HUG) project was a collaborative research consortium comprising 20 partner organizations. Co-funded by Business Finland and the participating organizations, the project aimed to establish the foundation for a large-scale underground hydrogen storage concept in bedrock. HUG addressed the entire green hydrogen value chain, covering all phases from initial planning and construction to the operation and maintenance of a subterranean hydrogen storage facility. By emphasizing renewable, emission-free “green” hydrogen production, the project supported the green transition and efforts to mitigate climate change. Large-scale underground hydrogen storage was expected to buffer seasonal fluctuations in green hydrogen production and ensure a stable, year-round supply for diverse industrial sectors.

Led by VTT (the coordinating research institute) in partnership with the Geological Survey of Finland (GTK), the HUG consortium brought together companies, other private-sector stakeholders, and research organizations. The project was organized into five different substance-focused work packages that promoted close collaboration and knowledge exchange across the consortium. In addition, the project was carried out in cooperation with Valmet’s and Neste’s Veturi programs, strengthening links to leading industrial ecosystems and ensuring strong relevance for industrial development. International cooperation was also integrated to address key research challenges, reflecting the consortium’s strong emphasis on synergy and shared expertise.

Illustration of HUG project’s ecosystem and the holistic approach of the project’s content is given in figure 1.

**BUSINESS
FINLAND**

Dual Helix of Decarbonization



Project volume: ~ 2,6 M€

Project duration: April 2024 – June 2026

Figure 1. Illustration of HUG project's ecosystem and the holistic approach of the project's content.

2 WP1: Ecosystem & Business models

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Abstract:

WP1 developed an in-depth understanding of potential business models and ecosystems for future underground hydrogen storage (UHS). It mapped the UHS business ecosystem and its critical stakeholders as well as identified critical bottlenecks and uncertainties shaping underground hydrogen storage ecosystem co-evolution. WP1 explored how alternative future scenarios shape ecosystem configurations and business model viability. The work applies both qualitative methods, e.g. desktop research, semi-structured interviews, and facilitated workshops with ecosystem actors and System Dynamics modelling of hydrogen market development. Based on this integrated approach, WP1 defined alternative future scenarios, described viable UHS business models across different ecosystem configurations, and identified key leverage factors that support value creation and sustainable earning logic. The results provided actionable insights for coordinated ecosystem development and support holistic planning and design of UHS systems in Finland.

2.1 Introduction

WP1 built the foundation for understanding how viable business ecosystems and business models for future underground hydrogen storage can be developed under changing market and policy conditions. The work addressed the complexity of multi stakeholder ecosystems by systematically identifying critical actors, key topic areas, and structural bottlenecks that influence the co-evolution of underground hydrogen storage business ecosystems. WP1 explicitly linked business model development with ecosystem dynamics, recognizing that long-term viability depends on coordinated value creation, risk sharing, and earning logic across multiple actors.

WP1 applied mainly qualitative research methods, including interviews, workshops, and desktop research, to capture stakeholder perspectives, future development aspirations, and bottlenecks related to underground hydrogen storage business. The qualitative methods were complemented by System Dynamics modelling to simulate the development of the hydrogen market. In this project, two hydrogen market development simulations have been created both with Python programming language (text-based programs) and with Vensim System Dynamics modelling tool.

In the first simulation it was assumed that there are 6 potential investors that may each decide to build a UHS facility. First, they are waiting for hydrogen demand to build up, then for technology and regulations to mature. Only after that may they start their construction project.

In the second simulation it was assumed that there are 20 small companies that may decide to use hydrogen, and later to trade hydrogen with their peers. Then there are 6 larger companies that may each decide to build a local hydrogen pipe. Finally, the government may decide to build a national hydrogen pipe grid.

Based on the qualitative data and system dynamics modelling, WP1 explores alternative future scenarios shaped by external drivers and uncertainties and analyses how different ecosystem configurations and business models perform across these scenarios. The results supported holistic planning and design of underground hydrogen storage systems by providing mapping of the underground hydrogen storage business ecosystem, identifying and describing future scenarios for underground hydrogen storage, describing potential UHS business models, and identification of leverage factors that enable viable and futureproof business ecosystems.

2.2 Methods

2.2.1 Qualitative methods

The qualitative work was based on a combination of desktop research, semi-structured interviews, and facilitated workshops. Desktop research was used to review the relevant market, policy, and technology developments related to underground hydrogen storage business and ecosystem (e.g. understand what kinds of hydrogen storages are operational in Europe currently). This provided a contextual foundation for the empirical work and supported the identification of key topic areas for further analysis.

Interviews and facilitated workshops with ecosystem actors consisting mainly of organizations involved in HUG project, were conducted to gather in-depth insights into current practices, perceived bottlenecks, business opportunities, and future development ideas. In the beginning of the project, interviews for potential use cases were conducted to understand the current situation and future plans of the companies regarding UHS from business perspective. The data gained from the interviews together with WP3 Geological studies was used to choose three use cases for HUG project.

During the project, the interviews focused on identifying the most critical stakeholders and their possible roles, interdependencies within the ecosystem, and challenges related to the co-evolution of underground hydrogen storage business ecosystems. In the facilitated workshops, the most important requirements towards the future underground hydrogen storage ecosystem and business models were identified together.

The qualitative data from desktop research, interviews, and workshops was systematically analyzed and synthesized for (i) identifying and map the main ecosystem actors and stakeholder roles, (ii) identifying the main bottlenecks related to the UHS business, and (iii) defining alternative future scenarios and business models for underground hydrogen storage.

2.2.2 System dynamics modelling

System dynamic modelling (Stermann 2000) was used for determining dynamic phenomena of hydrogen storage ecosystem. The modelling was initiated by development of systemic holistic map based on expert interviews, literature and a group modelling workshop (Vennix 1996). The initial findings identified three bottleneck dynamics:

- Chicken-and-egg dynamics: Supply and demand are depending on each other, and this reinforcing loop is difficult to initiate.
- Weakest-link dynamics: Technology, customer acceptance, safety, regulation, business potential all have to align for success. If one is missing, then the ecosystem does not develop.
- Resource-competition dynamics: Once the previous bottlenecks are solved, every actor is competing on resources and significant delays are expected in the ecosystem.

These dynamic phenomena were further studied with system dynamic simulation models. Two different System Dynamics models have been created to simulate the hydrogen market development both with Python (text-based programs) and with Vensim modelling tool.

2.3 Findings / Key results

Work Package 1 (WP1) generated a structured and evidence-based understanding of underground hydrogen storage (UHS) business ecosystems, focusing on how viable business models can emerge under different future conditions. WP1 has four outcomes, each having their own key findings and results that are described more detailed below (Table 1).

Table 1. Key outcomes and findings of WP1.

Outcome	Title	Key Findings	Key Results / Outputs
O1.1	Mapping of the underground hydrogen storage business ecosystem	Main stakeholders involved in underground hydrogen storage ecosystem across the lifecycle from hydrogen production until end-use were identified including private and public sector actors as well as third and fourth sector actors. The mapping of the UHS business ecosystem also includes identification of key bottlenecks related to UHS design, construction and operation.	Structured mapping of the underground hydrogen storage business ecosystem, including critical stakeholders, their roles and the main bottlenecks affecting ecosystem co-evolution.
O1.2	Future scenarios for underground hydrogen storage	Four relevant future scenarios were identified based on external drivers and uncertainties in the Finnish hydrogen landscape. The analysis showed that ecosystem dynamics, actor roles, and business opportunities vary across alternative future conditions.	Descriptions and qualitative analysis of alternative future scenarios for underground hydrogen storage, supporting assessment of ecosystem development pathways and business model viability under uncertainty.
O1.3	Descriptions of potential business models in the underground hydrogen storage ecosystem	Various potential UHS business models were described using business model canvas tool to reveal the revenue streams, key value propositions, customer segments, and operational frameworks.	A set of alternative, ecosystem embedded, business model descriptions for underground hydrogen storage, linked to the ecosystem mapping (O1.1) and future scenarios (O1.2).
O1.4	Leverage factors for viable business ecosystems	Key leverage factors enabling viable underground hydrogen storage business ecosystems were identified by two System Dynamics simulations.	Identification of leverage factors and mechanisms supporting viable business ecosystems, consolidated into an ecosystem roadmap. Both simulations showed the importance of (optimistic) early adopters, which “pull” other companies considering hydrogen technology after them. Without such forerunners, the creation of hydrogen market may never happen.

2.3.1 Mapping of the UHS ecosystem and key bottlenecks

WP1 identified that underground hydrogen storage business ecosystem is inherently complex, involving a wide range of stakeholders with different roles, sizes, and interests. The UHS business ecosystem consists of both public and private sector organizations as well as third and fourth sector actors. Very important UHS ecosystem actor group is of course system operators and owners.

Critical stakeholders span the full UHS lifecycle, from hydrogen production, through conditioning/compression. The stakeholders have to select the site and do permitting, manage UHS construction, operations and digital monitoring, and post-storage delivery to the customers.

The research highlighted strong interdependencies between these actors, emphasizing that no single stakeholder can develop viable UHS business models in isolation. Ecosystem coordination and alignment of roles are therefore critical for successful co-evolution. Mapping of the entire ecosystem is reported in Outcome 1.1. Mapping of the ecosystem actors is used as basis for forming key takeaways for different stakeholders that are presented in Chapter 9 in this report.

Another central finding of WP1 is that key bottlenecks in UHS ecosystem development are not purely technical, but strongly linked to business and ecosystem dynamics. These **include uncertainty related to future market development and regulation, unclear allocation of risks and responsibilities, and challenges in defining sustainable earning logic for different stakeholders across the construction and operation phases of underground hydrogen storage.**

2.3.2 Future scenarios for underground hydrogen storage

During WP1, four relevant future scenarios reflecting different ownership and business models, and stages of hydrogen economy development in Finland were identified.

In the first scenario, **Open large-scale LRC in the transmission network**, the UHS offers nationwide access for hydrogen producers and users. The scenario is possible, if building and operation of such a storage is given as a task for e.g. Gasgrid or another storage operator by the Government and could be operational earliest in 2035.

In the second scenario, **Closed large-scale LRC in the transmission network**, the UHS is serving large hydrogen-using **owner** companies across the country under a joint ownership (Mankala-type) model. However, it is unclear whether this scenario will be regulative possible in the future. This is a long-term scenario where a closed LRC could be operational earliest in 2040.

In the third scenario, **Local small-scale LRS in the distribution network**, the UHS is owned and used by a single hydrogen producer or user. This scenario is well suited for the early scale-up phase and the small-scale LRS could be operational earliest in 2028-2029.

In the fourth scenario, **Local medium-scale LRC in the distribution network**, the UHS is serving a single user or a local hydrogen community. The storage would be owned and operated via a joint venture or service operator, and it could be operational earliest 2030.

The four scenarios with background information and timeline are reported in Outcome 1.2. Future scenarios for underground hydrogen storage and used as basis for identifying the potential future UHS business models and HUG Roadmap that is presented in Chapter 8 in this report.

2.3.3 Descriptions of potential business models in the underground hydrogen storage ecosystem

One key finding of WP1 is that UHS business models cannot be designed independently of ecosystem configuration. Value creation, cost allocation, and earning logic vary significantly depending on stakeholder roles, governance arrangements, and ecosystem maturity.

Five different potential business models were identified. In the **capacity-leasing model**, the owner(s) and/or operator builds and maintains the UHS. Hydrogen producers or traders lease storage capacity and pay capacity reservations and injection/withdrawal fees. In the **Infrastructure-as-a-service (IaaS) model**, a consortium builds and owns UHS and sells infrastructure services (storage access, operations, digital services and decision support services) to hydrogen ecosystem participants. The main difference between these two models is the way how revenue streams will be formed. In the **Market-driven model**, the operator buys hydrogen when the price is low, stores it to the UHS, and sells when prices are high. In the **One customer model**, a hydrogen producer (e.g. Power to X plant) or user builds storage to stabilize its own production and secure feedstock for downstream processes. In the **public-private partnership model**, public sector actor pays for maintaining a minimum hydrogen reserve for energy security, similar to oil or gas businesses. Private actors design, build, operate and maintain UHS.

The potential future UHS business models including the descriptions of their value propositions, key activities and resources, key customers as well as main costs and revenues, are reported in Outcome 1.3. Descriptions of potential business models in the underground hydrogen storage ecosystem used as basis for HUG Roadmap that is presented in Chapter 8 in this report.

2.3.4 Leverage factors for viable business ecosystems

WP1 identified key leverage factors and mechanisms that can support the emergence of viable UHS business ecosystems. The system dynamic modelling included chicken-and-egg, weakest-link and resource-competition dynamics, which were validated with two different simulation models. The business model used in these simulations was Market-driven model.

In the first simulation model, we are simulating the UHS market development, when there are 6 companies that may decide to construct a UHS facility.

In the first stage, everyone is waiting for the demand for hydrogen to go up. The demand increases slowly, but if nobody enters the market (i.e. creates supply), the demand peaks and then slowly disappears.

In the second stage, one or more players regard the hydrogen demand to be sufficient for UHS investments, but there are not yet sufficient regulations, standards or best practices for building UHS facilities. The same way as in stage 1, the standards' maturity will increase slowly. The players wait for the standards to reach sufficient maturity before moving to the next stage, that is, to start a hydrogen storage facility construction project.

In the third stage, a player starts a hydrogen storage facility construction project. However, two factors make the construction projects last longer and cost more: If other players are constructing simultaneously, there will be lack of resources (materials, construction workers etc.), which cause the time and price to go up.

In the fourth and last stage, the player has successfully constructed a hydrogen storage facility, and the simulation ends for that player. After this, the player starts earning money!

These simulation describe the all three bottlenecks dynamics identified in the holistic map.

In the second simulation model, we are simulating the Hydrogen market development, where there are different kinds of stakeholders.

First, the small players may decide to manage hydrogen technology in-house, and later they may decide to sell/buy hydrogen with other small companies. Each time a small company decides to start utilizing hydrogen technology, it advances the hydrogen technology maturity, which encourages other small companies to adopt hydrogen technology.

Second, if hydrogen technology penetration within the small companies gets big enough (i.e. maturity gets good enough), the medium-sized companies may decide to build a small local hydrogen pipe (~hundreds of meters long).

Finally, if the maturity is very high (and there are many local hydrogen pipes), the government may decide to build a state-wide hydrogen pipe network (i.e. grid). And later, the state may decide to start hydrogen export and import, too.

In the first stage, the small companies are waiting for the hydrogen tech maturity to go up. In the second stage, one or more of the medium-sized (local) companies may regard the hydrogen technology maturity to be sufficient for a local hydrogen pipe investment. Finally, when there is a sufficient number (at least 3) of local hydrogen pipes and high hydrogen tech maturity the state may decide to build a state-wide hydrogen pipelines network. When the pipe network decision is made, the hydrogen tech maturity will be increased.

Again, the result was that no national hydrogen grid is created on most runs, but in a few runs the national hydrogen grid does get built. And in some runs the national grid construction project has started but not finished during the simulation time horizon. Again, we can see that some early optimistic small investors "pull" many others to join them, which creates an incentive for the medium-sized companies to construct local hydrogen pipes, which then creates pressure for the government to construct a national hydrogen grid. But at any stage this accelerating process is easily delayed, which prevents the later stages from occurring at all.

2.4 Future research directions

The simulation models developed in this work packages should be extended to include a wider view of the hydrogen ecosystem including hydrogen derivatives and energy as well as external events affecting the hydrogen economy as further research.

The consistency of the future scenarios should be updated with latest information with such tools as AI-assisted morphological analysis. This would also create new future scenarios for further evaluation.

The business models and ecosystem stakeholders are to be re-reviewed after few years, and simulation models updated accordingly.

2.5 Conclusions

WP1 concludes that creating viable underground hydrogen storage in Finland is also an ecosystem-building challenge, not only a technical one. Because UHS spans the full hydrogen value chain (production to end-use) and involves tightly coupled public and private roles, business model viability depends on coordinated role definition, risk allocation, and shared earning logic across multiple actors.

Across the four future scenarios identified, WP1 finds that as actor roles, governance arrangements, and timelines differ, UHS planning should remain robust across alternative futures, with particular attention to regulatory clarity (e.g., market rules), permitting, and the conditions required to scale from local early deployments to larger network-integrated storages.

WP1 also concludes that UHS business models must be designed as ecosystem-embedded configurations. The five possible future UHS business models identified (capacity leasing, infrastructure-as-a-service, market-driven trading, one-customer, and public-private partnership/strategic reserve) represent different value propositions and revenue logics that become viable under different levels of market maturity, infrastructure availability, and public-sector involvement.

Finally, the system dynamics simulations reinforce a central leverage insight: early, sufficiently “optimistic” adopters can trigger reinforcing feedback loops that accelerate demand growth, standards and regulatory maturity, and subsequent investments—while the absence of such forerunners can cause market formation to stall. The simulations further indicate that delays in maturity standards and resource bottlenecks during parallel construction can materially slow or prevent later-stage outcomes (e.g., multiple storages or a national hydrogen grid), highlighting the need for coordinated sequencing, capability building, and policy support during the early scale-up phase.

References

- Sterman, J. D. (2000). Business dynamics: Systems thinking and modeling for a complex world. Boston, MA: Irwin/McGraw-Hill
- Vennix, J. A. M. (1996). Group model building: Facilitating team learning using system dynamics. Chichester, UK: John Wiley & Sons.

3 WP2: Safety, Sustainability and Responsibility

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Abstract:

The objective of Work Package 2 was to develop an understanding of safety, sustainability and responsibility aspects of hydrogen underground storage and the related ecosystem. Safety is understood as an emergent property of the sociotechnical system; it arises from how technical and social elements work together in practice. Responsibility and sustainability are considered from a safety perspective. Responsibility serves as a bridge between safety and sustainability: effective governance requires early design choices and operational safety arrangements to be aligned with the long-term viability and safety goals of the UHS system. Since the technical solutions needed for UHS are not fully defined yet, the hazard identification is conducted at general level, based on the knowledge gathered from the literature, public information about existing pilot storages and discussions with experts. We emphasize the importance of risk anticipation and systems thinking, as our research supports safety capacity building and comprehensive understanding of risks in a first-of-a-kind safety-critical UHS facility.

3.1 Introduction

Traditional engineering risk assessment provides a rigorous foundation by quantifying hazards, failure modes, consequences and system reliability by addressing technical phenomena. When multiple actors interact in UHS, the technical safety analysis needs to be complemented by an understanding of how technical factors interact with organizational, human, and cultural dynamics. Factors such as leadership, capabilities and competences, reporting, incentives, learning, communication and decision-making patterns are influential in shaping safety outcomes.

In WP2, we adopted a holistic view to safety and risk, grounded in sociotechnical system theory (Rasmussen, 1997) and contemporary understanding of risk as arising from the interplay of various factors in the system. We consider UHS as a sociotechnical system, in which human actors (operators, managers, regulators, policymakers, contractors), technical artifacts (machines, materials, infrastructure) and organizational structures and cultural assumptions interact.

Safety, responsibility and sustainability in the UHS context are closely related. Safety is understood as an emergent property of UHS as a sociotechnical system, where safety depends on technical, human, organizational, social license, and governance factors. Responsibility for safety involves proactive and continuous development of safety culture and leadership among all stakeholders, including the supply chain. Sustainability is about capacity to avoid long-term system degradation (environmental, social, economic), and to ensure long-term organizational capabilities to prevent accidents, which in turn influence public perceptions throughout the UHS lifecycle. Responsibility is seen as a bridge between safety and sustainability - effective governance needs to integrate both by ensuring early engineering design solutions and day-to-day operational safety are aligned with the long-term viability and safety goals of the UHS system.

The concept of Social License to Operate (SLO) originates from the extractive industries, such as mining. It describes an informal agreement rather than a written contract, where a project is accepted and approved by the local community and stakeholders. SLO also includes a moral dimension, covering legitimacy and the expectation that companies advance fairly, communicate honestly, and act responsibly (Breakey et al., 2025; Aaltonen et al., 2026). The subsurface nature of UHS may trigger “invisible risk” concerns among local communities and the general public, which needs to be acknowledged and managed from the very beginning.

In the context of emerging, high-level UHS concept, we emphasize the importance of *risk anticipation* and *systems thinking*, as our research supports safety capacity building and comprehensive understanding of risks in a first-of-a-kind (FOAK), safety-critical structure. The capacity to anticipate emerging issues before they become licensing obstacles, operational vulnerabilities, or safety-significant events is critical for preventing accidents and ensuring social acceptance. Risk arises from the dynamic behaviour of the sociotechnical

system as it adapts toward the boundaries of acceptable performance under multiple competing pressures, such as cost, optimization, or workload. Essentially, sustainability reflects whether the UHS system can prioritize safety and maintain acceptable performance over time under evolving pressures.

The storage concepts under consideration regarding technical safety are presented in Figure 2. LRC is constructed with drill & blast method. LRSs can be constructed in two different ways: From the surface with down-the-hole method, where the maximum depth is ~120 m and the diameter ~1,5 metres and from the bottom with raise boring method, where the depth can be ~1000 metres and the diameter 5...6 metres. The latter option requires access to the bottom level of the shaft; open pits or mines could be utilized as access tunnel to the required depth.

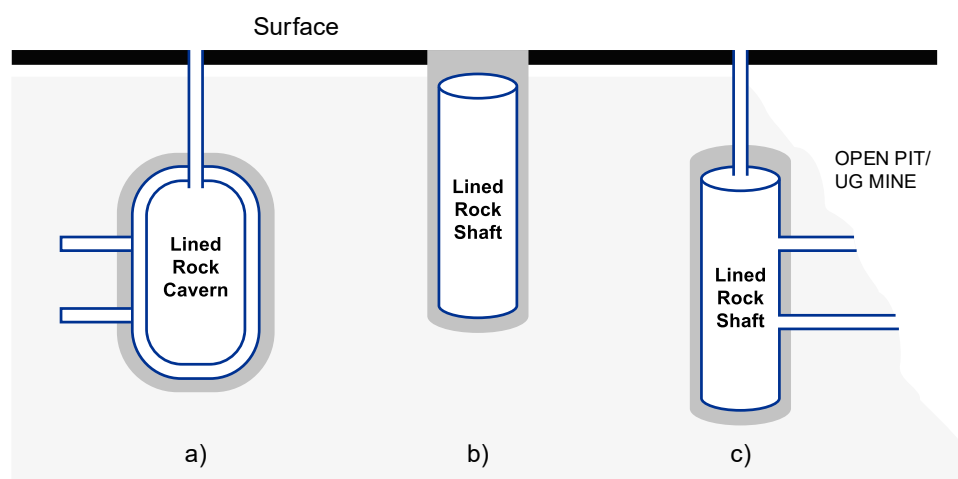


Figure 2. Three different UHS concepts: Lined rock cavern (a), lined rock shaft drilled with down-the-hole method (b) and lined rock shaft and lined rock shaft drilled with raise boring method (c). LRS in the middle (i.e., b) has the lowest capacity (i.e. volume), LRC and LRS drilled with raise boring method have considerably higher capacity.

During HUG project, WP2 researchers had several discussions with the Finnish Safety and Chemicals Agency (TUKES) representatives. At the moment, UHS permitting process goes according to the same principle as any other facility handling and storing hazardous chemical substances, no special rules are established for underground high-pressure gas storages. As the hydrogen storage capacity of UHS is large, several thousands of tons, the permitting process should follow the procedure for a facility that requires safety report. One essential part of the safety report is consequence analysis, which determines the safety distances in main hazards: dispersion of hydrogen, jet fire heat radiation and explosion. For all these, TUKES has set threshold limits that must not be exceeded. Additionally, according to the TUKES experts, currently there are no specific safety rules for underground gas storages as they are not obliged to follow the pressure equipment directive, but some discussions are already going on this matter among authorities and experts throughout the European Union.

3.2 Methods

The studies in WP2 adopted a mixed method approach, including qualitative, exploratory approach using literature review and expert discussions, as well as quantitative approach such as consequence analysis of hydrogen storage hazards. Literature survey was used as a research method for identifying technical and other categories of risks. There are only a few examples of underground hydrogen storages that are dedicated for hard rock areas, i.e. lined rock caverns or lined rock shafts. Main examples of LRC type of storages are hydrogen storage pilot within HYBRIT project and natural gas underground storage Skallen, both located in Sweden. Additionally, safety considerations of LRC structure have been discussed with experts within HUG project consortium. In collaboration with WP5, we analysed qualitatively also the data gathered by participatory expert elicitation method, namely the Whiteboard on the HUG project's Microsoft Teams space to inform how UHS ecosystem risks and safety issues are conceptualized from multidisciplinary experts' perspective.

Besides, we further analysed the key bottlenecks in UHS ecosystem development, identified in WP1 as additional basis to elaborate the understanding about the UHS ecosystem risks. To identify and characterize Social License to Operate high-level, preliminary requirements and risks, a set of guiding questions was developed to support structured stakeholder engagement and to elicit perceptions, concerns, expectations, and potential risk factors affecting social acceptance and legitimacy. The example questions function as an elicitation framework, enabling systematic exploration of SLO-related risks while allowing stakeholders to raise context-specific issues.

Macrae's (2022) SOTEC framework (Table 2) was used as the analytical lens for UHS ecosystem risks as it offers systematics to identify and address sociotechnical risks that arise from interactions of diverse factors: structural, organizational, technological, epistemic and cultural. It has also been recently applied to energy transition context in Australia (Hayes & Maslen, 2025).

Table 2. Sociotechnical risk framework (based on Macrae, 2022)

Source of risk	Description
Structural	Risks arising from interdependencies and interactions between different parts of the social and technical structures that constitute the system.
Organizational	Risks arising from social processes, organizing activities, and human/contextual factors that underpin the system.
Technological	Risks arising from the capabilities, affordances, and constraints inscribed into and produced by the material technologies of the system.
Epistemic	Risks arising from the ways knowledge and ignorance are constructed in relation to, and within, the system.
Cultural	Risks arising from the collective values, beliefs, norms, and practices that surround and shape the system.

3.3 Findings / Key results

First, we present the technical risk results, followed by elaboration of the UHS ecosystem sociotechnical risks. Hazardous situations in large-scale hydrogen storages can be divided into two main categories: contamination and loss of containment, i.e. leakage.

3.3.1 Contamination of hydrogen

In contamination scenario impurities of some kind enter the storage cavern filled with hydrogen. It is possible that contaminants enter the cavern due to deviations in the hydrogen production process, e.g. alkaline solution from alkaline electrolyzer enters the cavern. These contaminants can be critical for some hydrogen applications, like fuel cells. More serious safety-critical situations occur if the contaminant contains oxygen, either pure oxygen or air. Then the gas mixture in the cavern can be flammable and if ignited, the explosion can cause severe damage to the storage. In normal operating conditions of hydrogen storage, there is always overpressure in the cavern, therefore the contaminants must be pressurized outside the storage and there should be multiple layers of protection in the hydrogen production and compression processes to prevent this scenario happening.

Another possibility where contaminants, especially air, can enter the storage, is situation where the storage volume is depressurized. Depressurization can occur due to a leakage or if the storage is prepared for maintenance. As it is essential that the occurrence of flammable mixture in the storage is prevented, the decreasing pressure must not reach ambient pressure, it must be at least slightly over pressurized until all hydrogen is pushed out of the cavern. Nitrogen gas can be used for this purpose, but in large volume the quantity needed for complete emptying of storage is quite massive. For safe emptying of storage, water can be used to push out the residual hydrogen out of the storage without compromising the safety. Water can be used also when filling the storage for the first time or after maintenance break; then the pressurized hydrogen

pushes the water out of the storage. Nitrogen can also be used for the same purpose, but as the gases mix in the storage, the hydrogen quality is lower for some time because of the nitrogen content.

3.3.2 Leakage

In practice, all leakages of lined rock storages are caused by the gas-tight liner failure. There are numerous causes for liner failures: The liner material, presumably stainless steel can have fractures due to embrittlement hydrogen causes in the long run. Liner can fail also due to failure in the sliding layer behind the steel liner: If this layer, presumably made of bitumen, is worn out or too thin, the metal liner starts leaking due to mechanical wear. The next cavern wall layer behind the sliding layer is the concrete structure: The containment of the cavern lies on the structural integrity of the concrete structures and bedrock mass. Without structural support the metal liner cannot hold the forces of high-pressurized hydrogen. The concrete mixture and casting quality control is essential to ensure that structural support holds the forces as planned. The bedrock is not uniform; there are cracks and weak points in the rock mass. Therefore, the bedrock properties must be studied carefully so all the necessary enforcements are ready before the concrete casting takes place. In the worst case, the bedrock can move (earthquakes), which can cause deformations in the structure and lead to a leakage. Pipeline joints with the liner are also points that have a higher risk to leak, as the liner is a floating structure that moves slightly according to the pressure variations and the joints are fixed in place.

Small leakages are probable in lined rock storages. To detect the leakages and possible leakage rate increase, an easy pathway for hydrogen must be arranged where leakages accumulate and are possible to detect. In the basic lined rock storage wall structure, there are drainage pipelines that can be utilized to pump out groundwater from the outside of the storage structure. These pipes can also be utilized in the leakage detection as the hydrogen raises upwards quite rapidly, even if the drainage pipes are filled with water.

In large leakage case, the safest way to handle the situation is to transport the as much hydrogen from the leaking storage to another storage or pipeline as possible. Therefore, a modular solution of a storage is preferred, where some free capacity is always available for emergencies in one storage module. In addition to the high monetary value of the hydrogen, intentional release of hydrogen to atmosphere is not risk-free. High-pressure hydrogen releases can ignite and cause either explosion or jet fire.

Catastrophic leakage can happen, if the storage structure fails completely. This can happen in LRC as uplift failure where the rock mass above the cavern lifts up due to forces caused by the pressure inside the storage. Another scenario for massive failure is plug failure; the tunnels used for excavation must be plugged with special concrete structure attached to the rock mass. If the plug fails, the gas-tight structure will fail and cause massive leakage through the tunnel. Similar scenario can happen in LRS, as the plug in the top of the shaft is very critical construction. These scenarios must be managed by careful structural design.

3.3.3 Risks of common storage

As the large underground hydrogen storage is a huge investment, it is probable that a single storage has multiple users simultaneously. One issue in common hydrogen storage is hydrogen quality. It must be defined which quality of hydrogen the storage contains and how the companies ensure that the quality stays in desired level. As some hydrogen applications are very sensitive to hydrogen quality, the quality should not vary. Even small amounts of contaminant can deteriorate contents of the whole storage.

Another issue in the common storage is capacity. Easiest way to handle the capacity is to divide the storage capacity in fixed parts. If the capacity is used either way, the consumer/producer cannot use more capacity, even there is storage volume or hydrogen available. It is possible that a more flexible way of operation will be developed around the common hydrogen storage where capacity can be bought from another operator if needed. This also prevents unexpected situations where e.g. storage capacity is used faster than assumed.

Other risks are related to coordination between different actors in the ecosystem, which are further addressed in 3.3.5 from a governance perspective.

3.3.4 Consequences of hydrogen releases

As there are no large-scale lined rock hydrogen storages, there was no real case for consequence analyses study conducted during HUG project. Some imaginary cases were studied, where hydrogen was released from the surface connection pipeline which is probably the largest pipeline in diameter and has the highest pressure. These are the leakage cases Finnish Safety and Chemicals Agency (TUKES) want to get analysed and consequences assessed. The consequences were analysed from three different viewpoints: the reach of the flammable cloud, thermal radiation of a jet fire and pressure level of flammable hydrogen cloud explosion. TUKES specifies the required reference values for chemical concentrations (dispersion), heat radiation, and explosion pressure in its guidance, "Siting of production plants: 4.1.5 Quality and content requirements of an impact analysis".¹

Consequence analyses are usually conducted with dedicated software products. During the HUG project, two freely available programs were tested with a set of different release pipe sizes and storage maximum pressures: ALOHA and ADAM3. ALOHA is freely available for all and ADAM3 is meant for authority use within European Union. Additionally, Gexcon's Effects software was used for some cases and in the late phase of the project a release case with horizontal jet release was conducted by Sweco with DNV Phast software. The size of the safety area around the surface connection was mainly related to the direction of the release and the released mass flow. It is possible to affect jet direction with the structural design on the surface facility and the mass flow can be decreased by utilizing multiple smaller pipeline connections rather than a single larger pipeline.

3.3.5 UHS ecosystem sociotechnical risks

We developed an integrated UHS ecosystem sociotechnical risk framework, which aims at supporting safety capacity building and proactive risk anticipation capabilities in the future UHS ecosystem. A set of guiding questions was developed to support structured stakeholder engagement and to elicit perceptions, concerns, expectations, and potential risk factors affecting risks arising from different factors and their interactions. The questions function as an elicitation framework, enabling systems thinking and systematic exploration of risks by UHS stakeholders. The framework is grounded in Macrae's (2022) sociotechnical risk approach; the criteria for a good safety culture, based on VTT's Design for Integrated Safety Culture (DISC) model (Reiman & Oedewald 2009; Oedewald et al., 2011), and extends to include links to social license, responsibility, and sustainability-related risks.

The questions can be used to raise awareness about different factors that may affect safety of UHS, for example before site selection, material choices, permitting, or contracting takes place. It is important to note that these questions are not a complete list of all possible issues, and this is *not a checklist* or a compliance check. Key insight is that challenges and related risks in emerging complex infrastructure projects like UHS may not be technical in nature but can stem from the interaction of diverse stakeholders with varying values, knowledge, cultures, goals, and business models in an inter-organizational environment, as well as their interfaces with technical and external factors.

¹ <https://tukes.fi/en/siting-of-production-plants#requirements-impact-analysis>

Table 3. UHS ecosystem sociotechnical risks dimensions and example questions for stakeholder consideration.

	Risk dimension	Example questions
1.	Structural risks	☐ What critical interdependences could turn small problems into major consequences, and how are these managed? ☐ Is there clear system-level integrator to constrain total storage, rates, or interacting uses across companies? ☐ How organizational structures ensure information flow and prevent formation of silos? ☐ Do actors have structural means to intervene proactively when cumulative risk trends upward?
2.	Organizational coordination and collaboration risks	☐ What organizational conditions create challenges for work to be done with high quality (e.g., insufficient resources, unclear accountabilities)? ☐ Are coordination mechanisms designed also for abnormal or degraded conditions, not only normal operation? ☐ Who can raise concerns if commercial pressures push against system safety limits, and how response is coordinated? ☐ How is the responsibility for identifying and managing interface risks (e.g., between organizations or systems) recognized and explicitly owned?
3.	Technological risks	☐ What new constraints or affordances does technology introduce that may change how work is done in practice? ☐ Does the technology make some important aspects of the underground storage system harder for people to observe or understand? ☐ Can monitoring systems detect small changes that may indicate an emerging leak, contamination or integrity problem? ☐ Can operators understand why an automated system recommends or initiates a particular action?
4.	Epistemic risks (knowledge and knowledge gaps, uncertainty)	☐ Where are we operating at the edge of knowledge, and how do we detect overconfidence? ☐ Is there a structured effort to increase public awareness of underground hydrogen storage by addressing misconceptions and knowledge gaps proactively? ☐ Are the key assumptions behind geological, operational, and regulatory models made explicit and shared? ☐ Are the possible effects of automation bias (overreliance on automation) monitored to ensure human knowledge is adequate and at all times available to ensure safety?
5.	Social license risks	☐ Have local communities and stakeholders been engaged before technical options were narrowed? ☐ Are there established mechanisms for continuous dialogue on opportunities and impact, concerns handling, and feedback (two-way communication)? ☐ Are benefits framed also in concrete and measurable societal terms (security, jobs, growth), not only technical performance? ☐ Are the uncertainties communicated openly to communities, not only benefits?
6.	Safety culture	☐ What assumptions are taken for granted and rarely questioned, and how are these made visible and discussed? ☐ How do different groups (engineering, operations, management, contractors) conceptualize and understand risks and safety, and how are these discussed? ☐ Can concerns be raised without negative consequences, and how this is done in practice? ☐ Are activities organized in a manageable way, even in unexpected situations, and how does it show in practice?
7.	Responsibility risks	☐ In a dynamic UHS ecosystem, who takes the overall responsibility for safety?

		☐ Do companies go beyond compliance and own focus area to demonstrate responsibility for safety functioning of the entire storage system? ☐ Is responsibility articulated for long-term subsurface and surface impacts, beyond project or contract lifetimes? ☐ Are responsibilities understood as both legal and ethical obligations?
8.	Sustainability risks	☐ How are the chronic issues and cumulative trends analyzed and monitored long-term to ensure risk awareness, and what action is taken to control hazards? ☐ Have various sustainability impacts - environmental, social, institutional, economic - been assessed at system scale, not per operator? ☐ Is there a governance mechanism for learning, knowledge preservation and adaptation over decades? ☐ Is the infrastructure sufficiently adaptable if climate and energy-system conditions differ significantly from those assumed during design?

Table 4. Key outcomes and findings of WP2.

Outcome	Title	Key Findings	Key Results / Outputs
O2.1	UHS's Social License to Operate requirements	The novelty, size, site selection and subsurface nature of UHS require early stakeholder engagement, transparent communication of benefits and uncertainties, and mechanisms for ongoing dialogue and feedback for obtaining SLO. Regulatory confidence and public confidence need to co-evolve.	Integrated in HUG final report (3.3.5) Output report O2.1 (PowerPoint presentation)
O2.2	Preliminary risk analyses of underground H2 storage concepts	Main hazards of UHS are related to leakages and contamination of hydrogen. Leakages of the surface connection or plug structures are the most severe ones due to large amount of released hydrogen. The most hazardous contaminant is oxygen and therefore the procedures when filling and emptying the storage must be carefully planned.	Conference article Confidential research report
O2.3	UHS ecosystem risks	The storage capacity can be divided in different ways; there can be a fixed capacity or a stock market, where the companies can buy storage capacity according to the demand. We developed UHS ecosystem sociotechnical risk framework presents example questions for exploring different dimensions of risk by UHS stakeholders to support safety capacity building and proactive risk anticipation capabilities in the future UHS ecosystem.	Integrated in HUG final report (3.3.5) Output report 2.3 (PowerPoint presentation)
O2.4	Consequence analysis results of possible hydrogen leakage/fire/explosion related to UHS operations	Main factors that affect the safety zones are the mass flow of the released hydrogen and the direction of the leaking jet. The surface connection of the UHS is the most probable source of massive leakage. The zone can be decreased by reducing the pipeline size, as the authorities require consequence analysis for the pipelines with highest pressure and largest cross-dimensional area. The size of the leakage in these pipelines under consideration is 10% of the cross-sectional area of a pipe in question.	Public research report

3.4 Future research directions

During HUG project a lot of scenarios that might lead to either leakages or contamination were identified. In future research, these scenarios' relevance should be studied, and mitigation possibilities should be investigated. From the materials research perspective, the operating conditions of UHS and the behavior of the materials should be defined. As the environmental conditions are always site-specific, the requirements for materials can be interpreted to other sites without need for complete tailoring.

Now, underground gas storage is not considered as pressure equipment according to TUKES experts. Eventually, they probably will be classified as pressure vessels of certain kinds and there probably will be inspections that must be considered in the storage inspectability design. In practice, inspectability means that it must be possible to enter the cavern or shaft safely to conduct periodical inspections without compromising the structural integrity while emptying and refilling the storage with pressurized hydrogen and the gas tightness during normal operation.

The UHS construction methodology was not studied extensively during HUG, but it can be stated that the way of construction affects heavily the safety and reliability of the storage. The quality of the construction work is essential, as all faults that occur during construction can cause serious problems later, as corrective maintenance of UHS structure is demanding or even impossible. The construction quality issues will probably be connected to pressure equipment legislation issues, as the UHS is always at least partly tailored structure and a separate approval is required before it can be taken into operational use. Construction phase also involves use of contractors and subcontractors, which increases the organizational complexity, fragmentation of work and risks related to e.g., deficiencies in communication and coordination. Moreover, understanding the hydrogen safety significance of the work versus occupational safety during UHS construction is another important consideration.

Operational scenarios of a UHS can affect a lot on storage safety. During high injection or withdrawal periods the pressure and temperature of hydrogen inside the storage volume can vary a lot causing stresses on the structure. Currently, the safety margins for the structure are uncertain; e.g. is it allowed that the temperature of the storage goes under zero degrees. These questions can at least partly be studied by modelling, so comprehensive models where different operational scenarios can be studied, are recommended to be created.

Insights from the practitioners at the HUG final seminar highlighted questions requiring further research regarding leadership and overall responsibility for safety in a dynamic UHS ecosystem, ensuring long-term reliability of materials and the system as a whole, and developing capability to detect early and act effectively early upon weak signals that can jeopardize safety and integrity of the UHS.

Regarding the Social License to Operate and UHS ecosystem risks, future research could test and further elaborate the integrated UHS ecosystem sociotechnical risk framework, enabling systematic exploration of risks and strengthening safety capabilities by the UHS stakeholders in Finland. The high level SLO requirements need to be further developed as a part of the permitting process and translated into methods for tracking local trust in developers and regulators, perceived safety, fairness of siting and land-use planning, adequacy of benefit sharing, and changes in acceptance across the project lifecycle.

3.5 Conclusions

Current knowledge about UHS structures still involves significant uncertainties, reflecting the epistemic risks typical of first-of-a-kind facilities and the need to communicate uncertainty clearly to support social licence. Technically, material durability and strength must be carefully designed and tested to prevent loss of containment, such as leakage. In underground caverns or shafts, safety relies mainly on the surrounding rock mass, as the thin gastight layer cannot withstand cyclic gas-storage loads on its own.

Many risks can be managed, but key details remain uncertain because there are few practical examples of gas storage in rock caverns or shafts. Skallen natural gas storage is the closest reference, although it differs from UHS in gas properties and operating modes. Construction quality is a key challenge for full-size UHS. Installing the required layers may be demanding, and any faults could be difficult or costly to correct afterwards, making high-quality installation, supervision, and verification essential.

This study developed a preliminary set of SLO requirements and sociotechnical risk framework for the UHS ecosystem to support stakeholders in building social license and develop safety capacity. The elicitation example questions and the SLO requirements encourage early stakeholder engagement and early identification of risks before they become licensing barriers, operational vulnerabilities, or safety-significant events. Given the novelty, scale, location, and subsurface nature of UHS, future projects require early stakeholder engagement, transparent communication of benefits and uncertainties, and continuous dialogue to support social license. Overall, the findings highlight the importance of social license and sociotechnical risk elicitation in understanding and managing ecosystem risks, while supporting the UHS long-term safety and value for society.

References

- Macrae, C. (2022).
Learning from the Failure of Autonomous and Intelligent Systems: Accidents, Safety, and Sociotechnical Sources of Risk. *Risk Analysis*, 42: 1999-2025. <https://doi.org/10.1111/risa.13850>
- Hayes, J. & Maslen, S. (2025).
Preparing for Public Safety Assurance in the Energy Transition, Future Fuels CRC, Australian Government.
- Glamheden, R. & Curtis, P. (2006).
Excavation of a cavern for high-pressure storage of natural gas. *Tunnelling and Underground Space Technology*, 21(1), 56–67. <https://doi.org/10.1016/j.tust.2005.06.002>
- Energimyndigheten (2019).
National Preventive Action Plan for Sweden 2019. Available at: [link](#) (Accessed 30 Jan 2026).
- Johansson, F., Spross, J., Damasceno, D.R., Johansson, J. & Stille, H. (2018).
Investigation of research needs regarding the storage of hydrogen gas in lined rock caverns: Prestudy for Work Package 2.3 in HYBRIT Research Program 1.
- CH2ESS – Luleå University of Technology (2024).
The Swedish Hydrogen Conference 2024: AI Report. Luleå University of Technology. Available at: [link](#)
- Intelligent Techniques for Prediction of Drilling Rate for Percussive Drills in Topically Weathered Limestone .
Available from: https://www.researchgate.net/figure/Top-hammer-and-DTH-drilling-process_fig2_361054731 [accessed 9 Mar 2026]
- Gaudry, C., Ouffroukh, H., Moscone, L. & Taherzadeh, R. (2019).
Constraints, design and construction methods of the Cigéo five deep shafts.
https://www.researchgate.net/publication/333172415_Constraints_design_and_construction_methods_of_the_Cigéo_five_deep_shafts

4 WP3: Design and technology – Geological site criteria, key rock design parameters

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Abstract:

Underground hydrogen storage (UHS) is essential for large-scale hydrogen deployment, but conventional storage formations such as salt caverns and depleted hydrocarbon reservoirs are scarce in crystalline bedrock regions like Finland. In such settings, hydrogen storage in lined rock caverns (LRCs) presents a viable alternative, provided that storage site is characterized by suitable geological conditions to ensure mechanical stability and long-term containment. Brittle fractures, faults, and heterogeneous bedrock properties represent key challenges that must be addressed through careful site selection.

This study proposes preliminary geological criteria for selecting LRC hydrogen storage sites in crystalline bedrock, drawing on methods from UHS research and nuclear waste repository site assessments. Finally, a preliminary LRC rock engineering concept was developed by Sweco Finland Oy as part of HUG-project. In addition, the industrial partners together with VTT and GTK compiled preliminary technical boundary conditions for lined rock shaft (LRS) type UHS storage.

4.1 Introduction

Storing gaseous hydrogen poses technical challenges due to, e.g., high storage pressure, hydrogen's low density, high diffusivity, and chemical reactivity, which can lead to leakage, ignition, and material embrittlement. These factors have motivated the use of geological formations for long-term, large-scale Underground Hydrogen Storage (UHS; Masoudi et al., 2024). Salt caverns and depleted hydrocarbon reservoirs, characteristic to sedimentary bedrock settings, have proven effective, but such formations are largely absent in regions of crystalline bedrock, such as Finland.

In crystalline bedrock, the main challenge for pressurized hydrogen storage is the presence of brittle geological structures, such as fractures and faults, which pose stability risks during construction and operation, and act as conduits for gas and fluid migration that may compromise containment. Engineered barriers, such as gas-tight linings, are therefore required to maintain both structural and containment integrity. Despite these challenges, hard crystalline bedrock remains a promising storage medium due to its high strength and ability to withstand elevated pressures under favorable bedrock stress conditions (Damasceno et al., 2023).

This study aims to determine preliminary geological criteria for the selection of LRC hydrogen storage sites in crystalline bedrock settings. The work focuses on revising criteria commonly presented in (i) UHS related geological studies and (ii) nuclear waste disposal site assessments. Criteria such as bedrock stability and long-term containment, originally considered relevant for nuclear waste repositories, are also relevant for hydrogen storage, as both require secure formations that prevent leakage and maintain stability over time. Research emphasis is placed on evaluation of bedrock deformation zones, lithology, overburden thickness, earthquake proximity, and overall homogeneity of the study areas as these factors affect safety, construction feasibility, and operational reliability. The study also introduces restrictive criteria, such as groundwater zones and conservation areas, which are recommended to be excluded from site areas due to, e.g., environmental and permitting purposes. Furthermore, a scoring framework was developed to rank nine preliminary study areas based on the geological criteria. Subsequently, three sites (referred to as use-case sites) out of the nine preliminary areas were selected for a more detailed, local-scale analysis. Finally, one site was recommended for geological field investigations. The location-bound results are available for HUG consortium only while the description of the workflow is openly available. As part of the study, conceptual engineering guidelines for LRC hydrogen storage was developed by Sweco Finland Oy, and preliminary technical boundary conditions for LRS hydrogen storage was developed as in-kind work by the HUG project industrial partners.

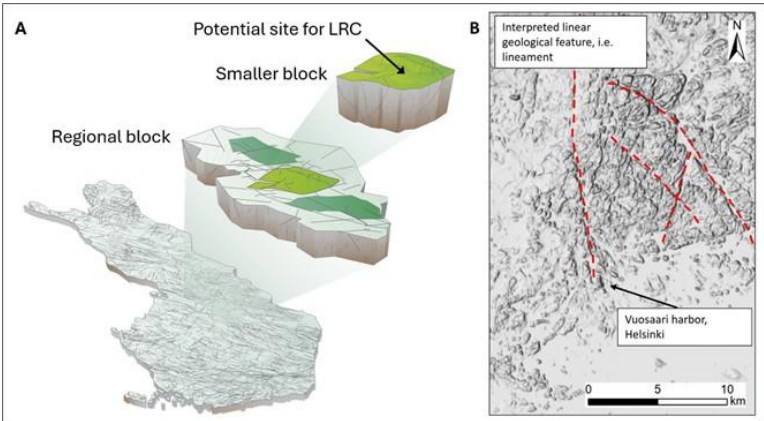
4.2 Methods

4.2.1 Site selection criteria

Optimizing geological conditions for an LRC site requires systematic geological investigations throughout the project lifecycle. Initiating the investigations prior to the decision of the site location is crucial for ensuring that natural conditions of a site are favorable, and thereby few costly mitigation measures are required.

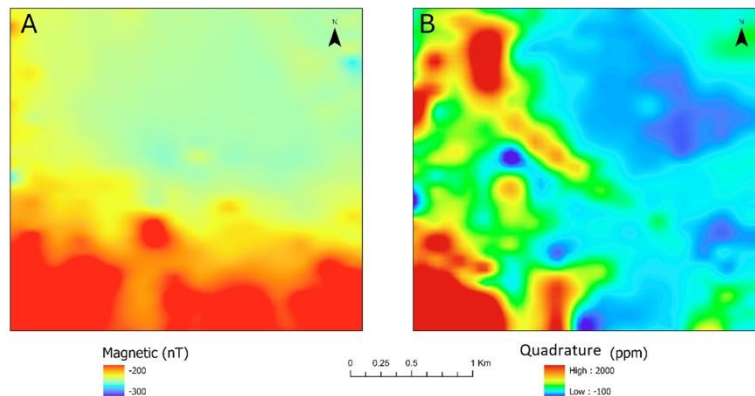
The geological site selection process begins with screening of potential site areas based on predetermined geological criteria and existing geological datasets. The first interpretations focus on regional scale, and subsequently, the interpretations are refined to local scale with the aim of locating areas that have the most potential geological properties. Comparable geological characterization methods have been applied in nuclear waste management site selection to identify high-quality rock mass sites for subsequent characterization and evaluation (e.g., McEwen and Äikäs, 2000). The workflow in HUG-project differs from this approach as the nine preliminary study areas were suggested by the industrial partners (Business Oulu (Oulu); Hycamite (Kokkola); Green North Energy (Naantali); jointly by Helen, Vantaan Energia, and Neste (Helsinki and Sipoo); and Fortum Power and Heat (Porvoo) at the beginning of the project. Table 5 presents the geological criteria used and their background.

Table 5. Geological criteria

Rationale	Used data
Bedrock block structures Finnish bedrock exhibits a block mosaic structure that occurs at multiple spatial scales (Fig). The boundaries of large bedrock blocks generally correspond to major bedrock deformation zones, such as faults and fracture zones, which may pose a major stability risk to LRC hydrogen storage. Toward smaller blocks nested within the regional blocks, the length of these deformation zones and width of their influence zone generally decrease. Therefore, potential storage sites are recommended to be located within smaller local-scale bedrock blocks.  <i>A) Principles of the block within block concept and B) interpretation of bedrock blocks, i.e. lineament interpretation (red dashed lines) using LiDAR data © NLS.</i>	0,5p and 5p LiDAR data (National Land Survey of Finland, 2024, 2019) Airborne magnetic and electromagnetic data (Geological Survey of Finland, 2016a, 2016b).
Favorability and number of rock types An ideal host rock for LRC hydrogen storage is homogeneous, isotropic, mechanically strong, and contains a pre-existing fracture network. Recommended rock types are reported in more detail in the HUG outcome report O3.1 (Lindqvist et al., 2026)	Bedrock of Finland, scale free (Geological Survey of Finland, 2022)

Geophysical homogeneity

Geophysical homogeneity refers to the uniformity and consistency of subsurface properties across a potential LRC site, as interpreted from geophysical datasets such as magnetic and electromagnetic data.



Example of geophysical homogeneity. A) Airborne magnetic data shows homogenous conditions in the North whereas the southern side is more heterogeneous. Units in nanotesla (nT). B) Airborne electromagnetic map shows homogeneous conditions in the northeast and more heterogeneous conditions in the west.

Airborne magnetic and electromagnetic data (Geological Survey of Finland, 2016a, 2016b).

Distance to earthquakes

Distance to earthquakes refers to the distance from the epicenters of earthquakes to the LRC study areas. While the earthquake frequency and magnitudes in the Fennoscandian shield can be considered low compared to seismically active areas (e.g. Fülöp et al., 2023), an earthquake may cause damage if one occurs in vicinity of LRC hydrogen storage. Potential LRC sites are recommended to be located away from earthquake epicenters.

Earthquake epicenters data (Institute of Seismology University of Helsinki, 2024)

Overburden thickness

Overburden thickness strongly influences investigability of a study area by obscuring the underlying bedrock and therefore increases the uncertainty of geological interpretations. Thick overburden may also correlate with major fault zones, as glacial erosion tends to preferentially erode mechanically weaker parts of the bedrock. Consequently, areas with thin overburden are generally preferred in LRC site selection.

Superficial Deposit Thickness Map 1:1 000 000 scale (Geological Survey of Finland, 2018)

Restrictive criteria

Several criteria may be considered restrictive for LRC site selection, for instance, from geological and permitting viewpoints.

i) Only favorable rock types, **ii)** No protected buildings, cultural heritage sites, ancient relics, nor world heritage sites, **iii)** Overburden 10 meters or less, **iv)** No mineral deposits, mining and exploration areas, **v)** No conservation or groundwater areas, **vi)** No unfavorable superficial deposits -e.g. eskers, thick peat

i) Only favorable rock types (Appendix A in Lindqvist et al., 2026)

ii) Finnish Heritage Agency, n.d.

iii, iv and vi) Geological Survey of Finland, 2018, 2016c, 2016d, 2015a, 2015b, 2015c

v) Finnish Environmental Institute, n.d.

The site selection was done in two phases. The first phase involved the following steps:

- i) Lineament interpretation of major bedrock deformation zones and bedrock block structure at 1:200 000 scale within and surrounding the preliminary study areas (Bedrock block structure, Table 5).
- ii) Identification of favorable areas within the preliminary study areas by filtering restrictive subareas (Restrictive criteria, Table 5).
- iii) Scoring of the preliminary study areas based on the geological criteria (Table 5 and 6). Each criterion was divided into three categories, corresponding to scores of 1, 0, or -1 (Table 6). The scores of each criterion were then summed up to obtain a total score for each preliminary study area. Finally, the top three preliminary study areas were selected as the use-case study areas.

The second phase focused on detailed infinite scale lineament interpretation in which the analysis of geological structures was conducted using flexible scales to identify potential fracture zones at the use-case sites. The Porvoo area use-case showed the best results and was selected for geological field investigations.

Table 6. Scoring scheme of the preliminary study areas

Score	Overburden thickness	Number of rock types	Rock type suitability	Distance to earthquake epicentre (km)	Geophysical homogeneity	Number of possible fracture zones
1	Bedrock exposed or minimal overburden	1	Only favorable rock types	>8	Good	Very few if any
0	Areas of exposed bedrock and thick (some meters) overburden	2	Areas of favorable and unfavorable rock types	5-8	Fair	Few lineaments
-1	Area covered up to 10 m thick overburden	>2	Only unfavorable rock types	<5	Poor	Several lineaments

4.2.2 Site characterization

The geological field investigations at the Porvoo site were initiated in April 2025 and they consisted of lithological and structural mapping of the bedrock and geophysics. The mapping was done first followed by the ground geophysical surveys that were targeted based on the mapping results.

Geophysical ground surveys gave an image of, and aid in the understanding of the overburden- and subsurface structures, which are essential for solving fault networks for site assessment. The geophysical methods used are listed in table 7.

A small drill program to validate the mapping and geophysical results was carried out in the fall of 2025. The drillings included two boreholes (total 569 m) done with hammer drilling, and no rock samples (drill core) were obtained. Imaging the drill holes was performed with OBI40-2G optical and ABI40 2G acoustic downhole devices and cameras which enable structural measurements to be taken from the images.

The site characterization process with the methods used represents the initial stage of work for the site and forms the foundation for future work.

Table 7. Methods used in geological surveys

Method	Amount of survey
Electric Resistivity Tomography (ERT)	6 survey lines of 200 m =1200 m
Ground Penetrating Radar (GPR)	9 survey lines, 4.2 km in total
3D active seismic survey	The survey was done as an irregular 3D acquisition over approximately 0.25–0.35 km ²

4.3 Findings / Key results

Table 8. Key results of GTK's part in the HUG project.

Outcome	Title	Key findings	Key Results/Outputs
O3.1	Site selection criteria report	Early-stage, geological site selection studies are essential for any LRC hydrogen storage project. Site areas should be selected away from major bedrock deformation zones. The crystalline bedrock in Finland is inherently heterogeneous, and therefore, geological site evaluation is recommended prior to finalizing the site location.	The determined criteria were applied to nine study areas that were proposed by the industrial partners in the consortium. Three use-case study areas were selected for a more detailed study, and one final site for geological field investigations. (Lindqvist et al., 2026)
O3.2.1	A report with preliminary design parameters and required properties of the produced cavern	LRC Lined rock caverns (LRCs) are technically feasible for large-scale hydrogen storage in Finnish crystalline bedrock. The most suitable host rock is competent but fractured. Cavern depth is critical for safety and liner durability. A multi-layer liner system is essential. Steel liner fatigue and hydrogen embrittlement are the governing design constraints. Construction schedules are long but predictable, estimated to be 4.5–5.5 years. Risk-based design and long-term monitoring are essential. LRS Lined Rock Shafts (LRS) for hydrogen storage are technically feasible at depths of ~100–120 m and diameters ~1.5 m in competent Finnish bedrock. Estimated shaft construction cost (excluding liner) is ~2 300–2 500 €/m³. Recommended shaft spacing: FEM results indicate >4D (ideally 4–5× shaft diameter) centre-to-centre spacing to limit yielding and displacements. Cap rock / anchoring concept: Traditional cone models are overly conservative for competent, highly stressed rock. LRS using raise boring is technically feasible. It enables large diameter (~3–7.5 m), deep (~100–150 m, potentially longer) vertical shafts but requires existing access to the bottom of the shaft.	LRC Conceptual design of a lined rock cavern hydrogen storage (Siren et al., 2025). LRS Several documents provided by industrial partners. The materials are available in HUG project outcome materials.
O3.2.2	Thermo-mechanical modelling-webinar and workshop	The workshop provided insights how to develop numerical models regarding thermo-mechanical behavior of rock masses associated with lined rock cavern hydrogen storage.	The materials are available in HUG project outcome materials.
O3.3	Site characterization report	Geological site characterization for a conceptual lined rock cavern hydrogen storage site was successfully implemented at the Porvoo site providing important information about the geological properties of the site and a framework for further data needs for subsequent investigations. The Porvoo site is characterized by homogenous bedrock with little to moderate fracturing. The bedrock is well exposed for detailed planning of field investigations.	Outcome report for HUG-project consortium only.

4.4 Future research directions

The purpose of the geological criteria proposed in this report is to guide future LRC site selection studies toward identifying geologically high-quality sites for hydrogen storage. However, the locations of geologically favorable site areas do not necessarily coincide with areas of significant hydrogen supply or demand. Therefore, future studies on geological site selection should also address geological characteristics of areas that are less optimal. Such characteristics may include, for example, thick overburden and unfavorable overburden composition, such as the presence of acid sulfate soils, and their implications on the cost and engineering design of LRC facilities in these areas. Furthermore, detailed field studies are needed to improve the understanding of optimal fracture network characteristics within the LRC host rock. I.e., too fractured rock mass may pose a competency and stability hazard whereas few dominant fractures may be hazardous for liner integrity if they open too much due to the high pressure within the storage.

4.5 Conclusions

Geological studies focused on the delineation of geological criteria for the selection of site areas suitable for LRC hydrogen storage in crystalline bedrock settings. These criteria are essential for guiding successful selection of hydrogen storage sites, as the future demand for storage capacity is expected to be significant. By incorporating geological considerations at an early stage of site selection, it is possible to significantly enhance cost-efficiency, reduce technical uncertainties, and improve the overall feasibility of storage solutions. The criteria can also be used to design safety requirements for LRC hydrogen storage.

One of the most important criteria is the absence of major bedrock deformation zones within a site area. This can be achieved by initiating geological site selection studies prior to making location decisions. However, the complete avoidance of fractures and minor faults is not feasible under known conditions in the Finnish crystalline bedrock. Such features are likely to be encountered to some extent; however, their scale and impact on the design and construction of LRC hydrogen storage can be minimized through careful optimization of geological conditions during the site selection process.

The site characterization process with the methods used for the LRC site investigations represent the initial stage of work for the site and forms the foundation for further work. Diamond drilling will be essential in future to obtain drill core samples. Drill core sampling and more drilling at the site will enable rock mechanical, hydrogeological and discrete fracture network modelling, which in turn will enable the decision-making process for final construction, operation and monitoring of the LRC facility.

References

- Damasceno, D.R., Spross, J., Johansson, F., 2023. Rock mass response for lined rock caverns subjected to high internal gas pressure. *Journal of Rock Mechanics and Geotechnical Engineering* 15, 119–129. <https://doi.org/10.1016/j.jrmge.2022.03.006>
- Finnish Environmental Institute, n.d. Conservation and groundwater areas. Finnish Environmental Institute. Available at: <https://www.syke.fi/en/environmental-data/downloadable-spatial-datasets>. Reference date 2024 May 15th.
- Finnish Heritage Agency, n.d. Spatial data sets on the cultural environment. Finnish Heritage Agency. Available at: <https://www.museovirasto.fi/en/services-and-guidelines/data-systems/kulttuuriympaeristoen-tietojaerjestelmae/kulttuuriympaeristoen-paikkatietoaineistot>. Reference date 2024 May 15th.
- Fülöp, L., Mäntyniemi, P., Malm, M., Toro, G., Crespo, M.J., Schmitt, T., Burck, S., Välikangas, P., 2023. Probabilistic seismic hazard analysis in low-seismicity regions: an investigation of sensitivity with a focus on Finland. *Nat Hazards* 116, 111–132. <https://doi.org/10.1007/s11069-022-05666-4>
- Geological Survey of Finland, 2022. Bedrock of Finland scale-free. Version 2.3. Geological Survey of Finland, Hakku service. Available at: <https://hakku.gtk.fi/en/locations/?id=181>. Reference date 2026 Mar. 18th.

- Geological Survey of Finland, 2018. Superficial deposit thickness 1:1 000 000. Version 1.1. Geological Survey of Finland, Hakku service. Available at: <https://hakku.gtk.fi/en/locations/?id=113>. Reference date 2024 May 15th.
- Geological Survey of Finland, 2016a. Aeromagnetic anomaly map of Finland. Version 1.0. Geological Survey of Finland, Hakku service. Available at: <https://hakku.gtk.fi/en/locations/?id=6>. Reference date 2026 Mar. 18th.
- Geological Survey of Finland, 2016b. Aeroelectromagnetic imaginary component map of Finland. Version 1.0. Geological Survey of Finland, Hakku service. Available at: <https://hakku.gtk.fi/en/locations/?id=28>. Reference date 2026 Mar. 18th.
- Geological Survey of Finland, 2016c. Mines. Geological Survey of Finland, Hakku service. Available at: <https://hakku.gtk.fi/en/locations/?id=61>. Reference date 2024 May 15th.
- Geological Survey of Finland, 2016d. Mineral deposits. Geological Survey of Finland, Hakku service. Available at: <https://hakku.gtk.fi/en/locations/?id=62>. Reference date 2024 May 15th.
- Geological Survey of Finland, 2015a. Superficial deposits of Finland 1:200 000 (sediment polygons). Version 1.0. Geological Survey of Finland, Hakku service. Available at: <https://hakku.gtk.fi/en/locations/?id=3>. Reference date 2024 May 15th.
- Geological Survey of Finland, 2015b. Superficial deposits 1:100 000. Version 1.0. Geological Survey of Finland, Hakku service. Available at: <https://hakku.gtk.fi/en/locations/?id=115>. Reference date 2024 May 15th.
- Geological Survey of Finland, 2015c. Superficial deposits 1:20 000 / 1:50 000. Version 1.0. Geological Survey of Finland, Hakku service. Available at: <https://hakku.gtk.fi/en/locations/?id=1>. Reference date 2024 May 15th.
- Institute of Seismology University of Helsinki, 2024. Earthquakes in Finland and adjacent areas. Available at: <https://www.seismo.helsinki.fi/EQs/query.php>. Reference date 2024 May 15th.
- Lindqvist, T., Hietava, J., Paananen, M., Wik, H., Huotari, T., Wiberg, M., 2026. Geological criteria and methodology for site selection of underground hydrogen storage in crystalline bedrock settings. Geological Survey of Finland 39/2026.
- Masoudi, M., Hassanpouryouzband, A., Hellevang, H., Haszeldine, R.S., 2024. Lined rock caverns: A hydrogen storage solution. Journal of Energy Storage 84, 110927. <https://doi.org/10.1016/j.est.2024.110927>
- McEwen, T., Äikäs, T., 2000. The site selection process for a spent fuel repository in Finland: summary report. Posiva Oy, Helsinki.
- National Land Survey of Finland, 2024. Laser scanning data 5 p. Available at: https://asiointi.maanmittauslaitos.fi/karttapaiikka/tiedostopalvelu/laserkeilausaineisto_5p?lang=en. Reference date 2024 May 15th.
- National Land Survey of Finland, 2019. Laser scanning data 0,5 p. Available at: https://asiointi.maanmittauslaitos.fi/karttapaiikka/tiedostopalvelu/laserkeilausaineisto_05?lang=en. Reference date 2024 May 15th.
- Siren, T., Barrón Francisco, P., Valtonen, R., 2025. Conceptual design of a lined rock cavern hydrogen storage. Sweco Finland Oy.

5 WP3 Material technology solutions for H2 storages

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Abstract:

The objective of WP3 part – Material technology solutions for H2 storages was to screen existing and potential new material solutions for the lined rock cavern (LRC) for gaseous hydrogen storage. Based on current survey there are several different LRC and lined rock shaft (LRS) concepts for underground hydrogen storage, but only one small test pilot exist in Sweden. A review showed that significant gaps remain in understanding the long-term behaviour of LRC and LRS under cyclic loading. As a top challenges being the performance of the multilayer material solution consisting of hydrogen-compatible steel liner, optimized concrete to ensure that the internal stress can be safely and evenly transferred to the surrounding rock structure, and a sliding layer between them to reduce the friction between steel lining and concrete lining. Based on the review and discussions with several experts' requirements and specifications for the multilayer system are screened in terms of LRC operation and process characteristics.

5.1 Introduction

Large amounts of gaseous hydrogen can be stored in underground in multiple ways, major approaches being utilization of geological structures like depleted gas/oil fields and aquifers, and (engineered) salt caverns created by mining. For regions without suitable geology, lined rock caverns (LRCs) are considered a prospective solution because they have potential to store large amounts of gaseous hydrogen at high pressures (Masoudi et al., 2024 and Leong et al., 2025).

A typical LRC gas storage consists of the inner steel liner followed by a sliding layer and outermost concrete lining and shotcrete facing the bedrock (Fig. 3). Although this multilayer structure does not carry primary loads it must withstand stresses and strains resulting from the rock/cavern wall deformation imposed by cycling pressure, temperature variations, exposure to hydrogen and chemical attacks by ground water.

Similarly, lined rock shafts (LRSs) are an emerging technology to store moderate amounts of hydrogen. The typical LRS concept is like the LRC, i.e., has a steel liner and concrete support to ensure gas tightness, with the surrounding rock mass providing structural support (Fig. 4), and expected to offer a cost-effective medium capacity storage system with less tight demands for geological conditions compared to the LRCs.

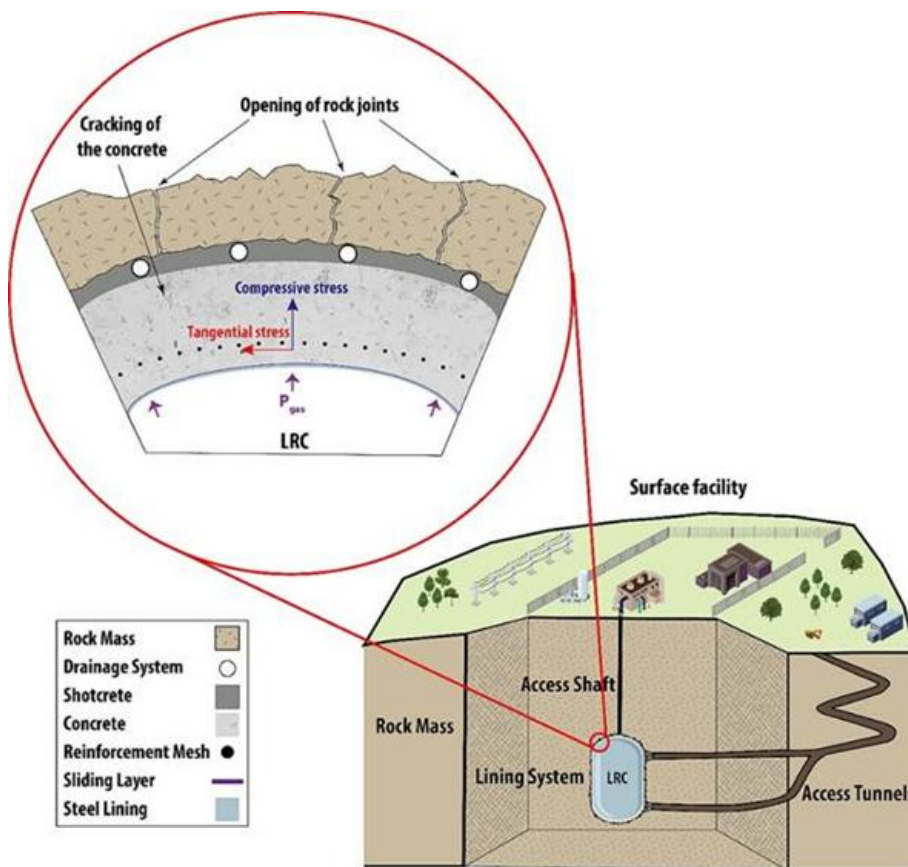


Figure 3. A Schematic of LRC concept designed for hydrogen storage. Picture retrieved from Masoudi et al (2024).

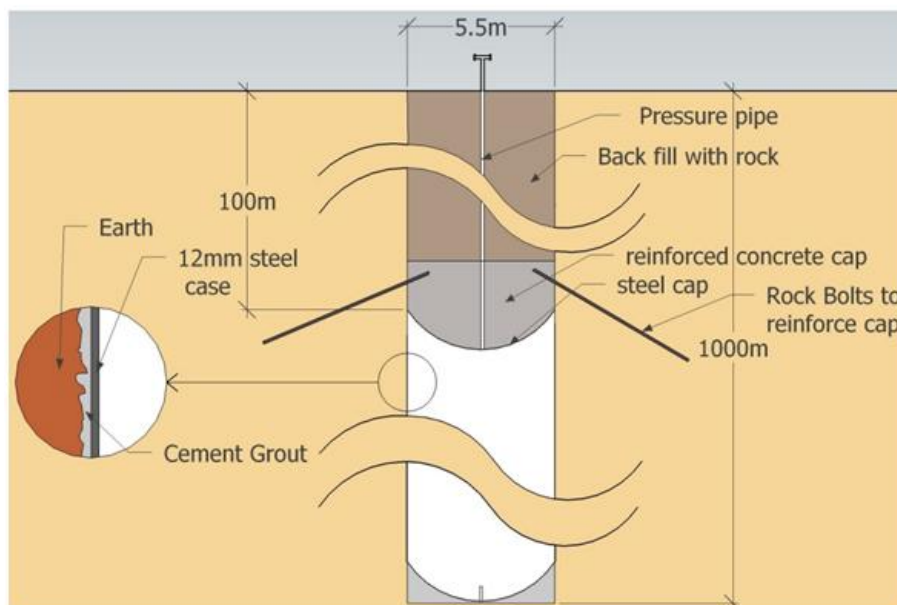


Figure 4. A schematic of LRS concept for underground gas storage. Picture retrieved from Lavine et al (2016).

5.2 Methods

A literature survey regarding concrete and other cement-based materials within hydrogen storage concept was carried out earlier, within another project (H2Matters) at VTT. The report discusses the storage structure material (liner concrete), but not specifically the shotcrete, or bolting grouts nor rock injection grouts which typically are part of rock engineering design. For those cases, mainly similar material specifications are valid as in storage structure. The focus of concrete materials in this HUG project was to identify the further research needs for concrete durability and mechanical properties.

Similar literature survey was conducted also for the inner liner focusing on the design concepts and proposed material solutions. This was then complemented with the current knowledge from materials used for gaseous hydrogen storage and transportation at intermediate pressures.

In addition to this, a patent survey was carried out at the beginning of the project to map and evaluate technological trends, identify high-value patents and freedom to operate issues.

5.3 Findings / Key results

The key findings are summarized below, and more detailed information will be presented in forthcoming “steel liner” and “concrete” reports.

Steel liner

Steel is the most likely selection for the inner liner although also polymers like high density polyethylene (HDPE) is also mentioned as candidate (Leong et al., 2024 and Wang et al., 2026). The steel liner plays a critical role in ensuring the safety and integrity of the LRC hydrogen storage facility. The primary function of the liner is to provide a gas-tight barrier that prevents hydrogen leakages. Though the steel liner does not carry primary loads it must withstand the maximum operating gas pressure and resist the deformation due to cyclic loadings as well as withstand stresses and strains resulting from the cavern wall deformation at the presence of hydrogen.

Although carbon steel liner is successfully used in the natural gas LRC and low alloys steels have good track record from the natural gas and hydrogen transport pipelines the most probable selection for the LRC and LRS inner liner will be stainless steel despite high costs. Austenitic stainless steels, particularly type EN 1.4404 that have relatively high content of Ni and Mo, have generally excellent resistance to hydrogen embrittlement and have superior hydrogen permeation resistance compared to the low alloy steels (Pakarinen et al., 2025, Soundararajan et. al. 2025 and Wang et al., 2026) These steels are also formable and their weldability is good, which is essential when considering that large LRC will have kilometres of welds.

Even though there is plenty of knowledge and performance data from austenitic stainless steels in gaseous hydrogen there are marked knowledge gaps from environments and operating conditions unique and relevant to LRC's and LRS's e.g., how the operational cycling conditions effect on hydrogen embrittlement and fatigue performance (high strain low cycle fatigue) and what is the role welds and of hydrogen impurities. Another big question is then the liner corrosion in ground water and the role of concrete chemistry and sliding layer.

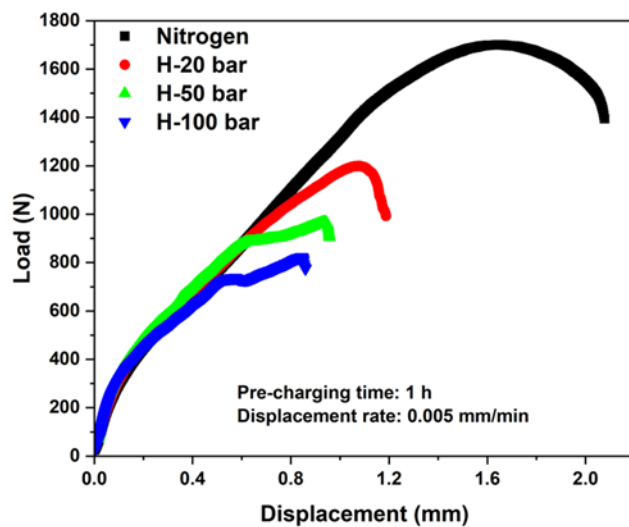


Figure 5. Effect of hydrogen pressure on stress–strain curves of the X70 pipeline steel. (Soundararajan et. al. 2025)

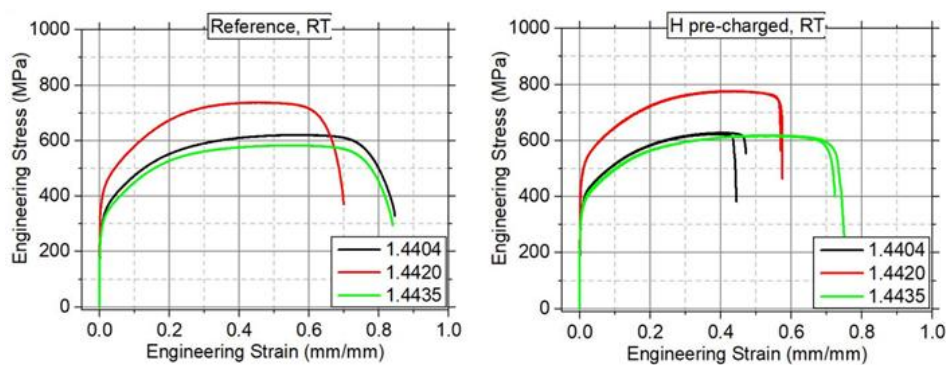


Figure 6. Effect of internal hydrogen on the tensile properties of EN 1.4404 and variants. Hydrogen pre-charging for two weeks at 1380 bar and 300 °C to saturation (140 wt-ppm H) and tested in air. (Pakarinen et al. 2025)

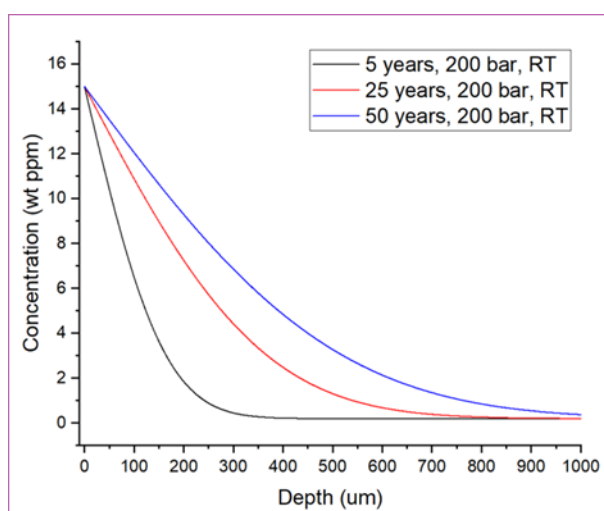


Figure 7. Hydrogen solubility and diffusion in the type EN 1.4307 austenitic stainless steel based on thermodynamic calculations.

Concrete liner: The antecedent literature survey report is only discussing what type of research has been done so far, in relation to hydrogen and concrete/cement-based materials. That report does not discuss the durability or mechanical requirements to be set for storage structure materials. The boundary conditions for these (requirements) will be created from the basis of literature survey, environmental exposures on construction site area, and from the basis of intended operational variables in relation to pressure, temperatures etc. Some assumptions can be made about environmental exposures and other topics, but comprehensive material research in relation to durability and mechanical properties of concrete is needed before any pilot project or industrial scale plant implementation.

The chemical composition of concrete mix defines the durability and mechanical properties of concrete and thus, the capabilities to achieve the intended service lifetime of concrete structure. This chemical composition concerns the cement and other binder materials of a concrete mix, not so much of the chemical composition of concrete aggregates – not at least here in Finland (where the quality of concrete aggregates is generally speaking very high). The chemical properties of concrete raw materials are thus depending on the raw material sources, which leads to the fact that concrete mixes designed for use in Finland must be tested with raw materials (manufactured and) commonly used in Finland. This is the reason why concrete mixes cannot be just copied from one country to another.

Typically, groundwaters can contain high amounts of sulphate and chloride compounds, and the pH of groundwater can be quite low – even acidic. These all are harmful to concrete. Also, several other compounds in groundwater can be detrimental to concrete and other cement-based materials, so the chemical composition of concrete needs to be designed properly to minimize or prohibit these harmful effects. Besides the chemical composition of groundwater, the permeability and transport properties of concrete are determining how aggressive the chemical attack can be, or what will be the rate for damage to induce. The permeability properties of concrete have also a significant role in gas-tightness of concrete, in case of hydrogen leakages. The effects of different type degradation mechanisms on underground hydrogen storage concrete and concrete structure, and research need for that are dealt with within the outcome O3.4/5 of this HUG project.

Structural concrete is needed to support the steel liner and to carry the loads from operating cyclic pressure and stresses and strains resulting from the cavern bedrock wall itself. Thus, the concrete layer in liner structure will be heavily reinforced and a massive structure as well, on order of 1,5 meters thick. This massiveness creates several challenges to be taken into account in concrete mix design and construction work of the storage walls, to fulfil all the durability and strength requirements of the structure: It is probable that after each cast section, the structure will need simultaneous cooling and heating, to avoid too big thermal stresses and temperature gradients during the concrete hardening.

All the mechanical properties to be set for the liner concrete are quite specific type, in relation to many other typical industrial plants. Unlike many other concrete containers e.g., like containment buildings, this storage structure cannot be post-tensioned structure, due to the risk of hydrogen embrittlement in tendons. Completely crack resistant or crack-free concrete doesn't exist, but the cracking tendency of it should be minimized as much as possible. Also, the size of the structure (total height) will be very high, and the moisture content in concrete can locally vary a lot, which makes the creep properties quite significant here. And further, the concrete also needs to resist well some level fatigue exposures and deformations due to operational pressure changes. Due to these reasons, quite extensive development and testing of concrete mechanical properties is needed as well, within a research project carried out before any pilot or industrial scale plant implementation. These research needs are dealt with the outcome document O3.4/5 of this HUG project.

Monitoring of the liner structure was also discussed within this HUG project. When having a (forthcoming) plant in operation, different types of inspections and investigations are quite difficult or even impossible to carry out during the service lifetime of the storage liner. Even the use of non-destructive (NDT) methods will be quite challenging, at least with the LRC case structure. Some actions may be possible, but this must be taken into account already in the design phase, and it requires quite detailed design work. Anyway, monitoring systems and comprehensive instrumentation are needed. This (instrumentation) must be constructed/installed at the same time with reinforcement and other mechanical installations of the liner structure. Monitoring needs for concrete liner are discussed e.g. in the outcome document O3.4/5 of this HUG project. Monitoring installations can be tested for the first time in the mock-up cast connected to material research project but also in the forthcoming pilot project. This topic (monitoring) most probably is the one which lives most, i.e., cannot be completely locked in very early phase.

5.4 Future research directions

In the future, the focus should be on bridging the knowledge gaps regarding material performance in intended environments and operating conditions unique and relevant to LRC's and LRS.

Multi-scale analysis and coupled physical simulations must be developed and advanced to analyze how different operating conditions affect thermodynamic, structural, and mechanical states, and what is the impact to the cavern wall and multi-material liner.

Advanced concrete mixes must be developed to fulfil the special requirements of mechanical and durability properties needed in the concrete liner.

Multiple, interacting degradation mechanisms, such as hydrogen embrittlement and low cycle fatigue of the steel liner, ageing of the sliding layer, and concrete durability at the presence of groundwater and cyclic loads, must be assessed to predict the long-term durability of the liner structure in this very specific environment.

5.5 Conclusions

Due to the specific requirements of mechanical and durability properties of concrete, most probably conventional concrete mix designs in this type of structure are out of question. This type of project needs a specific mix design, and the only way to find out what that will be is a comprehensive material research and testing phase. The results of that will partially (from the chemical point of view) cover also the shotcrete, bolting grout and rock injection grouts needed in the construction of rock caverns.

Based on current understanding of the pipelines, the most probable selection for the LRC and LRS inner liner will be type EN 1.4404 austenitic stainless steel despite high costs. Despite that there are plenty of performance data from austenitic stainless steels in gaseous hydrogen there are marked knowledge gaps concerning the unique operating conditions and targeted long service life relevant to LRC's.

Regarding the materials in a hydrogen storage liner structure, no specific material research was done within this HUG project. Anyway, this HUG project showed and gave ideas, which still needed to be researched and studied, before any pilot project or industrial scale plant implementation. Preparation of HUG2 for these material research purposes is ongoing.

References

- Masoudi, M., Hassanpouryouzband, A., Hellevang, H. & Haszeldine, R.S. 2024.
Lined rock caverns: A hydrogen storage solution, *Journal of Energy Storage*, Volume 84, Part B, 2024, 110927. <https://doi.org/10.1016/j.est.2024.110927>.
- Kekäläinen, P., Gu, Y. 2024.
Hydrogen and Concrete – literature survey. WP1 Report in H2Matter project. VTT Technical Research Centre of Finland, 29 pp.
- Lavine, A.S., Lovegrove, K.M., Jordan, J., Anleu, G.B., Chen, C., Aryafar, H. & Sepulveda, A. 2016.
Thermochemical energy storage with ammonia: Aiming for the sunshot cost target. *AIP Conf. Proc.* 1734, 050028 (2016). <https://doi.org/10.1063/1.4949126>
- Leong, C.M., Ghayesh, M.H., Nathan, G.J., Salmachi, A. & Rajabi, M.
A review of the mechanics of lined engineered cavities and their implications on hydrogen storage. *International Journal of Hydrogen Energy*, Vol. 102, 2025, Pp. 749-766.
<https://doi.org/10.1016/j.ijhydene.2024.12.467>
- Pakarinen, J., Huttunen-Saarivirta, E., Pohjanne, P., Moilanen, P., Nandy, S., Ronevich, J.A. & San Marchi, C. 2025.
Effect of Composition on Tensile Properties of AISI 316 Variants with Internal Hydrogen. *ASME 2025 Pressure Vessels & Piping Conference (PVP2025)*, July 20-24, 2025. Montreal, Canada.

- Paukku, E., Fülöp, L. 2026.
HUG project – WP3 Concrete liner (A review for the use of concrete or other cement-based materials, and their general requirements in underground hydrogen storage structures, 46 pp.). In preparation.
- Pohjanne, P., Fedoroff, A. & Pakarinen, J. 2026.
HUG project – WP3 Steel liners. In preparation.
- Soundararajan, C., Rantala, J., Nurmela, A. & Huttunen-Saarivirta, E. 2025.
Gaseous hydrogen embrittlement behavior of API-X70 pipeline steel investigated using in-situ small punch test. 7th International Small Sample Test Techniques Conference. 16. - 18. September 2025, Freiberg, Germany.
- Sun, Z., Wu, J., Fager, A. & Crouse, B. 2024.
Numerical analysis of hydrogen storage in lined rock cavern under high pressure and its implications to hydrogen embrittlement, International Journal of Hydrogen Energy, Volume 80, 2024, Pages 1021-1029. <https://doi.org/10.1016/j.ijhydene.2024.07.208>.
- Wang, Z., Jia, W., Zhang, W. & Li, M. 2026. A generic study on static stability of lined rock cavern subject to an internal pressure of 10 MPa. Renewable Energy, Vol. 256, Part F, 2026, 124330.
<https://doi.org/10.1016/j.renene.2025.124330>.

6 WP4: Techno-economic feasibility of LRC operation and process concept options

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Abstract:

WP4 focused on assessing the techno-economic feasibility and operational characteristics of lined rock cavern (LRC) hydrogen storage concepts. The work combined state-of-the-art reviews, dynamic process modelling, computational fluid dynamics (CFD), investment cost analysis and optimization of green hydrogen production. The results demonstrated significant economies of scale for LRC storage, strong sensitivity of cost to total storage volume rather than cavern count, and the importance of thermodynamic behaviour during charging and discharging. In addition, large-scale hydrogen storage was shown to reduce green hydrogen supply costs by improving utilisation of renewable electricity and decoupling hydrogen delivery to end-user from the short-term power market variability. The findings and tools provide solid foundations for the more detailed design of the H₂ LRC storage.

6.1 Introduction

Lined rock cavern (LRC) technology is increasingly considered as a promising option for large-scale underground hydrogen storage, particularly in regions where suitable salt formations are not available. While the basic LRC concept has been demonstrated in industrial scale for natural gas storage for more than 20 years, its application to hydrogen introduces new uncertainties. Although a small-scale hydrogen LRC pilot exists in Luleå, Sweden, public-domain information on hydrogen-specific operational behavior is scarce.

The aim of WP4 was to move beyond descriptive state-of-the-art reviews and provide quantitative insights into the technical and economic feasibility of LRC hydrogen storage specifically for Finland. The work comprised a set of closely linked activities aimed at addressing the key knowledge gaps related to LRC hydrogen storage:

- **First**, an updated state-of-the-art review was conducted to consolidate current knowledge on LRC storages, identify critical uncertainties and knowledge gaps, and define initial specifications.
- **Second**, dynamic process modelling was applied to analyse pressure and temperature behaviour during storage operation – including potential means for temperature control – providing insight into feasible filling and withdrawal rates and their implications for storage and liner design. The resulting temperature behaviour was further benchmarked against more detailed CFD simulations to assess the adequacy of simplified models for describing the gas behavior and thermodynamics in a large storage vessel.
- **Third**, a techno-economic assessment was performed to derive cost functions for LRC storage under Finnish conditions, with particular emphasis on economies of scale and cavern configuration.
- **Fourth**, a dedicated compressor study was carried out to identify the suitable large-scale hydrogen compression technologies and design a suitable compressor train configuration for LRC. Special focus was on operating flexibility as compressors need be able to cope with highly varying input flows.
- **Fifth**, a market-oriented optimisation model was developed to quantify the role of large-scale hydrogen storage in enabling the production of RFNBO²-compliant hydrogen. The model

² Renewable fuels of non-biological origin as described in Renewable Energy Directive (EU 2018/2001)

jointly optimises renewable electricity capacity, electrolyser capacity, and hydrogen storage sizing. The aim was to study how hydrogen storage affects the techno-economic performance and RFNBO compliance of produced hydrogen. This was executed by creating different scenarios, where hydrogen demand levels and the presence and size of storage were varied.

6.2 Methods

Several modelling approaches were applied to address both storage-level physical phenomena and system-level operation of LRC hydrogen storage under electricity market conditions.

A dynamic process model of LRC hydrogen storage was developed using Apros™, a transient simulation environment developed by VTT and Fortum, for energy and process systems analysis. The model represents the cavern, liner, piping, and auxiliary systems with a level of detail sufficient to describe pressure and temperature evolution during filling and withdrawal. Heat transfer between the stored gas, liner, and surrounding rock is included, enabling analysis of temperature variations as a function of operating rates. The modelling framework allows representation of alternative operating conditions and temperature control concepts, such as gas recirculation with heating or cooling. The model is used to analyse operating envelopes, including filling and withdrawal rates and cycle durations, and to provide process-level input for equipment dimensioning and control concept development.

To evaluate the validity of the one-dimensional (1D) representation of thermal behavior assumed in the dynamic Apros™ process model, simplified CFD simulations were carried out for selected operating cases. The CFD analysis focused on gas phase temperature distribution within the cavern, thermal stratification, and local temperature gradients during transient operation. The simulations were carried out for a 40 000 m³ LRC using OpenFOAM-dev version with the computational mesh generated using cfMesh+. In addition to the full three-dimensional (3D) model, a two-dimensional (2D) axisymmetric model was also used. This was motivated by the very long runtimes associated with the 3D simulations, which necessitated a relatively coarse mesh, whereas the 2D model is computationally more efficient and allows the use of a denser mesh and a shorter time step. The three-dimensional domain consists of about 600,000 cells. All walls were treated as adiabatic, and all remaining model parameters and boundary conditions were kept as consistent as possible with the corresponding Apros™ simulations to ensure comparability. A case, where the surrounding steel tank, concrete layer and surrounding rock have been taken into account, was also examined. To monitor the axial evolution of the flow and temperature fields, nine probe locations were positioned along the central axis of the domain at equal spacing.

An optimisation model for green hydrogen production was developed in Matlab to generate insight into the storage capacities and operating profiles required under realistic market conditions, thereby providing input for the technical design of hydrogen storage concepts. The design of the system employed a techno-economic tool based on a two-layer approach: the optimal system configuration is determined by particle swarm optimisation (PSO) algorithm on the outer layer, while dispatch is managed on the inner layer by an energy management strategy (EMS). The optimisation objective is the minimisation of the levelised cost of hydrogen (LCOH) supply.

The model operates at an hourly time resolution over an annual time horizon. It incorporates hydrogen demand profiles, renewable electricity generation and day-ahead electricity price data, electrolyser operational constraints, storage capacity limits and maximum filling and withdrawal rates, and investment and operating costs. The PSO is used to determine the sizing of key system components, including electrolyser capacity, LRC storage volume, and renewable electricity generation capacity, subject to the operational constraints represented in the model. System operation is described using the EMS, which is a rule-based control logic. At each time step, the EMS compares the electricity price with a given threshold (here 25 €/MWh), which serves as a proxy for RED III temporal correlation requirements. When the price is at or below the threshold, grid electricity may supplement RE for electrolyser operation; otherwise, only RE can be used. Renewable electricity is supplied through pay-as-produced PPAs. If RE and stored hydrogen are insufficient and grid electricity exceeds the threshold, fossil hydrogen is purchased at a fixed price to meet demand.

The EMS then determines operating actions based on hydrogen demand. In this study, demand is always present. When sufficient RE and, if permitted, grid electricity are available, the electrolyzer produces hydrogen to satisfy demand, with any surplus stored subject to storage capacity and charging constraints. If production is insufficient, hydrogen is withdrawn from storage within discharge and minimum storage level limits. Any remaining deficit is supplied by fossil hydrogen.

Adopting a rule-based dispatch instead of co-optimising both capacity and dispatch enables a computationally light approach. Furthermore, the rule-based dispatch could be perceived as more realistic compared to perfect foresight. In reality, the day-ahead prices are known for the next day, which is information that the model does not utilise. This trade-off is accepted because the study focuses on comparative design insights and policy-threshold sensitivity rather than absolute theoretical minimal.

6.3 Results

6.3.1 State-of-the-art review

Several key knowledge gaps were identified in the state-of-the-art review. These included, e.g., limited understanding of filling and withdrawal rates under dynamic operation, insufficient representation of thermodynamic effects during charging and discharging, uncertainty in cost scaling with storage size and cavern configuration. In addition, it was found out that LRC feasibility is strongly influenced by site-specific conditions, which means that during the planning of a LRC storage, it is necessary to consider local conditions early on, as the more generic cases can provide only very limited information regarding the construction choices, operational limits, and costs.

6.3.2 Dynamic process and CFD modelling

A dynamic process model of a 40,000 m³ lined rock cavern hydrogen storage was developed using Apros™ (Figure 6.1) and the temperature behavior inside the storage was validated against CFD simulations with a specific focus. The combined modelling demonstrates that thermal effects are significant during both filling and withdrawal operations and represent a key operational constraint. Following observations were made:

- Gas withdrawal leads to pronounced cooling of the cavern, which can restrict operational flexibility with respect to both withdrawal rate and duration. Minimum temperature limits must be maintained safely above 0 °C to avoid freezing–thawing cycles of groundwater.
- During filling, thermal stratification develops. The temperature of the injected hydrogen governs the thermal conditions in the lower part of the cavern, while the upper part experiences progressive heating, leading to vertical temperature gradients (Figure 9).
- Temperature can be actively influenced through gas recirculation combined with heating during withdrawal or cooling during filling, thereby extending the feasible operating envelope.
- Heat-exchange with surroundings needs to be considered due to the long time-scales involved in LRC operation.
- Predictive and anticipatory control strategies provide additional flexibility. For example, if forecasts indicate periods of low wind power production and high electricity prices, the storage cavern can be preheated in advance to enable increased hydrogen withdrawal without violating temperature constraints.
- Dynamic simulation is a key enabler for LRC concept development, as temperature behavior directly affects material selection, liner integrity, and safe operation, and cannot be captured adequately using steady state approaches.
- CFD simulations are needed to accurately capture the thermal behaviour in large storages and to pinpoint the most critical areas for material integrity. The two-dimensional axisymmetric approach was found to be a good compromise between accuracy and computational demands.

- Apros model showed somewhat more pronounced temperature changes during filling and withdrawal compared to CFD simulations. Some further calibration is required to improve agreement between the models and ensure consistent predictions of the thermal behaviour.

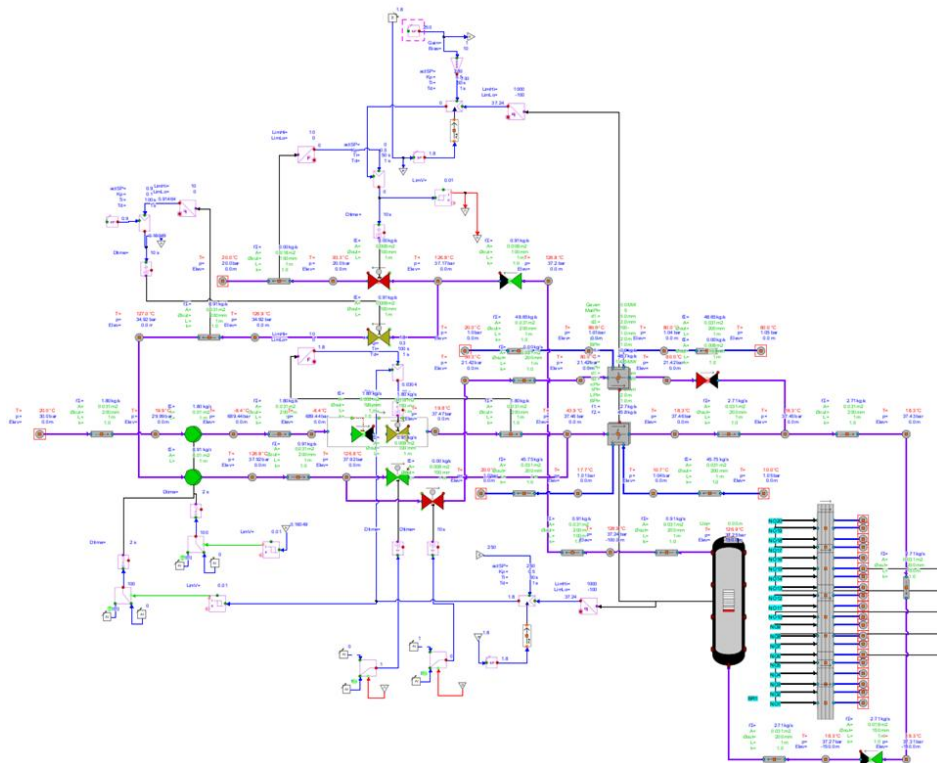


Figure 8. Dynamic process model of H₂ LRC storage with gas recirculation system for temperature control developed in Apros™ modelling tool.

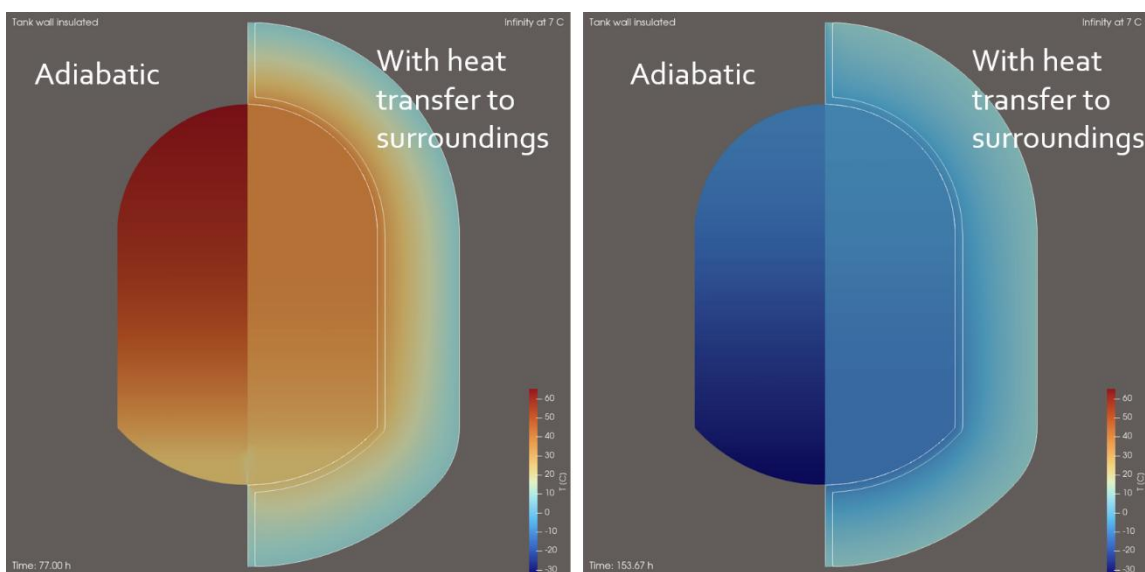


Figure 9. Example CFD result graph showing storage temperature stratification after storage is filled from 25% to 75% (left) and then emptied back to 25% (right) with and without considering heat transfer to surroundings.

6.3.3 LRC storage investment costs and economies of scale

Based on Sweco's conceptual level rock engineering report (Siren et al., 2025), a cost function was developed to estimate the investment costs of different size of LRC hydrogen storages in Finland for both single- and multi-cavern configurations. The function applies to LRCs operated at a maximum pressure of 200 bar and explicitly accounts for the number of caverns. Hydrogen compressor costs are excluded. The total investment cost is calculated as:

$$Cost = Cost_{Ref} \times \left(\frac{V}{V_{Ref}} \right)^{Exponential\ factor} \times (1 + (N - 1) \times (aV^2 + bV + c)) ,$$

where

Cost = investment cost of LRC (M€)

Cost_{Ref} = investment cost of reference LRC = 27.3 M€

V = cavern volume (m³)

V = cavern volume of reference LRC (m³) = 40,000 m³

N = number of caverns

a = -1.9495E-11

b = 5.4460E-06

c = 0.40742

Exponential factor = 0.6

The model was calibrated for cavern sizes of 40,000–120,000 m³ but can be extended to 20,000–160,000 m³ with reasonable accuracy. The number of caverns is not strictly limited but in practice, concepts having more than 6 caverns are not typically considered.

The results indicate strong economies of scale when increasing the volume of a single cavern, as reflected by the exponential scaling factor of 0.6 (Fig. 10). This is due to the fact that that relatively high share of the costs – such as the cost of tunnels – are not related to the cavern size. Below ca. 20,000 m³, specific costs start to increase rapidly.

By contrast, dividing the total storage volume into two or three caverns does not lead to a significant increase in total investment costs (Fig. 11) as long as cavern sizes are > 20 000 m³. As a result, multi-cavern LRC configurations may be attractive from the operational perspective. They are safer and offer improved resilience to operational disturbances, as storage operation could continue in unaffected caverns if one cavern experiences technical issues. In addition, hydrogen could be transferred from the cavern having issues to the other caverns if needed. This is particularly relevant for storage sites not directly connected to high-capacity hydrogen pipeline infrastructure.

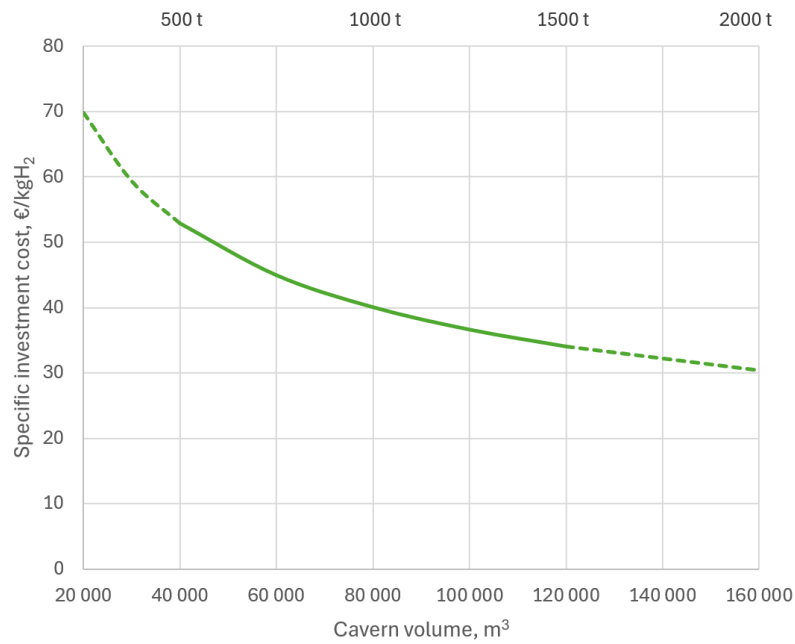


Figure 10. Specific investment costs as function of cavern volume corresponding to exponential factor of 0.6.

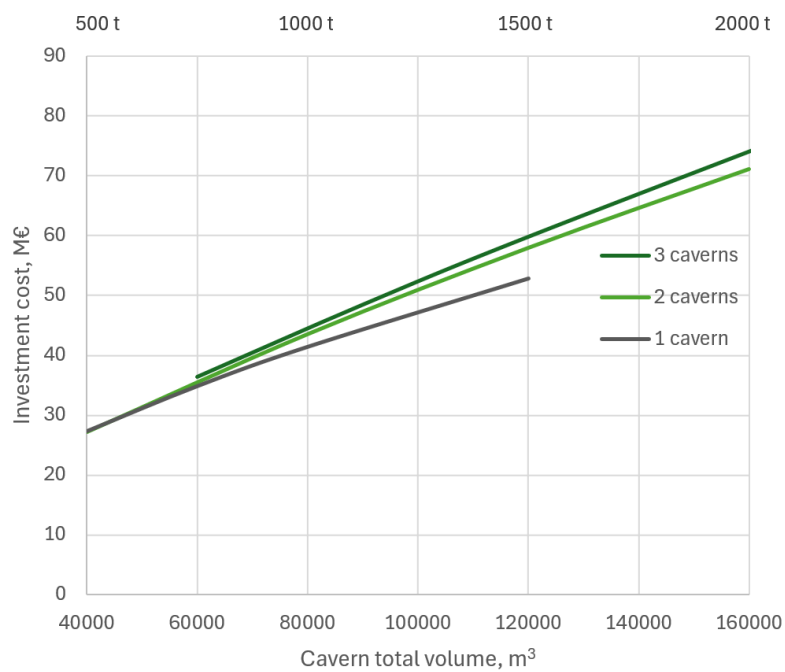


Figure 11. Comparison of investment costs of single- and multi-cavern options.

6.3.4 Large-scale H₂ compressors for LRC storage

- Compression was identified as a possible constraint for flexible LRC operation. The ability to inject hydrogen is not primarily limited by electrolyzer flexibility but by the compressor system's capability to follow the varying hydrogen flows.
- Reciprocating compressors are the most suitable technology for LRC storages today, as they can deliver the required combination of high pressures and large mass flows. Centrifugal compressors, despite their high flow capability, are constrained by low achievable pressure ratios for hydrogen and are therefore mainly applicable to low-head duties such as pipeline pressure boosting.
- Oil-free reciprocating compressors are preferred for LRC hydrogen storage to avoid hydrogen contamination, but this choice entails higher mechanical wear, lower allowable discharge pressures, and increased sensitivity to cyclic operation, necessitating conservative design and operating strategies.
- Operational flexibility of reciprocating compressors is inherently limited. Speed control alone typically allows turndown only to about 60–70% of nominal capacity (EFRC 2022), necessitating additional control measures for LRC applications with strongly fluctuating hydrogen supply.
- Selective cylinder unloading, clearance pockets and recycle control are key enablers of extended turndown (EFRC 2022). The final high-pressure stage generally dictates the minimum achievable load, due to mechanical, thermal, and valve-dynamic constraints for cylinder unloading and lower number of cylinders.
- System-level measures significantly improve operability. Parallel compressor trains enhance both load range and availability/resilience, while upstream hydrogen buffer storage effectively damps short-term mass-flow fluctuations, reducing compressor cycling and reliance on inefficient recycle operation.
- Overall, the results demonstrate that compressor systems must be co-designed with both electrolyzer operation and LRC storage requirements. Compressor configuration and control strategy decisively influence the achievable flexibility, robustness, and economic viability of LRC hydrogen storage systems.

6.3.5 Optimization of renewable hydrogen production and the role of H₂ storages

Power-to-Hydrogen system, which included power generation through wind and solar, grid connection, electrolyser, LRC storage, and constant H₂ demand, was compared to a similar system without a LRC storage. The aim was to study the effect of hydrogen storage on the optimal renewable electricity and electrolyser capacities which can meet the given demand. The results show that the inclusion of LRC can

- Enable a system that produces hydrogen which can be classified as RFNBO without the need for a fossil backup
- Reduce the operating expense of the system by providing the possibility to shift electricity demand to cheaper hours
- Decrease the LCOH compared to the configuration without storage, i.e., the operating cost savings offset the additional capital investment to storage and electrolyser capacity.
- Additionally, in the scenarios without storage, no configurations were found by the optimization which did not rely on fossil H₂ backup.

Figure 12 presents two LCOH breakdowns for a scenario with 6000 kg/h hydrogen demand and grid price threshold of 25 €/MWh. Wind and solar power generation as well as day-ahead prices were based on year 2023. The results revealed a cost premium of approximately 1 €/kgH₂ for fossil-free H₂ delivery, which was made possible by storage. In the no-storage scenario, the share of fossil H₂ was 40% of the total delivered H₂. The contribution of the LRC storage to the LCOH was up to 7%.

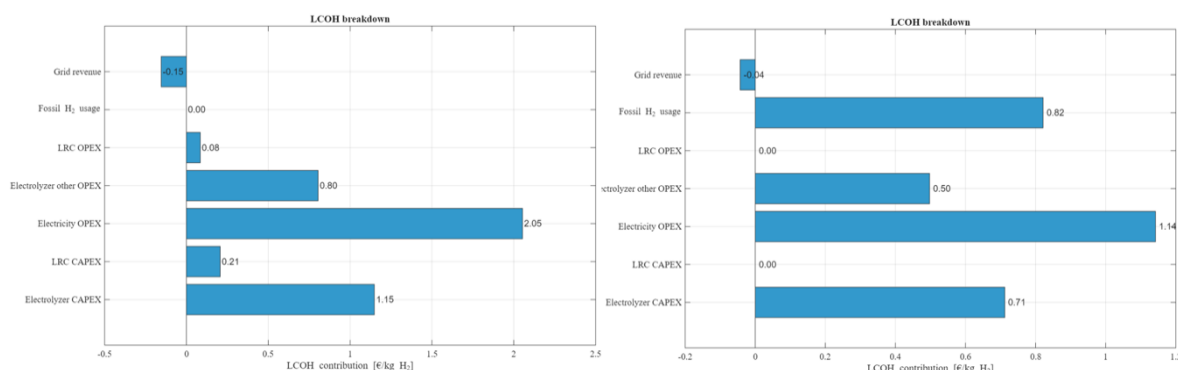


Figure 12. LCOH breakdowns of a scenario with 6000 kg/h hydrogen demand a) with and b) without a storage. Stack replacement costs are included in 'Electrolyzer other OPEX', compressor investment cost was included in 'LRC CAPEX', and compressor electricity consumption and O&M costs were included in 'LRC OPEX'. The total LCOHs for the scenarios a and b were 4.1 €/kgH₂ and 3.1 €/kgH₂, respectively. In scenario b, 40% of hydrogen was fossil (valued at 2 €/kg).

The sensitivity of the results with respect to the storage volume was tested by limiting the maximum allowed storage volume in the optimization. Table 9 presents the key numbers of the optimization. The resulting electrolyser capacity did not considerably increase when limiting the storage capacity from the 33 days (240 000 m³) suggested by the unlimited optimization to 10 days (80 000 m³). The wind and solar production capacity increased substantially; oversizing of the PPA and electrolyzer is the only option to respect the no-fossil rule when storage size and grid electricity purchase is strongly limited. As a result, the LCOH increased by 0.2 €/kgH₂, which indicates that the exact storage size is not economically critical, as a wide range of storage capacities deliver nearly identical costs.

Table 9. The resulting capacities and performance of the system when maximum storage volumes were limited to 120 000 and 80 000 m³.

Storage capacity m ³	240 000 (unlimited)	120 000	80 000
Wind capacity, MW	754	866	1 035
Solar capacity, MW	0	0	182
Electrolyzer capacity, MW	567	561	580
Storage capacity, d	33	15	10
Storage cycles, /y	3.7	7.4	9.4
Electrolyzer utilization rate, % (h)	60 (7 201)	59 (7 319)	57 (7 702)
Share of grid electricity	34	29	22
Share of RE	66	71	78
Share of external fossil	0	0	0
LCOH, €/kg	4.1	4.1	4.3
Grid sales effect	-0.1	-0.3	-0.7
LRC CAPEX, M€	138	74.8	58.1

The sensitivity of the LCOH to policy decisions was tested by relaxing the grid electricity price threshold from 20 €/MWh to 70 €/MWh. The idea was to imitate policy changes using the grid electricity price as a proxy: the system was allowed to utilize more expensive electricity from the grid stepwise, than what is allowed under the current RFNBO rules. The resulting highest CO₂ intensity of the H₂ production was around 1 kgCO₂-eq/kgH₂ for the 70 €/MWh threshold, while the emission intensity for unabated steam methane reforming (SMR) is 10–13 kgCO₂-eq/kgH₂ and approximately 1.5 kgCO₂-eq/kgH₂ with carbon capture using best

available technology. These findings indicate that RFNBO compliance rules have a substantial impact on system optimization and project economics. Moreover, where the electricity system already exhibits a low CO₂ emission intensity, less restrictive RFNBO requirements could yield both economic and environmental benefits by improving profitability and reducing overall emissions. More flexible procurement between power purchase agreements (PPAs) and grid, could improve the economic feasibility of H₂ production as well as allow smaller electrolyser capacities and higher capacity factors. Even when the storage capacity increased, the savings through cheaper electricity and smaller electrolyser investment cost offset the higher storage investment cost.

The results and optimal configurations suggested by the model were highly sensitive to the selected electricity price year. Therefore, further studies should focus on incorporating multiple weather and price years, which would allow robustness assessment of the optimal capacity portfolios. Despite the limited price and weather years used in the study, it can be concluded as general observations that

- Electricity is likely to remain the main cost driver of hydrogen production via electrolysis but CAPEX will also have a significant impact especially in near-term,
- The contribution of LRC to the LCOH is a small fraction of the total cost. Majority of the additional costs for 100% RFNBO hydrogen production comes from the need to oversize the electrolyzers, and
- It is highly probable that RFNBO hydrogen production is not economically feasible without a source of flexibility, be it hydrogen storage, battery energy storage, demand size flexibility, or something else.

Table 10. List of outcomes

Outcome	Title	Key Findings	Key Results / Outputs
O4.1	Deepening the state-of-the-art in LRC	Most of the literature refers still to Skallen natural gas LRC. Only one 100 m ³ H ₂ LRC pilot exists Lot of knowledge caps regarding the operation of H ₂ LRCs – e.g. gas withdrawal and filling rates and temperature control, leaks, safety, long-term operation	Comprehensive and up-to-date overview of the current status of LRC technology, including identified knowledge gaps and research needs.
O4.2 & O4.3	Techno-economics and optimization of green hydrogen production	Increasing the total volume of caverns shows high economies of scale while dividing the total volume to several caverns does not lead to markedly higher costs at >20,000 m ³ caverns LRC is a pre-requisite for 100% RFNBO production within the weather and electricity price years used in the modelling LRC constitutes a relatively small fraction of the levelized cost of RFNBO hydrogen production (<10%), even when the storage volumes seemed oversized	Finland-specific investment cost functions for multi-cavern LRCs A power-to-hydrogen optimization model with LRC storage Optimal storage sizes and renewable electricity production capacities for example cases, and main sensitivities. A scientific article regarding the role of H ₂ storage in a Finnish case study (to be submitted)
O4.4	Dynamic LRC process model	Temperature control will become a key issue in LRC operation Temperatures can be managed by recirculating gas and either heating or cooling it CFD simulations are needed to accurately predict the thermal behaviour and pinpoint the locations with highest risks for structural integrity Two-dimensional axisymmetric approach is a good compromise between accuracy and computational demands	Dynamic LRC process model Simplified CFD models

O4.5	Hydrogen compressor system design for LRC storage	Reciprocating and centrifugal compressors are suitable technologies for LRC Multi-stage oil-free reciprocating compressors are currently the most suitable technology for LRC applications. Without proper design, compressors can become the limiting factor for LRC storage flexibility Flexible and robust operation is enabled by combining selective cylinder unloading, clearance pockets and recycle control with parallel compressor trains, and optionally an upstream buffer storage.	Conceptual compressor system configurations to improve flexibility, availability, and operational robustness of LRC storage systems.
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6.4 Future research directions

Regarding dynamic process modeling, more extensive CFD simulations are required to cover a wider range of operating scenarios including cases with gas recirculation. These results should be used to develop simplified or reduced-order thermal models that can be efficiently implemented in Apros™ for system-level design and operational studies.

In techno-economic modelling, expanding the modelling to cover multiple weather and electricity price years would improve the robustness of the results. Using future energy market projections instead of relying on historical data would provide more insightful results but is limited by availability of such data. Furthermore, the accuracy of cost assessments and operational analyses could be enhanced by incorporating predictive dispatch strategies. Furthermore, more comprehensive modelling of hydrogen storage systems is required, including dynamic operating constraints, degradation mechanisms, and site-specific geological characteristics, to improve the reliability of cost and performance estimates. Expanding the scope of the analysis to consider sector coupling applications, such as heat integration and synthetic fuel production, as well as participation in electricity markets, would also enable a more holistic evaluation of the overall system benefits of hydrogen storage. Lastly, the role of demand side flexibility should be studied.

6.5 Conclusions

The following key conclusions can be drawn:

- Lined rock caverns (LRCs) are technically feasible and cost-effective for large-scale hydrogen storage in Finland.**

LRC technology is well suited for hydrogen storage capacities ranging from a few hundred tonnes up to several thousand tonnes per site, positioning LRCs clearly above conventional above-ground pressure vessel solutions and below salt caverns. LRC storage exhibits strong economies of scale, with indicative specific investment costs in the range of approximately 30–75 €/kg H₂ (excl. compressors). Dividing total capacity into multiple caverns incurs only a modest cost penalty and offers advantages in operational flexibility, resilience, and risk management. These costs are a magnitude lower than those of above ground storage but significantly higher than for salt caverns. Overall, the investment cost of LRC storage constitutes only a minor share of the total green hydrogen supply cost.
- Large-scale hydrogen storage plays a decisive role in optimizing green hydrogen production systems.**

Flexibility is essential for RFNBO hydrogen production. By decoupling inflexible hydrogen demand from short-term electricity market variability and renewable intermittency, LRC storage enables higher utilisation of renewable electricity, supports RFNBO-compliant hydrogen production, and can reduce the levelised cost of hydrogen under realistic demand and price dynamics.
- For large-scale LRC applications, multi-stage oil-free reciprocating compressors are the most promising technology.**

Flexible and robust operation is enabled by combining selective cylinder unloading, clearance pockets, and recycle control with parallel compressor trains and upstream buffer storage.

- **Thermodynamic behaviour is a critical design and operational driver for LRC storage.**
Dynamic simulations showed pronounced temperature variations and thermal stratification during filling and withdrawal, which can constrain storage operation and can affect liner and rock integrity. Accurate prediction of temperature behaviour in a large cavern requires advanced modelling, namely CFD.
- **Dynamic process models are essential tools for LRC design and operation.**
Transient simulations support the design of thermal management concepts such as gas recirculation, definition of operating envelopes, development of control and automation strategies, predictive optimization, and integration of storage with compressors and upstream hydrogen production.

References

- Siren, T., Barrón, P. & Valtonen, R. 2025.
Conceptual design of a lined rock cavern hydrogen storage, Sweco
- EFRC (European Forum for Reciprocating Compressors) 2022, "Hydrogen compression – Boosting the hydrogen economy"

7 WP5: Life-cycles and operations

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Abstract:

WP5 aimed to develop an integrated understanding of how underground hydrogen storage (UHS) can be operated safely, responsibly, and efficiently across its entire lifecycle. Adopting a sociotechnical approach, it treats UHS as a complex, safety-critical system where technical solutions, human operators, organizational processes, and regulatory requirements are tightly interlinked. The WP5 work integrated human factors engineering (HFE) with reliability, availability, maintainability, and safety (RAMS) in a holistic lifecycle model, ensuring human roles and safe practices were addressed from the earliest design phases. Key methods included a targeted literature review, work domain analysis (WDA), participatory expert elicitation on operations and monitoring, and concept development of digital monitoring tools and operator interfaces. These efforts produced foundational insights into UHS operation, enabling the systematic inclusion of human and organizational considerations in the design and development of the underground storage systems that continue supporting safe and sustainable operations throughout their lifecycle.

7.1 Introduction

The objective of WP5 Lifecycles and Operations was to develop an integrated understanding of how underground hydrogen storage systems should be operated safely, responsibly, and efficiently across the lifecycle. WP5 approached UHS as a complex, safety-critical sociotechnical system, where technical solutions, human work, organizational arrangements, and regulatory requirements are tightly interlinked and co-evolve, meaning that their impact on safety can only be understood through a broader, integrated system-level perspective.

WP5 focused particularly on:

- Defining an appropriate life-cycle model for UHS,
- identifying critical operational features, human operator roles, and tasks,
- integrating Reliability, Availability, Maintainability and Safety (RAMS) with Human Factors Engineering (HFE) program,
- and formulating user requirements for digital tools and information support for operations and maintenance.

The WP5 work demonstrates that integrating human factors engineering (HFE) and generally operational perspective from the earliest design phases is essential for developing safe, operable, and sustainable UHS systems, and forms a necessary foundation for operational concept development and long-term asset management.

7.2 Methods

WP5 applied a combination of analytical, participatory, and concept development methods to investigate the future UHS from a lifecycle and operational perspective, with a particular focus on human factors and socio-technical system safety.

A targeted **literature review** was conducted at the beginning of the HUG project to *examine existing research* on hydrogen storages, comparable safety-critical underground facilities, and human and organizational factors in storage operation. The review focused on operational practices, incident and accident analyses, monitoring and control challenges, and was used to identify HFE related knowledge gaps and to help framing the subsequent research work.

To *establish a system-level understanding of UHS operations*, **Work Domain Analysis (WDA)** (Naikar, 2013) was applied. WDA is one of the core analysis phases within the broader Cognitive Work Analysis (CWA) framework (Naikar, 2013). WDA was used to model UHS as a socio-technical system in terms of its purposes, constraints, functions, processes, and resources, still independent of specific technical solutions, tasks, or organisational arrangements (Salmon et al, 2024). The resulting WDA model provided a structured foundation for identifying operational dependencies, critical human tasks, and safety-relevant system characteristics across the UHS life cycle.

A comparative analysis of Reliability, Availability, Maintainability and Safety (RAMS) and Human Factors Engineering (HFE) program approaches was conducted to explore how these two perspectives can be integrated to support a *system-level understanding of UHS operations across the lifecycle*.

WP5 also employed **participatory expert elicitation** methods to complement analytical modelling and to capture domain-specific expert knowledge produced in the HUG project in the other work packages. Multidisciplinary experts from the consortium participated in structured collaborative exercise that was established on the **Whiteboard on the HUG project's Microsoft Teams space**. The exercise was used to elicit *expert insights primarily on UHS monitoring*. However, also operational risks, system behaviour and life-cycle challenges were enquired. The collected expert insights were analysed qualitatively to identify recurring themes, critical information needs, and cross-cutting operational concerns and system interdependencies. Analysis informed the development of concept of operation and preliminary user requirements for UHS from an operator perspective.

In the final phase of the HUG project, WP5 conducted **concept development and interface exploration workshops** on UHS monitoring. These activities focused on producing *illustrative monitoring concepts and human-system interface mock-ups*, such as the UHS overview displays and alarm panel. The purpose of this work was to support further discussion and conceptual exploration rather than detailed system design.

Together, these methods were planned to complement each other and support an integrated, **human-centered analysis of UHS** life cycle and operations.

7.3 Findings / Key results

The following section focuses on presenting the key results of WP5, highlighting the main outcomes related to the lifecycle, operational concepts, human factors, and monitoring of UHS storage system.

7.3.1 Literature review on UHS operations and human factors

WP5 conducted a targeted literature review and benchmarking on UHS and comparable safety-critical industrial operations, with a particular focus on human factors and operational work. The review showed that although H₂ storage is widely studied from technical and material perspectives, **research addressing operational practices, human operator roles, and human-technology interaction in UHS remains very limited**.

The reviewed literature and incident databases indicate that hydrogen-related accidents are frequently associated with design shortcomings, inadequate operating procedures, insufficient monitoring of the system and human and organisational factors, rather than isolated component failures (i.e., purely technical reasons). Thus, existing studies largely address human error retrospectively, while providing little insight into everyday operation work, system supervision, and anticipatory safety.

Overall, the literature reviewed revealed a clear gap in **human-centered, operation-focused knowledge** related to UHS. Consequently, the identified gap emphasizes the importance for early integration of human factors engineering and sociotechnical perspectives in system design.

7.3.2 Life-cycle perspective for UHS

RAMS and HFE share a common lifecycle structure that they address from complementary perspectives. RAMS emphasizes system-level performance and decision points (e.g. reliability targets, safety requirements, cost-effectiveness, and strategies for maintaining acceptable performance levels) whereas HFE focuses on the human role within the system (e.g., user needs, situational awareness, usability, health and safety considerations, and the role of operators in detecting, responding to, and preventing deviations).

- In previous research in nuclear engineering, it was discovered that as a result of engineering organisations struggling with integrating human factors integration early in the process, preventable human-machine interface issues would only be addressed nearing the end of the development cycle, at a time when making major changes is often thought too expensive to implement (Hugo 2013). Combined RAMS/HFE analysis approach would estimate both the developing system's technological maturity as well as the human factors maturity levels. Combining these approaches provides a more comprehensive framework for UHS design and operation, ensuring that both technical system performance and human capabilities are considered from the outset. This approach is more likely to identify and address preventable issues early during development and work towards preventing operational issues or costly design alterations later.

Currently, concepts related to hydrogen (H₂) storage under Nordic conditions - particularly the lined rock cavern (LRC) concept - are still at a very early stage of development. In practice, the only well-established characteristic is that, once constructed, the expected lifespan of the first storage facility will exceed 50 years. Consequently, detailed asset lifecycle management activities are difficult to define at this stage.

Nonetheless, planning for such activities should aim at balanced and proactive asset management throughout the lifecycle, aligned with business objectives. Guidance for planning these activities can be drawn, for example, from the ISO 55000 series as well as from other application domains. One such reference is EN 50126, which provides guidance on RAMS (Reliability, Availability, Maintainability, and Safety) program planning in railway environments. This reference is quite often used when planning practical lifecycle activities to long lasting systems with high reliability and safety requirements, since it offers a very practical framework for lifecycle management planning.

7.3.3 Work domain analysis of UHS as a sociotechnical system

WP5 produced a work domain description of UHS that articulates the functional structure, constraints and safety-critical dependencies of UHS operations from a socio-technical perspective (Koskinen et al, 2025). The results clarify the core purpose of UHS, the values and priorities of driving safe operation, and the key system functions that must be achieved across the storage lifecycle.

The work domain analysis highlights that UHS safety and operability emerge from the interactions of multiple interdependent elements, including storage integrity, real-time monitoring and control function, operational decision-making and maintenance activities, and regulatory compliance. The analysis makes visible that operator work is not limited to executing predefined tasks, but involves continuous sense-making, anticipation of degradation, and coordination across technical systems and organizational boundaries.

The resulting WDA model (Figure 13) provides a structured basis for identifying safety-critical human functions and information needs, supporting the development of operational concepts, monitoring strategies, and user requirements. WDA results support a shift from purely technical component-focused view towards a system-level understanding of UHS operation that suites well to early-phase design and further use-case specific refinements.

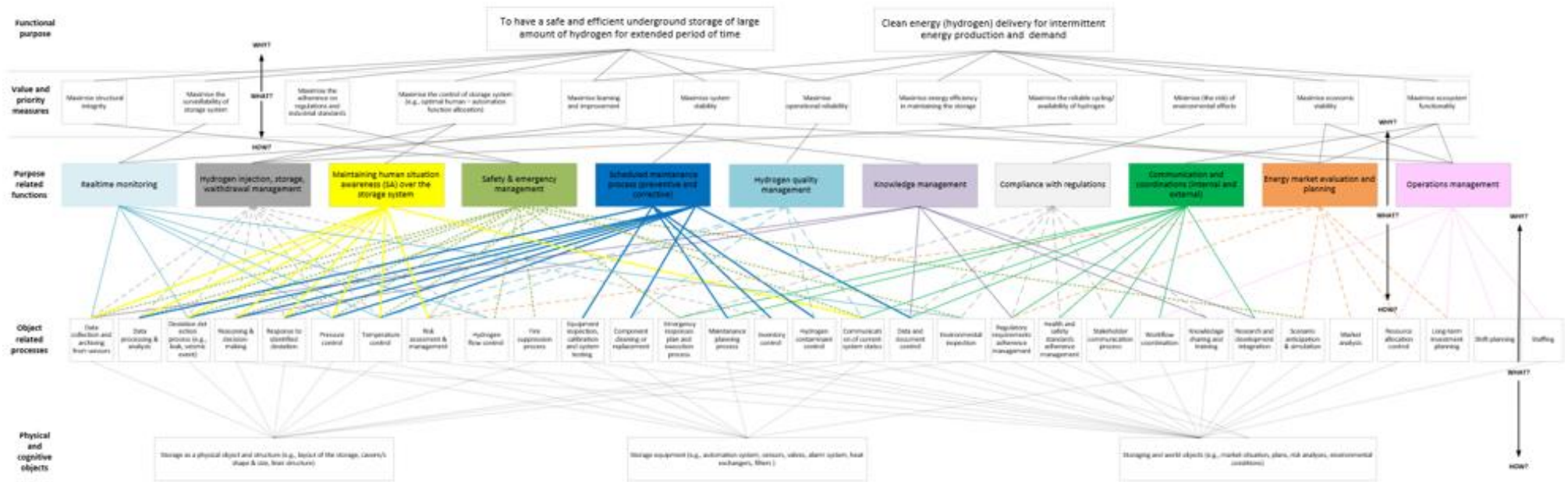


Figure 13. Representation of the WDA model developed for UHS

The WDA details the following five abstraction levels (see in Figure 13 left-hand side): uppermost the functional purpose (“the why”), second, the values and priority measures (“the what”), middle row the purpose-related functions (“the how”), following the object-related processes and at the bottom, the physical and cognitive objects (tools, materials, equipment) in the system.

7.3.4 UHS monitoring concept

WP5 developed an initial monitoring concept for UHS, focusing on information needs relevant for system-level oversight and safe and effective decision-making. First, through expert elicitation key monitoring themes and operator-critical information requirements were identified. These monitoring themes included, for example, storage integrity, hydrogen quality and inventory, environmental impacts, injection and withdrawal dynamics, as well as maintenance visibility. A set of operator-critical information requirements were defined (see Table 11, Koskinen et al, 2026). The information requirements encompass needs for real-time monitoring, information exchange between shifts, across organizational groups, and among various storage stakeholders, as well as more general knowledge and competency requirements for the UHS process operator profession. These high-level requirements are expected to be elaborated into more detailed, phenomenon- and task-specific requirements as the design of the storage system advances, including the specification of concrete parameter values, many of which remain uncertain at this stage.

Table 11. Initial information requirements for UHS operation. In Table 11 context, the term “operator” denotes the process operator responsible for the control and monitoring of the storage system at the workstation level, to whom the information requirements apply.

Subject	Information requirement
H ₂ quality	Operators require timely and reliable information on H ₂ purity and impurity levels at key points of the storage process, particularly at the end of the refining stage and during the injection and withdrawal. This includes visibility into applicable quality standards (which may vary by end users), acceptable impurity types and thresholds, and the source of potential impurities arising from production, purification, storage, or maintenance activities. Operators require explicit information on safety-critical impurities such as oxygen or air, whose presence may lead to flammable mixtures independently of end-use quality requirements. In addition, quality information must be interpretable in relation to storage pressure and operational state (e.g., normal operations, depressurisation, or maintenance), taking into account the limitations of sample-based measurements. Clearly defined decision criteria and response measures are needed to prevent escalations to hazardous conditions.
Structural integrity	Operators require continuous and reliable information on pressure and temperature levels, their rates of change and cycling, and their effects on the structural integrity of the storage system. This includes visibility into the condition and degradation mechanisms of key barrier components, such as the steel liner (e.g., embrittlement, cracking), the sliding layer (e.g., wear or loss of functionality), concrete structures (e.g., cracking, creep), and surrounding bedrock (fracture development, rock movements). Operators require monitoring of potential leakage pathways and critical points (e.g., liner joints, drainage systems) to detect leakage occurrence, accumulation, and rate changes. Early indicators of loss of gas tightness and large-scale structural instability (e.g., uplift or plug failure) must be identifiable. Operators also require clearly defined technical limits for allowable pressure and temperature variations, qualified acceptable leakage levels with escalation thresholds, and information on the reliability of monitoring equipment and its linkage to automated operational functions to support timely intervention.
Environmental impact	Operators require timely information on H ₂ leakage and transport pathways, including sudden leaks as well as long-term, diffuse H ₂ migration through liner and concrete structures. This includes leakage rates and qualities, H ₂ presence in surrounding bedrock and monitoring boreholes, and early indicators of H ₂ accumulation that may pose environmental or safety risks. Operators also require regular information on groundwater composition and levels, concrete moisture and permeability, and environmentally relevant operational releases such as flaring and emergency venting, including their qualities and reporting status.
Injection of H ₂	Operators require continuous and reliable information on H ₂ injection conditions, including flow rate, injected volume, pressure and temperature levels, and their gradients. This includes visibility into dynamic operating conditions, clearly defined technical limits where available, and early indicators of abnormal situations such as leakage during compression or excessive pressure or temperature transient. Operators also require assurance of instrumentation reliability and redundancy, explicit indication of safety-critical deviations (e.g., elevated oxygen content), and clear linkage between automated control actions and operator awareness to support safe fault handling.

H ₂ inventory	Operators require accurate information on stored H ₂ amount and pressure, defined minimum and maximum inventory limits, and awareness of temperature distribution and thermal gradients within the storage. This includes visibility into how storage pressure relates to end-use pressure requirements, compression needs, and electricity price forecasts, to support cost-efficient and safe inventory management while avoiding pressures that increase contamination risk or exceed structural limits. Operators also require forecasting support for storage levels based on expected demand and production, and visibility into operational constraints such as residual pressure requirements, cushion gas, and multi-storage interactions (if part of storage solution)
Withdrawal of H ₂	Operators require advance information on expected H ₂ demand, available withdrawal capacity, and defined capacity products and rules governing injection–withdrawal cycling. This includes visibility into both installed production capacity and usable operational storage capacity, as well as information on pressure and temperature changes during withdrawal and their effects on liner structures. Clear rules and system support are needed to prevent overconsumption, manage reservation-based demand, and handle situations where withdrawal requests approach or exceed defined limits.
Energy market	Operators require timely information on electricity price levels and volatility, H ₂ supply and demand forecasts, and renewable power availability, together with visibility into how UHS is positioned within the H ₂ value chain and entry – exit system. This includes reliable information exchange with market participants, energy management systems, storage utilization, capacity allocation, balancing actions, and compliance with evolving regulatory and business models.
UHS maintenance	Operators require up-to-date information on the condition, inspectability, and maintenance status of critical UHS structures and equipment. This includes visibility into which components can be inspected during normal operation, and which require shutdown or emptying of the storage, the condition and deterioration of liner materials (concrete and steel), and the operational status and maintenance needs of compressors. Operators also require access to maintenance plans and histories, availability of qualified maintenance personnel and critical spare parts, and early indicators supporting proactive maintenance and safe long-term operation.

Following the definition of information requirements, concept design workshops were organized to develop illustrations of monitoring displays and user interface mock-ups. These preliminary visualizations are not intended to represent finalized operational displays but rather to serve as a basis for discussion and further monitoring concept development. The ultimate objective is to structure and combine complex technical, environmental, and operational information to enhance operators' situation awareness (SA), support disturbance management, and early detection of abnormal conditions.

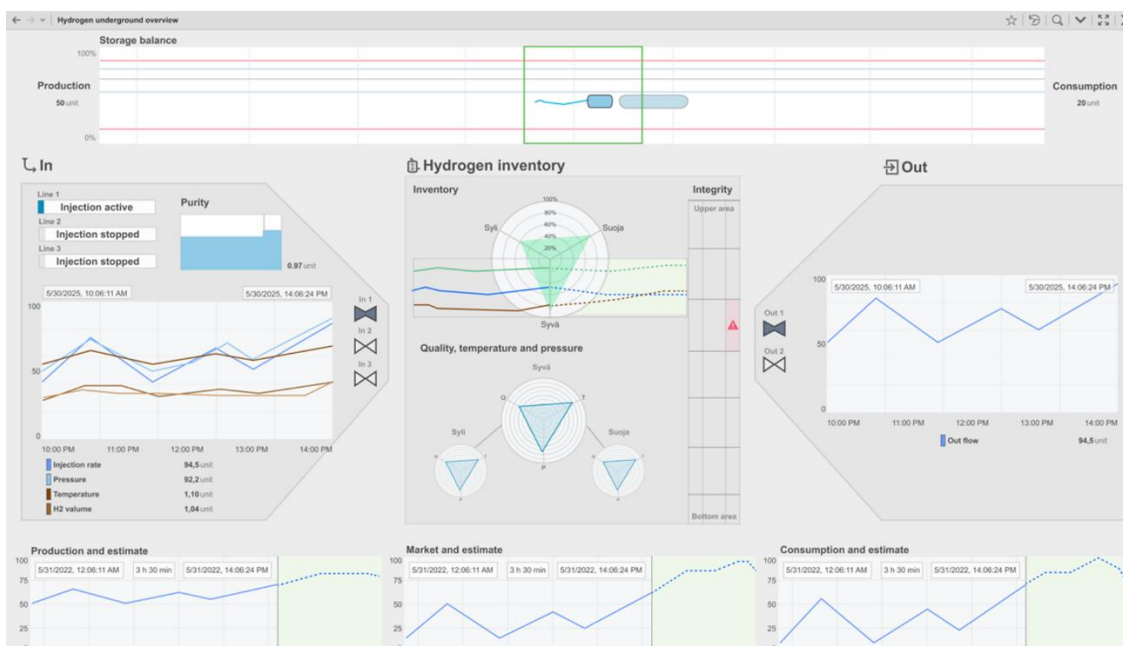


Figure 14. Illustrative mock-up visualization for the UHS overview display

The UHS overview display (Figure 14) aims to integrate critical process information into a coherent representation that supports operators' situation awareness across the storage system by linking key processes and states. At the top of the overview display, a UHS-specific storage balance graph that was developed to show production- consumption dynamics, current status, and how effectively the storage fulfills its balancing function (i.e., In WDA, the uppermost abstraction level, functional purpose of the UHS). However, several key parameters in the storage balance graph are still undefined, such as the optimal operation region of the UHS (illustrate by the green rectangle) and the precision of future state estimations (light blue dot), necessitating further development and collaboration with other engineering disciplines (e.g., censoring).

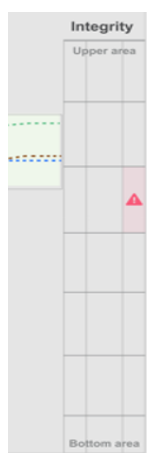


Figure 15. A visualization for a graph that brings together UHS storage integrity alarms into a unified view to support operator awareness.

In the storage integrity alarm graph (Figure 15), the storage tank is divided into zones associated with potential alarms, enabling, for example, spatial temperature variations and threshold exceedances to be readily visible to the operator (see the red warning sign in the zone grid). Again, the key design aspects remain unresolved, including the required number and size of zones and the selection of meaningful underlying sensor data and thus require further definition.



Figure 16. Interface mock-up featuring operator's overview of three (proposed) H₂ storage tanks (one main tank and two supporting tanks) with names proposed for easier identification. Overall status featured on the left-hand side, individual storage status featured on the right-hand side.

Table 12. List of Outcomes in HUG WP5

Outcome	Title	Key Findings	Key Results / Outputs
O5.1	HUG literature from human factors perspective – key findings	This literature review explores underground hydrogen storage from a human factors perspective. The findings indicate that safe UHS operation depends not only on technical solutions but also on effective monitoring, maintenance, organizational practices, and human performance. The reviewed studies identify human and organizational factors as major contributors to hydrogen incidents, emphasizing the need for human factors engineering in the design and operation of future UHS facilities.	Slide set
	and Operator Information Needs in Underground Hydrogen Storage Monitoring	This paper develops an initial monitoring concept for underground hydrogen storage from the process operator perspective. It identifies key operator information requirements and explores how interface concepts and visualisations can support situation awareness, decision-making, and safe operation.	Conference article
O5.2	HUG Life cycle management perspective	This document defines a lifecycle management framework for underground hydrogen storage based on RAMS principles. It outlines the activities required from concept development through operation, enhancement, and retirement to support safety, reliability, maintainability, and long-term performance.	Slide set
O5.3	RAMS and HFE in H2 storage planning	This document presents a framework for integrating RAMS and Human Factors Engineering throughout the lifecycle of UHS systems. It emphasizes that safe and effective UHS operation requires consideration of both technical system performance and human-system interaction from concept development to retirement. The work provides recommendations for incorporating RAMS and HFE activities into planning, design, commissioning, operation, and continuous improvement to support safe, reliable, and maintainable UHS facilities.	Slide set
O5.4	Concept of Operations (ConOps) – Underground Hydrogen Storage	The Concept of Operations describes how a future underground hydrogen storage facility could be operated from a process operator perspective. It defines key operational functions, operating modes, stakeholder roles, monitoring and control needs, and principles for safe and efficient operation. The document provides an initial operational framework to support the design and development of future UHS facilities	Public research report
	and Operational Insights into Safe Underground Hydrogen Storage System	This paper examines underground hydrogen storage from an operational and human factors perspective. Using Work Domain Analysis, it identifies the key functions, constraints, and human-system interactions required for safe and efficient UHS operation. The work highlights that successful UHS depends not only on technical solutions but also on effective monitoring, decision-making, safety management, and organizational practices, providing an initial foundation for future operational concept development.	Conference article
	and UHS Monitoring Whiteboard exercise	This document describes a collaborative whiteboard exercise used to identify operator information needs and monitoring requirements for underground hydrogen storage. The exercise collected multidisciplinary expert input to support the development of a UHS monitoring concept and situation awareness framework.	Slide set

7.4 Future research directions

WP5 highlights that UHS must be understood as a long-lived, safety-critical sociotechnical system, yet it also makes clear that the current knowledge base is limited and operational experience in Finnish context is largely absent. As a result, WP5 research insights should be seen as provisional, aimed at analyzing the foundations and structuring early learning rather than defining concrete solutions.

One evident area for future research concerns the role of human operators. WP5 suggests that operator work will remain central for safety and resilience, but the precise tasks, competencies, and training needs cannot yet be specified and greatly depends also on the storage model selected to be realized. Future research could therefore explore how operator roles might evolve in increasingly automated UHS environments, for example conducting further work and task analyses and through simulations to better understand the operating demands in dynamic energy market conditions. Iterative concept evaluation and testing throughout the storage development would be important to create the learnings and guarantee that the human role and aspect is adequately addressed. At this stage, such work would necessarily rely on assumptions and hypothetical scenarios rather than empirical UHS data.

A second cross-cutting theme relates to sociotechnical safety and governance. Safe UHS operation will depend not only on technical design but also on organizational practices, regulatory frameworks, and coordination among multiple actors that participate day-to-day operations and the handling of operational disturbances. Further research could examine how mechanisms for communication and exchange of critical information, and shared responsibilities might be established in the early phases of UHS deployment, while acknowledging that regulatory arrangements and governance models are still evolving and remain uncertain. Knowledge management and developing the training curriculum to establish appropriate know-how and competent personnel for the storage operation should be also initiated at early phase.

Lifecycle and asset management over very long lifetimes represents another major open question. Although UHS facilities are expected to operate for several decades, WP5 shows that concrete lifecycle management actions cannot yet be defined with confidence. Future studies could explore indicative lifecycle and maintenance strategies, drawing cautiously on standards and practices from other domains. However, long-term degradation behavior, inspection needs, and renewal strategies remain largely unknown, and any proposals would need to remain adaptive and revisable as evidence accumulates.

Related to this, WP5 points to the potential value of integrating RAMS and human factors engineering across the lifecycle, while also revealing that such integration is still largely conceptual for UHS. Future

research could investigate tentative ways of combining technical performance and human-system considerations in early design assessments, for instance through maturity models or qualitative evaluation frameworks. These should be treated as early hypotheses rather than validated methods.

Finally, monitoring, digitalization, and automation raise important but unresolved questions. WP5's monitoring concepts are illustrative and not yet validated from any respective perspective. Further work could explore which types of monitoring data and digital decision support might meaningfully support operator situation awareness and early detection of abnormal conditions, as well as how responsibilities should be shared between humans and automated systems as a part of the concept of operation (ConOps) description. More detailed level information requirements addressing specific process parameters and threshold values should be defined. Given the still limited publicly available operational experience from industrial-scale UHS facilities, such research would likely benefit from simulations, mock-ups, and pilot-scale experimentation, and analysis of emerging operational experiences from early UHS deployments.

Taken together, these directions underline that progress in UHS lifecycles and operations will depend on incremental, learning-oriented research, where conceptual frameworks are gradually tested and refined through cross-sector learning, simulation, and future pilot projects, rather than on early attempts to fix detailed lifecycle management solutions.

7.5 Conclusions

WP5 successfully established a holistic understanding of how UHS can be operated safely, efficiently, and responsibly over its entire lifecycle. By adopting a sociotechnical perspective, WP5 recognized that safe UHS operations depend on the tight interplay of technical systems with human roles, organizational processes, and regulatory frameworks. This comprehensive approach was reflected in the work package's integration of human factors engineering (HFE) with reliability, availability, maintainability, and safety (RAMS) considerations from the earliest design phases. Such early integration of human-centered and technical perspectives was found to be crucial in developing UHS systems that are not only technically sound, but also operable and sustainable throughout decades of successful use.

References

- EN 50126-2:2017+A1:2024.
Railway applications. The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS) Systems approach to safety
- Hugo, J. 2013.
Linking humans and systems in nuclear power. Nuclear Engineering International. 58 (702).
- SFS-ISO 55000:2024
Asset management. Vocabulary, overview and principles
- Naikar, N. (2013). Work domain analysis: Concepts, guidelines, and cases. CRCpress.
- Rasmussen, J. (1987). Information processing and human-machine interaction. An approach to cognitive engineering. North-Holland.
- Salmon, P.M., McLean, S., Carden, T., King, B.J., Thomson, J., Baber, C., Stanton, N.A., Read, G.J.M. (2024). When tomorrow comes: A prospective risk assessment of a future artificial general intelligence-based uncrewed combat aerial vehicle system. Applied Ergonomics, 117, 104245,

8 HUG Roadmap

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Abstract:

A roadmap for the underground storing of hydrogen in Finland was developed. Because the needs for underground storing of hydrogen will evolve along with the development of hydrogen economy in Finland, four scenarios were developed and concepts of underground storages were fitted into relevant scenarios. The scenarios are 1. Local LRS in the distribution network, 2. Local LRC in the distribution network, 3. Open LRC in the transmission network, 4. Closed LRC in the transmission network. A LRS in the distribution network could be reality already before 2030, and a medium-size LRC in the distribution network sometimes between 2031-2035. Large-size LRC in the transmission network (scenarios three and four) could be reality only near 2040 or beyond that year.

8.1 Introduction

Needs for underground storing of hydrogen will evolve along with the development of hydrogen economy. At the same time, it must be understood that hydrogen economy will not emerge solely on market terms; instead, demand is created by regulation that steers users toward clean hydrogen and its derivatives through obligations and incentives. The growth of hydrogen economy requires also large investments to the physical infrastructure by both public and private sectors.

Industrial investment decisions in Finland's green hydrogen sector are progressing slowly. One major reason is that the sector does not offer immediate financial returns: upfront investments are high, and profitability improves only once the market reaches sufficient scale. Nevertheless, there is progress. A recent roadmap by the Hydrogen Cluster Finland (2026) predicts that in the years 2020-2030 there will be 0.2–0.3 Mt/year of clean hydrogen production under construction. In the years 2030-2035 the same roadmap predicts that there will 0.4 Mt/year of clean hydrogen production in operation.

From the side of the public sector, the Finnish Government has given a task to Gasgrid to plan and build a national hydrogen transmission pipeline. According to current plans (Gasgrid, 2026), the pipeline will be from Tornio, through the West Coast to Southern Finland. The building will take place in the 2030s in cooperation with regions, industry, market participants, and other stakeholders. The regional development model would enable the hydrogen network to develop simultaneously across different parts of Finland. The approach will allow regional strengths to be leveraged, as it is anticipated that hydrogen economy will evolve, at first, in a few regions, and only later on develop nationwide.

Neither the roadmap of the Hydrogen Cluster Finland or the plans of Gasgrid will specify needs for the underground storing of hydrogen. The roadmap just identifies hydrogen storage as a key research area pertaining to hydrogen economy.

In this chapter, the first roadmap for Finnish UHS solutions will be presented together with assumptions done. Because the evolving of Finnish hydrogen economy and, accordingly, needs for underground storing of hydrogen are vague, the roadmap is linked to the four scenarios already mentioned in chapter 2 "WP1 Ecosystem & Business models" of the report, the scenarios representing alternative descriptions of potential futures from the viewpoint of hydrogen storing.

8.2 Methods

The HUG roadmap is largely based on discussions done during the project with different stakeholders, especially the industry participants involved in the HUG project, as well as with the technology experts in the project. Experts of the former group gave insight on how Finnish hydrogen markets and the need of hydrogen storing may develop. Experts of the latter group gave insight into what could be techno-economically feasible and when HUG could be realizable. Early drafts of the scenarios and the HUG roadmap were shown to the

industry participants of the project to receive feedback and suggestions for enrichment, and, finally, to validate the roadmap.

8.3 Key results

There was a question already when preparing the HUG project that who should build and operate the hydrogen underground storage? Should it be a hydrogen producer or a group of producers, or a user or a group of users of green hydrogen? Or should the builder and operator be a third-party actor whose ecosystem role would just be the operator of hydrogen storage?

When starting the HUG roadmap work, the question was modified to who would have incentives to build and operate the storage? The answer would depend on how the hydrogen markets of future will run, and what kind of business contracts there will be between producers and users of hydrogen. Long-term contracts with more or less fixed prices and steady delivery volumes would mean that it is under the interest of hydrogen producer(s) to have storage capacity to balance fluctuations in production volumes. On the other hand, if the price of hydrogen will be determined in the stock-markets of hydrogen, the incentives of hydrogen storages are for those users of hydrogen who will prefer steady availability of hydrogen with a moderate price (they will buy hydrogen from the markets when its price is low, store it, and use it when the market price is high). A separate (third-party) operator was seen possible in two cases: 1. In an early stage of hydrogen economy development when the storing business would not be economically viable, and 2. In a mature stage of hydrogen economy when the volumes will be high. In the first case, a public, not-for-a-profit actor would be needed, while the second case could be 100% business driven private actor.

From the technological perspective, the project gave an understanding that the planning and construction of a medium-scale lined rock cavern (LRC) with a volume of 10,000–40,000 m³ would take in minimum of four-five years. As described in the previous chapters of the report, there are still some technical questions to be solved before the building of such a storage facility could be started, so that first LRC pilot cannot be expected to realise during this decade.

Another concept identified in the HUG project is the lined rock shaft (LRS). LRSs are small-volume storages. Their technical readiness level is higher than that of LRCs, making LRSs particularly suitable for meeting short-term hydrogen storage needs in the late 2020s. Also, the construction work of LRS can be easier, if compared to LRC, because the shaft could be done by a drilling technique.

When putting together all what was said above, four scenarios for HUG in Finland was created: 1. Local LRS in the distribution network, 2. Local LRC in the distribution network, 3. Open LRC in the transmission network, 4. Closed LRC in the transmission network. Distribution network means here local pipelines and transmission network the nationwide hydrogen pipelines.

In the first scenario, the underground storage of hydrogen is a local small-size storage using the LRS technique and situated in the local distribution network. The LRS would serve only its owner (that is, storing for the own needs). The owner can be a hydrogen producer and/or a hydrogen user. If referring to the business models presented in Chapter 2.3.3., the one customer model would be well applicable in this scenario. LRS storages will be a good hydrogen storage option for the scale-up phase of hydrogen economy but may be competitive also in longer term. A LRS storage serving local needs could be reality in Finland in 2028-2029 at the earliest.

In the second scenario, the storage is still in a local distribution network, but it is a medium-size LRC type storage. The LRC would serve either a single (heavy) user of hydrogen or a local network of hydrogen producers and users. In the latter case a service operator of storage would be needed. Applicable business models could be the one customer model, if there is only one user for the storage, and public-private partnership or IaaS models, if there will be multiple users for the storage (see Ch. 2.3.3. for more information). The first storage in this scenario is the LRC pilot, the need of which has been broadly identified during the HUG project. Such a medium-size LRC pilot storage could be in operation in the first half of 2030s.

In the third and fourth scenarios, the storages are large-scale LRCs located on the transmission network. The third scenario is for a LRC to have open access, that is, everybody (hydrogen producers, marketers, users) accepting the rules of use can store or use hydrogen stored in the LRC type storage. The most potential

business models related to the open LRC in the transmission network are the capacity leasing model or the laaS model, but one cannot exclude the public-private partnership model if the development of national hydrogen markets is slower than anticipated now. Later on, when the hydrogen markets will be mature and volumes high, the market-driven business model may also be possible (see Ch. 2.3.3). The first open access large-scale LRC could be in operation in the second half of 2030s, if built and operated by Gasgrid under public-private partnership or another business model and if the experiences of the pilot LRC (scenario 2) will be positive. If built and operated by joint ownership of private companies, it may take more time, perhaps around 2040, at the earliest.

The fourth scenario is for a closed access, large-scale LRC in the transmission network, serving only for its owners who are large hydrogen-using companies across the country. Building and operation of the storage would take place by a service operator established by the owners using the Mankala-model. The business model would, thus, be capacity leasing. The fourth scenario could be realised only if the third scenario will not (exclusionary scenarios). Therefore, it is hard to believe that the fourth scenario would be realised before 2040. Furthermore, it is not clear when writing the report whether the fourth scenario would be regulatory possible or not.

The four scenarios are placed on the same timeline together with the estimated development of hydrogen economy according to the references (Hydrogen Cluster Finland, 2026; Gasgrid, 2026). The resulting Figure 1 is considered as the HUG roadmap.

8.4 Conclusions

The HUG roadmap, including four scenarios for the building and operation of underground storages of hydrogen in Finland, was presented. The roadmap is closely related to the evolution of hydrogen markets in Finland, the progress of the evolution being the main uncertainty in the roadmap. All technical issues related to the storage concepts are expected to be solved during the next few years.

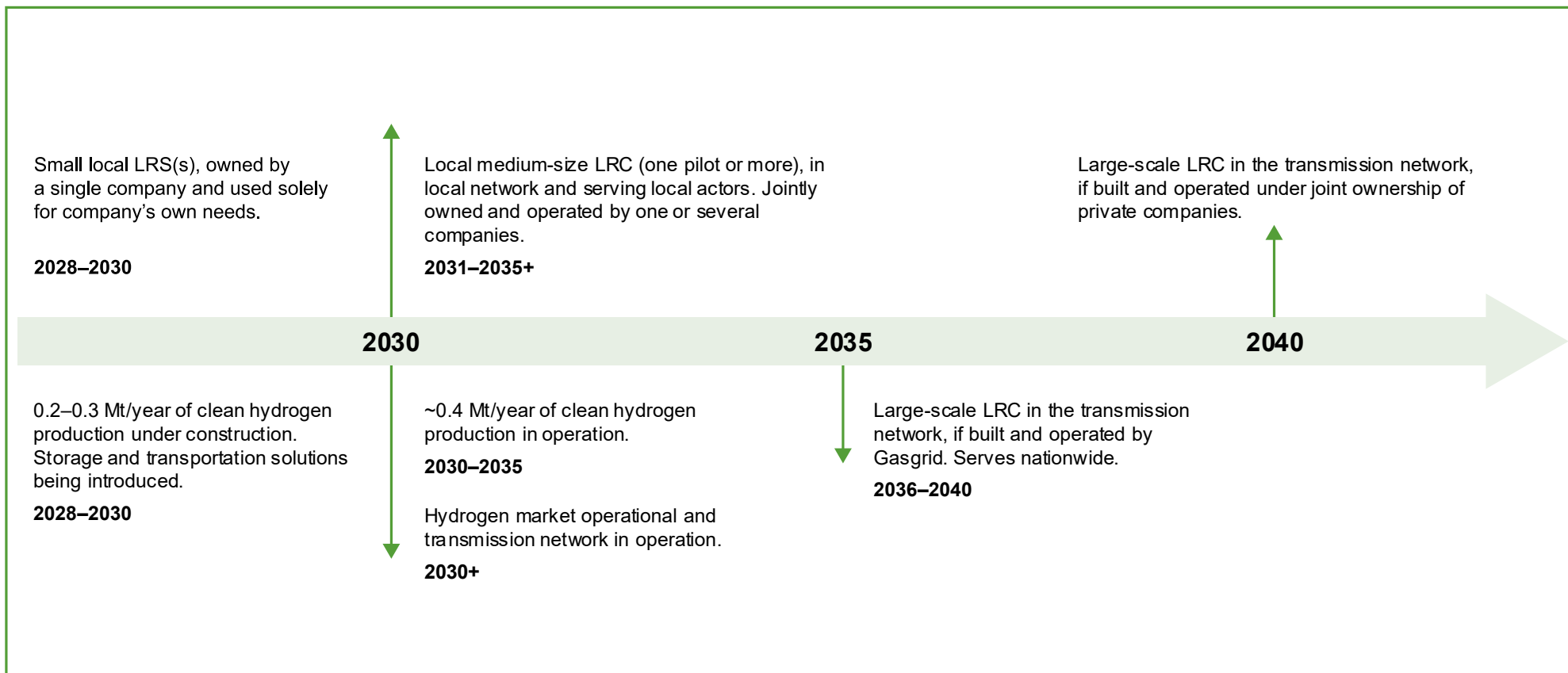


Figure 17. The HUG roadmap

Acknowledgement

The industry experts and researchers of the HUG project are thanked for sharing their thoughts about the development of hydrogen markets and hydrogen storing.

References

Hydrogen Cluster Finland 2026.

Vetytalouden tiekartta Suomelle: Euroopan kilpailukykyisin vetytalous. <https://h2cluster.fi/wp-content/uploads/2026/01/Vetytalouden-tiekartta.pdf> (Accessed April 29, 2026).

Gasgrid 2026.

Suomen kansallinen vedynsiirtoverkko. <https://gasgrid.fi/vetykehitys/suomen-kansallinen-vedynsiirtoverkko/> (Accessed April 29, 2026).

9 Cookbook: Key takeaways for different stakeholders

The aim of this chapter is to provide a high-level overview of how the results of the HUG support decision-making related to industrial-scale hydrogen storage at the early stages of the storage lifecycle. Stakeholders are addressed from a broad, system-level perspective. The following stakeholders are considered at this stage.

Investors and Project Developers

Actors that initiate, finance, and structure hydrogen projects across the value chain. They turn concepts into bankable projects by managing risks, coordinating stakeholders, and enabling project development from feasibility to operation.

Designers, Contractors and Suppliers

Actors responsible for designing, engineering, building, and supplying hydrogen infrastructure and equipment. They translate project concepts into operational assets and ensure technical feasibility, safety, and cost efficiency.

H₂ Storage Owners

Actors that own and finance hydrogen storage assets and are responsible for their performance, safety, and economic viability over the full lifecycle. They provide storage capacity and enable balancing of hydrogen supply and demand.

Green H₂ Producers

Actors that produce hydrogen using renewable energy, typically via electrolysis. They supply low- or zero-carbon hydrogen and drive scale-up, cost reduction, and market development.

Customers (Green H₂ Economy)

Actors that purchase and use green hydrogen or its derivatives for energy or industrial purposes. Their demand, contracts, and willingness to pay are key to market creation and project viability.

H₂ Storage Operators and Maintenance

Actors responsible for the operation, maintenance, and performance of hydrogen storage systems. They ensure safe, reliable, and efficient storage and manage capacity in coordination with other value chain actors.

Public Sector and Municipalities

Authorities that create the enabling environment through policies, regulation, planning, and public funding. They support deployment, reduce risks, and align hydrogen development with societal goals.

Regulators and Authorities

Public bodies that set and enforce rules, standards, and permitting processes for hydrogen activities. They ensure safety, compliance, and regulatory clarity, reducing uncertainty and supporting investment.

A simplified way to consider stakeholder participation in decision-making for industrial-scale hydrogen storage is to distinguish between:

- a) actors directly involved making the investment decision, and
- b) actors responsible for implementing the actions required after the investment decision, to realize the H₂ storage facility.

In practice, however, these roles often overlap, as several stakeholders may both influence decisions and participate in their execution. As a result, it is challenging to define clear boundaries between stakeholder roles in the development of industrial-scale hydrogen storage.

The following figures aim to draw maps of what are the HUG results that could be exploited in the decision-making situations described above. In the figures, the most probable and important exploitable results are marked with bolded text.

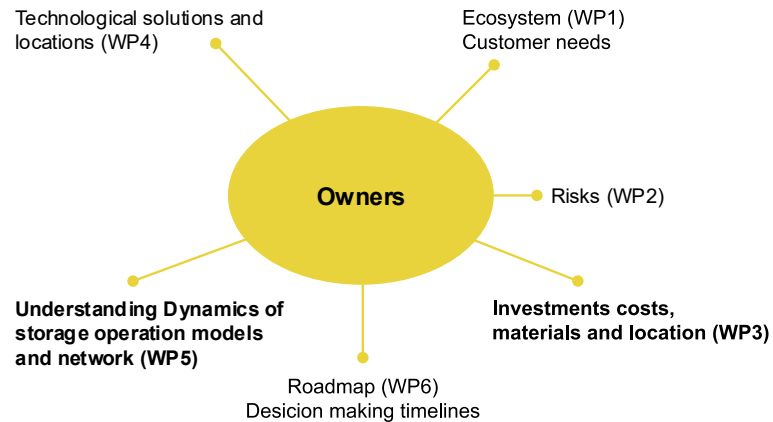
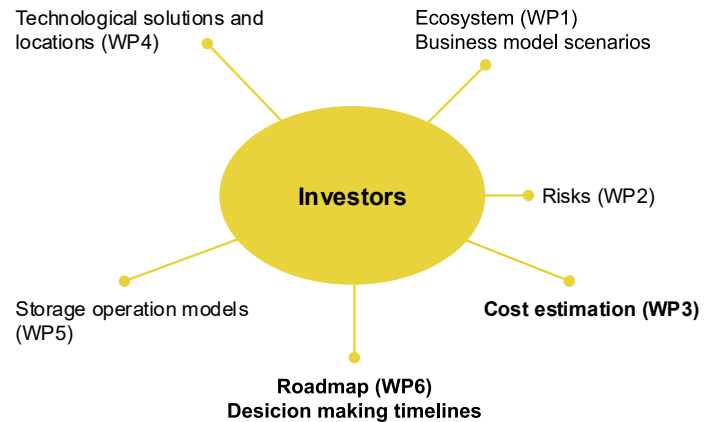
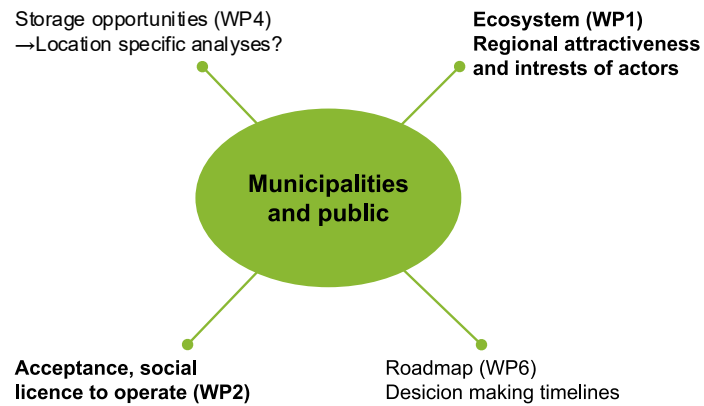
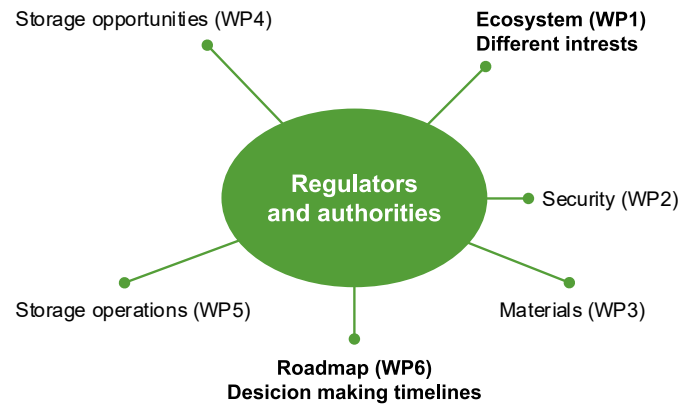


Figure 18. Main HUG results for actors directly involved before and making the investment decision

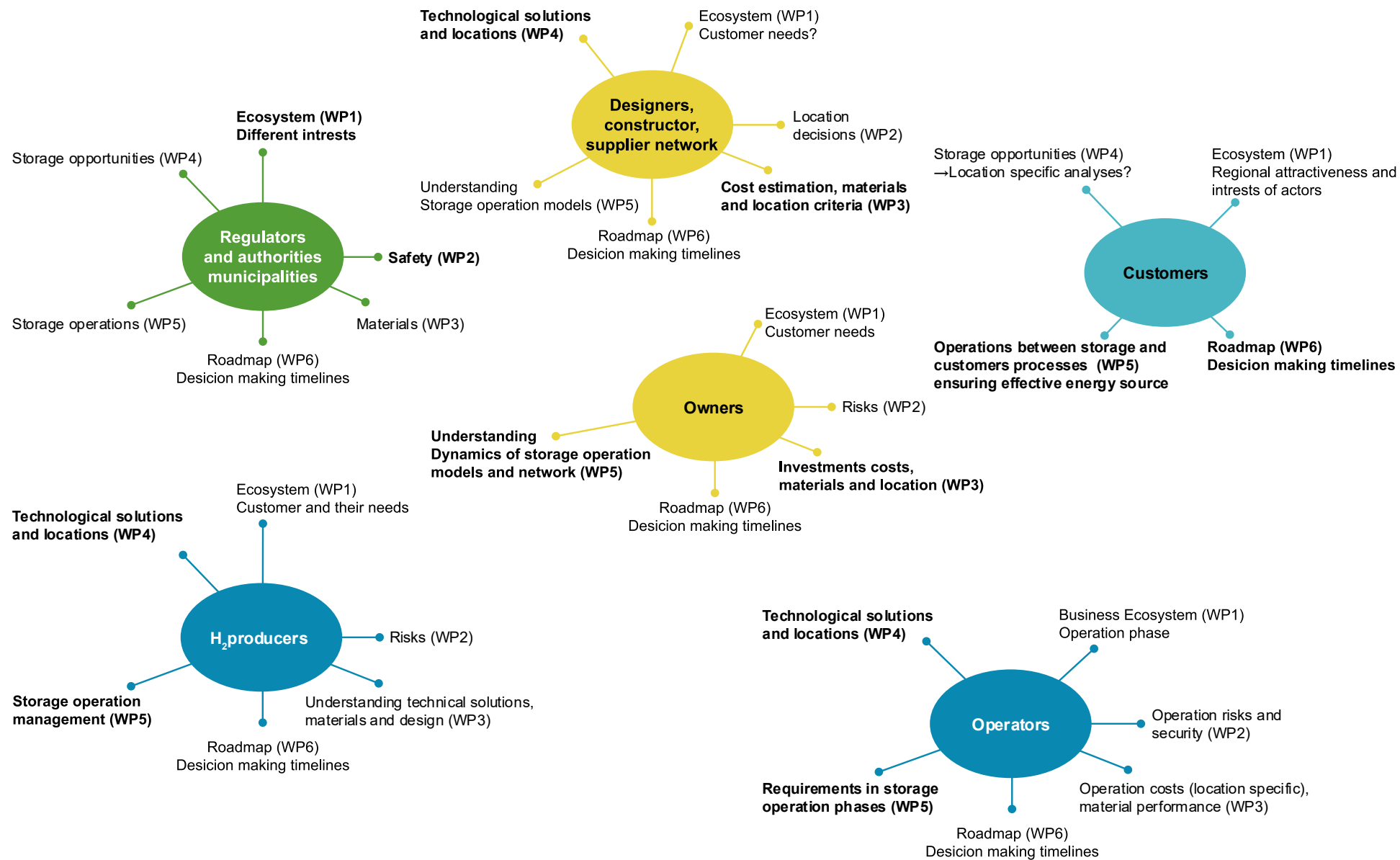


Figure 19. Main HUG results for actors responsible for implementing the actions required after the investment decision.

In appendix A, there will be more specifically listed and described how different HUG results could support decision-making, in both expected phases (before and during the investment decision and to the activities after investment decision has been made).

The following figure demonstrates how the HUG results table can be read and interpreted.

9.3 Owners across the lifecycle

WP	Outcome	Highlights / Description	Additional information
WP1	O1.1 Mapping of the HUG ecosystem.	Understanding the stakeholders and their earning logics and goals, presentation material O1.1 Key stakeholders of UHS.pptx	Result is targeted to support the decision-making concerning the H2 storage investment, especially in better understanding related to the required ecosystem composition.
	O1.2 Future Scenarios	Understanding different potential futures and their impacts on hydrogen storage ecosystem. Presentation material HUG OT1.2 Future scenarios for underground hydrogen storage.pdf	Result is targeted to support the decision-making concerning the H2 storage investment
	O1.3 HUG business models.	How to make money in HUG, Potential UHS business models, presentation material O1.3 FINAL.pdf	Result is targeted to support the decision-making concerning the H2 storage investment
WP2	O2.2 Technical risks of UHS across the life cycle.	Technical risks of different UHS concepts gathered to a confidential research report: O2.2 Preliminary study on risks of UHS concepts-Research Report VTT-R-00328-26 signed.pdf .	Result is targeted to support the H2 storage implementation activities
	O2.3 UHS ecosystem risks	Risks of capacity and quality issues when multiple companies are connected to a common storage. Also, coordination risks in inter-organizational context, and other sociotechnical risks emerging from interactions of technical factors and non-technical (human, organizational, social) factors. O2.3 UHS ecosystem risks.pptx	Result is targeted to support the H2 storage implementation activities and early risk anticipation and management. Results support systems thinking and leadership for safety capacity building.

Figure 20. An example of how the various HUG outcomes can inform decision-making in the early lifecycle phases of hydrogen storage projects (As the table is presented as an image, the links to the output data are not active in this context).

Acknowledgements

The Hydrogen Underground (HUG) project was made possible by the strong support of Business Finland – the primary public funder and enabler of this two-year co-research effort – and through co-funding by nearly twenty partner organizations across industry, research, and the public sector. We are deeply grateful to Business Finland for providing the funding, guidance, and collaboration platform that united such a diverse consortium. Every participating company and organization in the HUG consortium contributed valuable expertise and resources, and each partner's involvement was essential in shaping the project's outcomes. Close collaboration among work packages, industry partners, and municipal stakeholders ensured that our research remained aligned with both practical industry needs and public interest considerations.

We extend our sincere thanks to the participating companies and their expert teams for their dedication, including major industrial partners such as Fortum Power and Heat, Helen, Gasgrid vetyverkot, Neste, St1, Valmet Automation, Vantaan Energia, Ympäristöpooli c/o Adato Energia, EDR Medeso, Afry Finland, Dekra Industrial, Sweco Finland, Lujabetoni, Mincon Nordic, Danfoss Drives, Geomachine and Green North Energy. These organizations provided in-kind contributions, real-world data, use cases, and strategic insights that anchored our research in real-life conditions. We particularly recognize the engineering and design companies in the consortium for their willingness to share critical technical know-how and innovative solutions – for example, a leading engineering firm developed conceptual design guidelines for the lined rock cavern (LRC) concept, and industrial partners helped define preliminary technical criteria for the lined rock shaft (LRS) solution as part of their contributions. This open sharing of technical expertise (spanning rock engineering, construction methods, liner materials, and safety procedures) was instrumental in advancing the project's designs and recommendations. We emphasize that the achievements of HUG were only possible through the collective effort and co-creation of all partners, large and small, each providing essential input.

In addition, we acknowledge and thank the public and municipal stakeholders involved in HUG for highlighting the broader context of underground hydrogen storage, like Business Oulu and Tukes. Their insights ensured that urban development, city infrastructure, and land-use planning considerations (kaupunkirakentaminen ja kaavoitus) were integrated into the project's analyses – reflecting the importance of aligning underground hydrogen storage solutions with municipal planning processes and community needs. By incorporating these perspectives, HUG addressed not only technical and economic aspects but also urban planning and societal acceptance factors, reinforcing the relevance of underground hydrogen storage for urban environments and public safety.

Finally, we note the enduring impact of this collaboration. HUG's results – Finland's first integrated concepts for industrial-scale underground hydrogen storage – have established a robust foundation for future R&D and pilot projects, significantly improving industry readiness and ecosystem preparedness. These outcomes will directly support the next steps toward first-of-a-kind (FOAK) pilot implementations and investments in underground hydrogen storage. They will also inform policy development, safety guidelines, and land-use planning decisions related to hydrogen infrastructure, helping to secure social license to operate and facilitating the safe integration of hydrogen storage into Finland's energy system and urban settings. In sum, with continued public-private cooperation and early pilot initiatives, lined rock caverns and shafts can become cornerstone infrastructure of Finland's clean hydrogen economy - enhancing energy security, industrial competitiveness, and long-term decarbonization goals. We thank all funders and partners for their invaluable contributions to this pioneering effort.

Appendix A: Table of HUG results and their expected utilization by different stakeholders

This appendix aims to bring forward HUG results in total and give descriptions in what phase these results are expected to support decision-making.

9.1 Investors

WP	Outcome	Highlights / Description	Additional information
WP1	O1.1 Mapping of the HUG ecosystem.	Understanding the stakeholders and their earning logics and goals, presentation material O1.1 Key stakeholders of UHS.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment, especially in better understanding related to the required ecosystem composition.
	O1.2 Future Scenarios	Understanding different potential futures and their impacts on hydrogen storage ecosystem. Presentation material HUG_OT1.2 Future scenarios for underground hydrogen storage.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
	O1.3 HUG business models.	How to make money in HUG, Potential UHS business models, presentation material O1.3 FINAL.pdf . Presentation of market simulation results Simulations of Hydrogen Market Development.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
WP2	O2.1 UHS's Social License to Operate (SLO) requirements.	Presents best practices for UHS SLO by benchmarking other safety-critical domains. O2.1 UHS SLO requirements.pdf	The novelty, size, site selection and subsurface nature of UHS require early stakeholder engagement, transparent communication of benefits and uncertainties, and mechanisms for ongoing dialogue and feedback for obtaining SLO
	O2.2 Preliminary technical risks of different UHS concepts.	Technical risks of different UHS concepts gathered to a confidential research report: O2.2 Preliminary study on risks of UHS concepts-Research Report VTT-R-00328-26_signed.pdf	A conference paper on this topic was presented, and Special Session organized at the ESREL conference in Stavanger, Norway. This result was intended to support especially the H ₂ storage implementation activities.
WP3	O3.2.1 A report with preliminary design parameters and required properties of the produced cavern.	A report with preliminary design parameters and required properties of the produced cavern. This document provides also cost estimates of an LRC hydrogen storage and overview of the design process. O321a Conceptual design of a lined rock cavern hydrogen storage - FINAL VERSION.pdf .	The results are useful for investors to understand preliminary cost estimates of an LRC hydrogen storage and get an overall understanding of the engineering process.
	O3.4 and 5. Identification of structural material concepts and materials degradation and service life in LRC environment	A document including potential material recommendations of performance requirements for underground H ₂ storage liner structure and focused analysis of design concepts/material performance in it, to help understanding the effects of materials in this type of project. Report: O3.4&5 Concrete Final 2026-06-23 signed VTT.pdf . Still pending report on the use of steel	Results are targeted to support the decision-making concerning the H ₂ storage investment and especially to understand the importance of correct material selection.

		liners in underground hydrogen storage (Pohjanne, P., Fedoroff, A. & Pakarinen). The report will be completed in collaboration with another ongoing project.	
WP4	O4.1 Deepening the state-of-the-art in LRC	Reviews the current status of technology and highlights the identified knowledge gaps. Report: O4.1 Deepening the state-of-the-art in LRC.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility
	O4.2&4.3 Techno-economics and optimization of green hydrogen production	Investment cost estimates for different LRC storage configurations and capacities. Cost-optimal renewable energy, electrolyzer and storage capacities for different hydrogen demands, Cost-breakdowns of green hydrogen Report: O4.2&4.3 Techno-economics and optimization of green hydrogen production.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
	O4.4 Dynamic LRC process model	Enables studying the thermodynamic behavior of the storage in actual dynamic operation conditions which is needed for creating design specifications and dimensioning of the process components. Enables developing temperature control strategies, automation, predictive control etc. Report: O4.4 Dynamic LRC process model .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
	O4.5 Hydrogen compressor system design for LRC storage	Highlights suitable compressor technologies, their characteristics, and proposes initial compressor configurations for LRCs to enable flexible and robust operation Report: O4.5 Hydrogen compressor system design for LRC storage.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
WP5	O5.2 Techn. Lifecycle model.	Better understanding of the requirements related to different lifecycle phases of H ₂ storage system. Task will remain unfinished, due to the lack of information. Background material available O5.2 HUG LCM Background 250328.pdf .	This result was intended to support especially the H ₂ storage implementation activities, still should be considered also during investment decision-making.
	O5.3 Combined HFE + RAMS framework	New ability to pay attention to reliability and human factors engineering simultaneously. Result material O5.3 RAMS and HFE in planning.pdf .	This result was intended to support especially the H ₂ storage implementation activities, still should be considered also during investment decision-making.
WP6	O6.2 Roadmap, out- and timeline for H ₂ storage realization	O6.2 Roadmap, out- and timeline for H ₂ storage realization. Roadmap included in this report, chapter 8 .	Result is targeted to support the decision-making concerning the H ₂ storage investment

9.2 Designers, contractors, supplier network

WP	Outcome	Highlights / Description	Additional information
WP1	O1.1 Mapping of the HUG ecosystem.	Understanding the stakeholders and their earning logics and goals, presentation material O1.1 Key stakeholders of UHS.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment, especially in better understanding related to the required ecosystem composition.
	O1.2 Future Scenarios	Understanding different potential futures and their impacts on hydrogen storage ecosystem. Presentation material HUG_OT1.2 Future scenarios for underground hydrogen storage.pdf .	Result is targeted to support the decision-making concerning the H ₂ storage investment
	O1.3 HUG business models.	How to make money in HUG, Potential UHS business models, presentation material O1.3 FINAL.pdf . Presentation of market simulation results Simulations of Hydrogen Market Development.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
WP2	O2.2 List of technical risks during UHS lifespan.	Technical risks of different UHS concepts gathered to a confidential research report: O2.2 Preliminary study on risks of UHS concepts-Research Report VTT-R-00328-26 signed.pdf	Result is targeted to support technical risk assessment and management
	O2.3 UHS ecosystem risks	Designers, contractors and supplier network need to be aware of sociotechnical ecosystem level risks, learn how to prevent, assess and manage them. A good safety culture in the network should be established, assessed and continuously improved. O2.3 UHS ecosystem risks.pdf .	Result is targeted to support decision-making concerning risk awareness, risk anticipation and management in the whole multi-actor UHS system
	O2.4 Consequence analyses for site location assessment	Consequence analysis for different leakage scenarios according to TUKES requirements: O2.4 HUG-consequence analyses-Research Report VTT-R-00242-26 signed.pdf .	The revised version of the report includes also a couple of horizontal jet scenarios prepared by SWECO experts with DNV Phast software.
WP3	O3.1 Site selection criteria report for steering site selection process of new underground hydrogen storage sites.	Preliminary geological criteria and examples of source data and methods for the selection of high quality rock mass sites for LRC hydrogen storage: O31 Site selection criteria report.pdf . Additional material includes reactive transport modeling of water-rock-cement-hydrogen interactions: O3.1 Reactive transport modelling water-rock-cement-hydrogen.pdf .	The results are intended for engineers and designers, highlighting that geology-based LRC site selection can have a significant impact on site suitability, engineering and construction costs, and the efficiency of LRC operations. Public version of the document describes background, materials and methods whereas the HUG-consortium only version includes also maps.

	O3.2.1 A report with preliminary design parameters and required properties of the produced cavern.	This document provides initial information for engineering and design of a LRC hydrogen storage: O321a Conceptual design of a lined rock cavern hydrogen storage - FINAL VERSION.pdf. Additional material available: O3.2.1a Conceptual design of LRC H2storage. The results include preliminary boundary conditions for Lined Rock Shaft (LRS) type hydrogen storage. Several documents available: O3.2.1b LRS H2storage inkind contribution.	The results are intended for engineers, designers, and project owners in early-stage engineering of LRC hydrogen storage.
	O3.2.2 Thermo-mechanical modelling – webinar and workshop	This material can be used in designing of thermo-mechanical numerical modeling of pressurized underground hydrogen storage: O3.2.2 Thermo-mechanical modeling workshop.	The results are intended for scientists, designers, and engineers working with numerical modeling of pressurized underground hydrogen storage.
	O3.3 Site characterization report.	This material provides examples and recommendations of methods for geological field investigations of an underground hydrogen storage site.	The material is available for HUG-project consortium only due to the confidential spatial information.
	O3.4 and 5. Identification of structural material concepts and materials degradation and service life in LRC environment	A document including potential material recommendations of performance requirements for underground H₂ storage liner structure and focused analysis of design concepts/material performance in it, to help understanding the effects of materials in this type of project. Report: O3.4&5 Concrete Final 2026-06-23 signed VTT.pdf. Still pending report on the use of steel liners in underground hydrogen storage (Pohjanne, P., Fedoroff, A. & Pakarinen). The report will be completed in collaboration with another ongoing project.	Results are targeted to support the decision-making concerning the H₂ storage investment and especially to understand the importance of correct material selection.
WP4	O4.1 Deepening the state-of-the-art in LRC	Reviews the current status of technology and highlights the identified knowledge gaps. Report: O4.1 Deepening the state-of-the-art in LRC.pdf.	The results are intended to support both the investment decision-making as well as the implementation of H₂ storage facility
	O4.2&4.3 Techno-economics and optimization of green hydrogen production	Investment cost estimates for different LRC storage configurations and capacities. Cost-optimal renewable energy, electrolyzer and storage capacities for different hydrogen demands, Cost-breakdowns of green hydrogen Report: O4.2&4.3 Techno-economics and optimization of green hydrogen production.pdf.	The results are intended to support both the investment decision-making as well as the implementation of H₂ storage facility.
	O4.4 Dynamic LRC process model	Enables studying the thermodynamic behavior of the storage in actual dynamic operation conditions which is needed for creating design specifications and dimensioning of the process components. Enables developing temperature control strategies, automation, predictive control etc. Report: O4.4 Dynamic LRC process model.	The results are intended to support both the investment decision-making as well as the implementation of H₂ storage facility.

	O4.5 Hydrogen compressor system design for LRC storage	Highlights suitable compressor technologies, their characteristics, and proposes initial compressor configurations for LRCs to enable flexible and robust operation Report: O4.5 Hydrogen compressor system design for LRC storage.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
WP5	O5.1 Review of human operator benchmarking	A review of scientific publications from a human factors' perspective, focusing on content related to underground gaseous hydrogen storage. Material: O5.1 HF hydrogen literature review.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
	O5.2 Techn. Lifecycle model.	Better understanding of the requirements related to different lifecycle phases of H ₂ storage system. Task will remain unfinished, due to the lack of information. Background material available O5.2 HUG LCM Background 250328.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
	O5.3. RAMS and HFE interrelations.	New ability to pay attention to reliability and human factors engineering simultaneously. Result material O5.3 RAMS and HFE in planning.pdf .	This result was intended to support especially the H ₂ storage implementation activities
	O5.4. An operative concept document.	Results material related to this task, O5.4 Concept of Operation VTT-ResearchReport VTT R00342 26.pdf , and white board targeted for information collection to define an operative concept O5.4 UHS monitoring Whiteboard.pdf .	These results support especially the H ₂ storage implementation activities
WP6	O6.2 Roadmap, out- and timeline for H ₂ storage realization	O6.2 Roadmap, out- and timeline for H ₂ storage realization. Roadmap included in this report, chapter 8 .	Result is targeted to support the decision-making concerning the H ₂ storage investment

9.3 Owners across the lifecycle

WP	Outcome	Highlights / Description	Additional information
WP1	O1.1 Mapping of the HUG ecosystem.	Understanding the stakeholders and their earning logics and goals, presentation material O1.1 Key stakeholders of UHS.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment, especially in better understanding related to the required ecosystem composition.
	O1.2 Future Scenarios	Understanding different potential futures and their impacts on hydrogen storage ecosystem. Presentation material HUG OT1.2 Future scenarios for underground hydrogen storage.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
	O1.3 HUG business models.	How to make money in HUG, Potential UHS business models, presentation material O1.3 FINAL.pdf . Presentation of market simulation results Simulations of Hydrogen Market Development.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
WP2	O2.2 Technical risks of UHS across the life cycle.	Technical risks of different UHS concepts gathered to a confidential research report:	Result is targeted to support the H ₂ storage implementation activities

		O2.2 Preliminary study on risks of UHS concepts-Research Report VTT-R-00328-26_signed.pdf.	
	O2.3 UHS ecosystem risks	Risks of capacity and quality issues when multiple companies are connected to a common storage. Also, coordination risks in inter-organizational context, and other sociotechnical risks emerging from interactions of technical factors and non-technical (human, organizational, social) factors. Owners decisions may have safety implications, culture and leadership for safety are required. O2.3 UHS ecosystem risks.pdf.	Result is targeted to support the H ₂ storage implementation activities and early risk anticipation and management. Results support systems thinking and leadership for safety capacity building.
WP3	O3.1 Site selection criteria report for an overview what it means to select a site for an underground hydrogen storage.	Preliminary geological criteria and examples of source data and methods for the selection of high quality rock mass sites for LRC hydrogen storage: O31 Site selection criteria report.pdf.	The results are useful for project owners when defining requirements for an LRC project.
	O3.2.1 A report with preliminary design parameters and required properties of the produced cavern.	This document provides overview of the engineering and design process as well as the cost estimates which are key information for the owners.: O321a Conceptual design of a lined rock cavern hydrogen storage - FINAL VERSION.pdf. Additional material available: O3.2.1a Conceptual design of LRC H2storage. The results include preliminary boundary conditions for Lined Rock Shaft (LRS) type hydrogen storage. Several documents available: O3.2.1b LRS H2storage inkind contribution.	The results are intended for project owners in an early stage engineering of underground hydrogen storage.
	O3.4 and 5. Identification of structural material concepts and materials degradation and service life in LRC environment	A document including potential material recommendations of performance requirements for underground H ₂ storage liner structure and focused analysis of design concepts/material performance in it, to help understanding the effects of materials in this type of project. Report: O3.4&5 Concrete Final 2026-06-23 signed VTT.pdf. Still pending report on the use of steel liners in underground hydrogen storage (Pohjanne, P., Fedoroff, A. & Pakarinen). The report will be completed in collaboration with another ongoing project.	Results are targeted to support the decision-making concerning the H ₂ storage investment and especially to understand the importance of correct material selection.
WP4	O4.1 Deepening the state-of-the-art in LRC	Reviews the current status of technology and highlights the identified knowledge gaps. Report: O4.1 Deepening the state-of-the-art in LRC.pdf.	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
WP5	O5.2 Technical Lifecycle model.	Better understanding of the requirements related to different lifecycle phases of H ₂ storage system. Task will remain unfinished, due to the lack of information. Background material available O5.2 HUG LCM Background 250328.pdf.	This result was intended to support especially the H ₂ storage implementation activities.
	O5.3 RAMS and HFE interrelations.	New ability to pay attention to reliability and human factors engineering simultaneously. Result material O5.3 RAMS and HFE in planning.pdf.	This result was intended to support especially the H ₂ storage implementation activities
	O5.4. An operative concept document.	Results material related to this task, O5.4 Concept of Operation VTT-ResearchReport VTT R00342 26.pdf, and white board targeted for information collection to define an operative concept O5.4 UHS monitoring Whiteboard.pdf.	These results support especially the H ₂ storage implementation activities

WP6	O6.2 Roadmap, out- and timeline for H ₂ storage realization	O6.2 Roadmap, out- and timeline for H ₂ storage realization. Roadmap included in this report, chapter 8 .	Result is targeted to support the decision-making concerning the H ₂ storage investment
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9.4 H₂ Producers

WP	Outcome	Highlights / Description	Additional information
WP1	O1.1 Mapping of the HUG ecosystem.	Understanding the stakeholders and their earning logics and goals, presentation material O1.1 Key stakeholders of UHS.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment, especially in better understanding related to the required ecosystem composition.
	O1.2 Future Scenarios.	Understanding different potential futures and their impacts on hydrogen storage ecosystem. Presentation material HUG OT1.2 Future scenarios for underground hydrogen storage.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
	O1.3 HUG business models.	How to make money in HUG, Potential UHS business models, presentation material O1.3 FINAL.pdf . Presentation of market simulation results Simulations of Hydrogen Market Development.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
WP2	O2.2 Technical risks of a UHS during high demand of H ₂ storage capacity.	Storage pressure variations cause stress and temperature gradients inside the storage volume. Safe limits for these variations are not yet defined: O2.2 Preliminary study on risks of UHS concepts-Research Report VTT-R-00328-26 signed.pdf . H ₂ producers also need to adopt a holistic understanding of risks arising from technical and social elements of the UHS system, and how to monitor and manage them. Overall long-term safety of the storage requires more from the organizations involved than keeping engineering hazards at check.	This result was intended to support especially the H ₂ storage implementation activities
WP3	O3.4 and 5. Identification of structural material concepts and materials degradation and service life in LRC environment	A document including potential material recommendations of performance requirements for underground H ₂ storage liner structure and focused analysis of design concepts/material performance in it, to help understanding the effects of materials in this type of project. Report: O3.4&5 Concrete Final 2026-06-23 signed VTT.pdf . Still pending report on the use of steel liners in underground hydrogen storage (Pohjanne, P., Fedoroff, A. & Pakarinen). The report will be completed in collaboration with another ongoing project.	Results are targeted to support the decision-making concerning the H ₂ storage investment and especially to understand the importance of correct material selection.
WP4	O4.1 Deepening the state-of-the-art in LRC	Reviews the current status of technology and highlights the identified knowledge gaps. Report: O4.1 Deepening the state-of-the-art in LRC.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.

	O4.2&4.3 Techno-economics and optimization of green hydrogen production	Investment cost estimates for different LRC storage configurations and capacities. Cost-optimal renewable energy, electrolyzer and storage capacities for different hydrogen demands, Cost-breakdowns of green hydrogen Report: O4.2&4.3 Techno-economics and optimization of green hydrogen production.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
	O4.4 Dynamic LRC process model	Enables studying the thermodynamic behavior of the storage in actual dynamic operation conditions which is needed for creating design specifications and dimensioning of the process components. Enables developing temperature control strategies, automation, predictive control etc. Report: O4.4 Dynamic LRC process model .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
	O4.5 Hydrogen compressor system design for LRC storage	Highlights suitable compressor technologies, their characteristics, and proposes initial compressor configurations for LRCs to enable flexible and robust operation Report: O4.5 Hydrogen compressor system design for LRC storage.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
WP5	O5.2 Techn. Lifecycle model.	Better understanding of the requirements related to different lifecycle phases of H ₂ storage system. Task will remain unfinished, due to the lack of information. Background material available O5.2 HUG LCM Background 250328.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
	O5.3 RAMS and HFE interrelations	New ability to pay attention to reliability and human factors engineering simultaneously. Result material O5.3 RAMS and HFE in planning.pdf .	This result was intended to support especially the H ₂ storage implementation activities
	O5.4. An operative concept document.	Results material related to this task, O5.4 Concept of Operation VTT-ResearchReport VTT R00342 26.pdf , and white board targeted for information collection to define an operative concept O5.4 UHS monitoring Whiteboard.pdf .	These results support especially the H ₂ storage implementation activities
WP6	O6.2 Roadmap, out- and timeline for H ₂ storage realization	O6.2 Roadmap, out- and timeline for H ₂ storage realization. Roadmap included in this report, chapter 8 .	Result is targeted to support the decision-making concerning the H ₂ storage investment

9.5 Customers

WP	Outcome	Highlights / Description	Additional information
WP1	O1.1 Mapping of the HUG ecosystem.	Understanding the stakeholders and their earning logics and goals, presentation material O1.1 Key stakeholders of UHS.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment, especially in better understanding related to the required ecosystem composition.
	O1.2 Future Scenarios	Understanding different potential futures and their impacts on hydrogen storage ecosystem. Presentation material HUG OT1.2 Future scenarios for underground hydrogen storage.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment

	O1.3 HUG business models.	How to make money in HUG, Potential UHS business models, presentation material O1.3 FINAL.pdf . Presentation of market simulation results Simulations of Hydrogen Market Development.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
WP2	O2.1 UHS's Social License to Operate requirements	The customers are stakeholders and they also need to understand SLO. O2.1 UHS SLO requirements.pdf	The results are a starting point for understanding the requirements to ensuring social license and acceptance.
	O2.2 Technical risks of a UHS during high H ₂ demand	Storage pressure variations cause stress and temperature gradients inside the storage volume. The safe limits for these variations are not yet defined: O2.2 Preliminary study on risks of UHS concepts-Research Report VTT-R-00328-26 signed.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility by focusing on technical risk awareness.
	O2.3 UHS ecosystem risks (User prioritization according to safety criticality)	The capacity of the common storage must be shared. The simplest way is to divide the storage according to the capacity, but also flexible arrangement of capacity between the companies is possible. Safety effects depend on the nature of the company operations and their interactions. O2.3 UHS ecosystem risks.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility – the focus is on understanding holistic UHS system level risks beyond technical hazards.
WP4	O4.1 Deepening the state-of-the-art in LRC	Reviews the current status of technology and highlights the identified knowledge gaps. Report: O4.1 Deepening the state-of-the-art in LRC.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
	O4.2&4.3 Techno-economics and optimization of green hydrogen production	Investment cost estimates for different LRC storage configurations and capacities. Cost-optimal renewable energy, electrolyzer and storage capacities for different hydrogen demands. Cost-breakdowns of green hydrogen Report: O4.2&4.3 Techno-economics and optimization of green hydrogen production.pdf .	
WP5	O5.2 Techn. Lifecycle model.	Better understanding of the requirements related to different lifecycle phases of H ₂ storage system. Task will remain unfinished, due to the lack of information. Background material available O5.2 HUG LCM Background 250328.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
	O5.3 RAMS and HFE interrelations	New ability to pay attention to reliability and human factors engineering simultaneously. Result material O5.3 RAMS and HFE in planning.pdf .	This result supports especially the H ₂ storage implementation activities
	O5.4. An operative concept document.	Results material related to this task, O5.4 Concept of Operation VTT-ResearchReport VTT R00342 26.pdf , and white board targeted for information collection to define an operative concept O5.4 UHS monitoring Whiteboard.pdf .	These results support especially the H ₂ storage implementation activities
WP6	O6.2 Roadmap, out- and timeline for H ₂ storage realization	O6.2 Roadmap, out- and timeline for H ₂ storage realization. Roadmap included in this report, chapter 8 .	Result is targeted to support the decision-making concerning the H ₂ storage investment

9.6 Operators

WP	Outcome	Highlights / Description	Additional information
WP1	O1.1 Mapping of the HUG ecosystem.	Understanding the stakeholders and their earning logics and goals, presentation material O1.1 Key stakeholders of UHS.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment, especially in better understanding related to the required ecosystem composition.
	O1.2 Future Scenarios	Understanding different potential futures and their impacts on hydrogen storage ecosystem. Presentation document HUG_OT1.2 Future scenarios for underground hydrogen storage.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
	O1.3 HUG business models.	How to make money in HUG, Potential UHS business models, presentation material O1.3 FINAL.pdf . Presentation of market simulation results Simulations of Hydrogen Market Development.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
WP2	O2.2 Technical risk analysis	General knowledge of critical failures in a UHS and connection between storage operations. O2.2 Preliminary study on risks of UHS concepts-Research Report_VTT-R-00328-26 signed.pdf .	The results are intended to support both the design and implementation of H ₂ storage facility by advancing knowledge on technical risks.
	O2.3 UHS ecosystem risks	Supports operators understanding how different dimensions of risk interact and can affect the system operations. Holistic understanding of risks beyond technical phenomena, including structural, organizational, technological, epistemic and cultural dimensions of risk. O2.3 UHS ecosystem risks.pdf .	The results are intended to support both the investment decision-making as well as the safe implementation of H ₂ storage facility – supports operators' capability to ensure safety and to prevent unwanted events in the UHS.
WP3	O3.1 Site selection criteria report for steering site selection process of new underground hydrogen storage sites.	These documents are useful for operators in understanding that locations of underground hydrogen storage are recommended to be optimized in terms of the geological conditions. O31 Site selection criteria report.pdf .	The results are intended as guidelines for operators to understand that geological site selection and rock engineering significantly affects LRC efficiency and possible maintenance needs.
	O3.2.1 A report with preliminary design parameters and required properties of the produced cavern.	O321a Conceptual design of a lined rock cavern hydrogen storage - FINAL VERSION.pdf .	
	O3.4 and 5. Identification of structural material concepts and materials degradation and service life in LRC environment	A document including potential material recommendations of performance requirements for underground H ₂ storage liner structure and focused analysis of design concepts/material performance in it, to help understanding the effects of materials in this type of project. Report: O3.4&5 Concrete Final 2026-06-23 signed_VTT.pdf . Still pending report on the use of steel liners in underground hydrogen storage (Pohjanne, P., Fedoroff, A. & Pakarinen). The report will be completed in collaboration with another ongoing project.	Results are targeted to support the decision-making concerning the H ₂ storage investment and especially to understand the importance of correct material selection.

WP4	O4.1 Deepening the state-of-the-art in LRC	Reviews the status of technology and highlights the identified knowledge gaps. Report: O4.1 Deepening the state-of-the-art in LRC.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
	O4.2&4.3 Techno-economics and optimization of green hydrogen production	Investment cost estimates for different LRC storage configurations and capacities. Cost-optimal renewable energy, electrolyzer and storage capacities for different hydrogen demands, Cost-breakdowns of green hydrogen Report: O4.2&4.3 Techno-economics and optimization of green hydrogen production.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
	O4.4 Dynamic LRC process model	Enables studying the thermodynamic behavior of the storage in actual dynamic operation conditions which is needed for creating design specifications and dimensioning of the process components. Enables developing temperature control strategies, automation, predictive control etc. Report: O4.4 Dynamic LRC process model .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
	O4.5 Hydrogen compressor system design for LRC storage	Highlights suitable compressor technologies, their characteristics, and proposes initial compressor configurations for LRCs to enable flexible and robust operation Report: O4.5 Hydrogen compressor system design for LRC storage.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
WP5	O5.1 Review of human operator benchmarking	A review of scientific publications from a human factors' perspective, focusing on content related to underground gaseous hydrogen storage. Material: O5.1 HF hydrogen literature review.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
	O5.2 Techn. Lifecycle model.	Better understanding of the requirements related to different lifecycle phases of H ₂ storage system. Task will remain unfinished, due to the lack of information. Background material available O5.2 HUG LCM Background 250328.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
	O5.3 RAMS and HFE interrelations	New ability to pay attention to reliability and human factors engineering simultaneously. Result material O5.3 RAMS and HFE in planning.pdf .	This result supports especially the H ₂ storage implementation activities
	O5.4. An operative concept document.	Results material related to this task, O5.4 Concept of Operation VTT-ResearchReport VTT R00342 26.pdf , and white board targeted for information collection to define an operative concept O5.4 UHS monitoring Whiteboard.pdf .	These results support especially the H ₂ storage implementation activities
WP6	O6.2 Roadmap, out- and timeline for H ₂ storage realization.	O6.2 Roadmap, out- and timeline for H ₂ storage realization. Roadmap included in this report, chapter 8 .	Result is targeted to support the decision-making concerning the H ₂ storage investment

9.7 Municipalities and public

WP	Outcome	Highlights / Description	Additional information
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WP1	O1.1 Mapping of the HUG ecosystem.	Understanding the stakeholders and their earning logics and goals, presentation material O1.1 Key stakeholders of UHS.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment, especially in better understanding related to the required ecosystem composition.
	O1.2 Future Scenarios	Understanding different potential futures and their impacts on hydrogen storage ecosystem. Presentation material HUG_OT1.2 Future scenarios for underground hydrogen storage.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
	O1.3 HUG business models.	How to make money in HUG, Potential UHS business models, presentation material O1.3 FINAL.pdf . Presentation of market simulation results Simulations of Hydrogen Market Development.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
WP2	O2.1 UHS's Social License to Operate requirements	Clarifies the need for early stakeholder engagement, transparent communication of benefits and uncertainties, and mechanisms for ongoing dialogue and feedback for obtaining SLO. O2.1 UHS SLO requirements.pdf	The results are intended to support both the investment decision-making related to site selection and stakeholder engagement planning and implementation, as well as organizational development.
	O2.3 UHS ecosystem risks	Explores different dimensions of risk and supports holistic understanding of risks by UHS stakeholders. O2.3 UHS ecosystem risks.pdf .	The results are intended to support leadership and organizational development, safety capacity building and proactive risk anticipation capabilities in the future UHS ecosystem.
	O2.4 Consequence analysis	Consequence analysis for the worst-case scenarios to be utilized in e.g., land use planning: O2.4 HUG-consequence analyses-Research Report VTT-R-00242-26 signed.pdf .	The results are intended to support both the investment decision-making, for example land-use and infrastructure planning. Consequences of hazards are highly dependent on the site properties.
WP4	O4.1 Deepening the state-of-the-art in LRC	Reviews the current status of the technology and highlights the identified knowledge gaps. Report: O4.1 Deepening the state-of-the-art in LRC.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
WP5	O5.2 Techn. Lifecycle model.	Better understanding of the requirements related to different lifecycle phases of H ₂ storage system. Task will remain unfinished, due to the lack of information. Background material available O5.2 HUG_LCM Background 250328.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
	O5.3 RAMS and HFE interrelations	New ability to pay attention to reliability and human factors engineering simultaneously. Result material O5.3 RAMS and HFE in planning.pdf .	This result supports especially the H ₂ storage implementation activities
WP6	O6.2 Roadmap, out- and timeline for H ₂ storage realization.	O6.2 Roadmap, out- and timeline for H ₂ storage realization. Roadmap included in this report, chapter 8 .	Result is targeted to support the decision-making concerning the H ₂ storage investment

9.8 Regulators and authorities

WP	Outcome	Highlights / Description	Additional information
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WP1	O1.1 Mapping of the HUG ecosystem	Understanding the stakeholders and their earning logics and goals, presentation material O1.1 Key stakeholders of UHS.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment, especially in better understanding related to the required ecosystem composition.
	O1.2 Future scenarios	Understanding different potential futures and their impacts on hydrogen storage ecosystem. Presentation material HUG OT1.2 Future scenarios for underground hydrogen storage.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
	O1.3 HUG business models	How to make money in HUG, Potential UHS business models, presentation material O1.3 FINAL.pdf . Presentation of market simulation results Simulations of Hydrogen Market Development.pdf	Result is targeted to support the decision-making concerning the H ₂ storage investment
WP2	O2.1 UHS SLO requirements	Regulatory confidence and public confidence must co-evolve. Relevant for regulators and authorities because it improves understanding of social license and social acceptability, which are also related to regulatory requirements. O2.1 UHS SLO requirements.pdf	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility,
	O2.3 UHS ecosystem risks	Preliminary risks of UHS structure for establishing requirements for the future solutions. Supports regulators and authorities by raising awareness about different dimensions of risk, uncertainties and interdependencies, and the need for systemic approach to regulatory oversight that integrates human, technical and organizational factors, including culture for safety and leadership oversight. O2.3 UHS ecosystem risks.pdf .	The results are intended to support regulatory safety inspections and oversight, especially regulators' and authorities' capabilities to understand UHS risks holistically and UHS as a sociotechnical system, beyond technical risks – impact on safety of other interrelated factors (structural, organizational, technological, epistemic and cultural).
	O2.4 Consequence analysis	Consequence analysis for the H ₂ high pressure leakage from the UHS surface connection pipeline: O2.4 HUG-consequence analyses-Research Report VTT-R-00242-26 signed.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility. The revised version of the report includes also a couple of horizontal jet scenarios prepared by SWECO experts with DNV Phast software.
WP3	O3.1 Site selection criteria report	This report is valuable for regulators and authorities in understanding that selection of an underground hydrogen storage site needs careful planning and some of the criteria could be set as requirements in e.g. permitting and EIA. O31 Site selection criteria report.pdf .	The geological criteria presented in the report can be particularly useful for regulators and authorities.
	O3.4 and 5. Identification of structural material concepts and materials degradation and service life in LRC environment	A document including potential material recommendations of performance requirements for underground H ₂ storage liner structure and focused analysis of design concepts/material performance in it, to help understanding the effects of materials in this type of project. Report: O3.4&5 Concrete Final 2026-06-23 signed VTT.pdf . Still pending report on the use of steel liners in underground hydrogen storage (Pohjanne, P., Fedoroff, A. & Pakarinen). The report will be completed in collaboration with another ongoing project.	Results are targeted to support the decision-making concerning the H ₂ storage investment and especially to understand the importance of correct material selection.

WP4	O4.1 Deepening the state-of-the-art in LRC	Reviews the status of technology and highlights the identified knowledge gaps. Report: O4.1 Deepening the state-of-the-art in LRC.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
	O4.2&4.3 Techno-economics and optimization of green hydrogen production	Investment cost estimates for different LRC storage configurations and capacities. Cost-optimal renewable energy, electrolyzer and storage capacities for different hydrogen demands, Cost-breakdowns of green hydrogen Report: O4.2&4.3 Techno-economics and optimization of green hydrogen production.pdf .	The results are intended to support both the investment decision-making as well as the implementation of H ₂ storage facility.
WP5	O5.2 Techn. Lifecycle model.	Better understanding of the requirements related to different lifecycle phases of H ₂ storage system. Task will remain unfinished, due to the lack of information. Background material available O5.2 HUG LCM Background 250328.pdf .	This result was intended to support especially the H ₂ storage implementation activities.
	O5.3 RAMS and HFE interrelations	New ability to pay attention to reliability and human factors engineering simultaneously. Result material O5.3 RAMS and HFE in planning.pdf .	This result supports especially the H ₂ storage implementation activities
WP6	O6.2 Roadmap, out- and timeline for H ₂ storage realization.	O6.2 Roadmap, out- and timeline for H ₂ storage realization. Roadmap included in this report, chapter 8 .	Result is targeted to support the decision-making concerning the H ₂ storage investment

Appendix B:

Policy Brief: Strategic Deployment of Underground Hydrogen Storage

Finland aims to position itself among the leading countries in the European hydrogen economy. Achieving this goal requires large-scale production of green hydrogen from renewable energy sources, extensive industrial use - particularly in process industries - robust transmission infrastructure, and effective mechanisms for balancing variable supply and demand. While hydrogen contained in pipelines can buffer short-term fluctuations for a few hours, multi-day balancing will require large-volume underground storage.

In Central Europe and the UK, some salt caverns have been in use for hydrogen storage. Underground storage enhances system safety and enables high storage capacities. Salt formations are naturally impermeable and chemically inert, making them ideal for storing gas. Finland, however, lacks salt caverns, and underground hydrogen storage must therefore be excavated in crystalline bedrock. Sweden's experience with lined rock caverns (LRCs) for natural gas demonstrates that this approach is feasible, but hydrogen poses additional material challenges. As the lightest element, hydrogen can diffuse through some materials more easily, and not all solutions suitable for natural gas are directly transferable. Furthermore, crystalline bedrock is heterogeneous and contains naturally occurring fractures and faults, which may compromise liner performance, storage stability, and therefore, containment integrity. It is of key importance that sufficient geological site selection studies are carried out prior to the decision of storage site location.

This Policy Brief synthesizes findings from the Hydrogen Underground (HUG) project funded by Business Finland. The project set out to build a foundation for large-scale underground hydrogen storage in Finland by examining ecosystems and business models, safety considerations, social license, design concepts and technologies, and lifecycle operations. As the project concludes, we can state that the basis for such a concept now exists: first-of-its-kind high-level H₂ storage concepts have emerged, providing insights e.g., into storage model options, geological and safety requirements, technical and sociotechnical risks, investment estimates, and power-to-X optimization. However, several technical design questions remain open. Further research into suitable materials, construction methods, structural integrity, operation models and other design specifications for LRC hydrogen storage is therefore essential.

Another concept identified in the HUG project is the lined rock shaft (LRS). LRSs are small-volume storages. Their technical readiness level is higher than that of LRCs, making LRSs particularly suitable for meeting short-term hydrogen storage needs in the late 2020s.

The hydrogen economy will develop gradually. Finland is expected to first form regional hydrogen valleys, which will later be interconnected through Gasgrid's national hydrogen transmission network in the early 2030s. The need for underground storage will grow as hydrogen volumes increase. Large-scale storage will not be required in the early 2030s; instead, medium-sized facilities (10,000–40,000 m³) are likely to meet demand during that period—and potentially well beyond—especially if complemented by LRS units.

According to the HUG project, constructing a 40,000 m³ LRC storage would cost approximately 30 M€, although costs do not scale linearly with cavern size. Project estimates also indicate that the design and construction of such a facility, including permitting, would require four to five years.

Industrial investment decisions in Finland's green hydrogen sector are progressing slowly. One major reason is that the sector does not offer immediate financial returns: upfront investments are high, and profitability improves only once the market reaches sufficient scale. In this situation, public investment support is critical for accelerating the development of the hydrogen economy, including the establishment of underground hydrogen storage.

HUG Recommendations

For industry pursuing green hydrogen opportunities:

Transitioning into the hydrogen economy requires long-term strategic planning. Early movers, however, will play a defining role in shaping future markets, technologies, and business models for green hydrogen.

In the first place, de-risking UHS investment decision making requires *answering technological uncertainties*. Additionally, operation models, social license, UHS ecosystem, technical and organizational risks studies need to advance as the high-level concept is further developed into design specifications and piloting of the storage in a concrete location.

For public and private investors:

A *medium-sized pilot storage facility* would provide essential practical experience and validate the safety and performance of lined rock cavern hydrogen storage before scaling up to larger volumes. It would also serve as a balanced resource in the emerging hydrogen system. In addition, *early stakeholder engagement* and *early-stage geological site selection studies* enhance cost-efficiency, reduce technical and societal uncertainties, and increase the overall feasibility and value of storage solutions.

For research funders:

A *dedicated research project* focused on hydrogen LRC storage, its technical design requirements and concept specifications, is needed before initiating real pilot construction work. The research would also serve preparedness of implementation of lined rock shaft solutions in Finnish bedrock. Technical studies need to be complemented by studies of operational scenarios and organisational capabilities to manage safety.

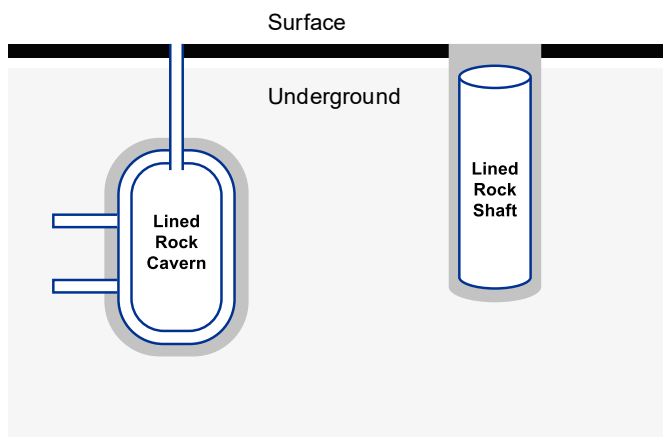


Figure: Schematic principles of lined rock cavern (LRC) and lined rock shaft (LRS) concepts for underground storing of hydrogen. LRCs will be made by underground mining, LRSs could be done by drilling the ground.

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