

HUG – HYDROGEN UNDERGROUND

Large scale Hydrogen underground storage efficiently decoupling hydrogen production and consumption.

Project summary presentation

Contents

Introduction

Key takeaways

- Ecosystem & Business models
- Safety and sociotechnical risks
- Design and technology
- Techno-economic feasibility
- Life-cycles and operations

Cookbook

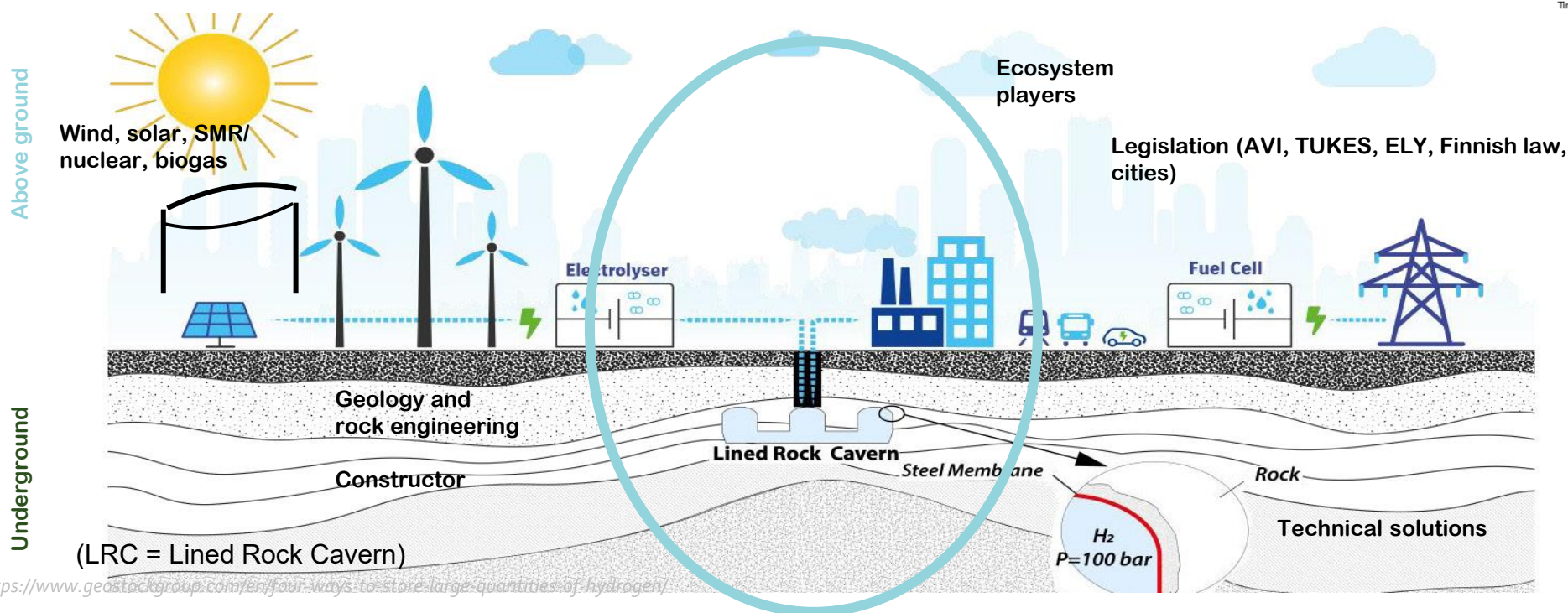
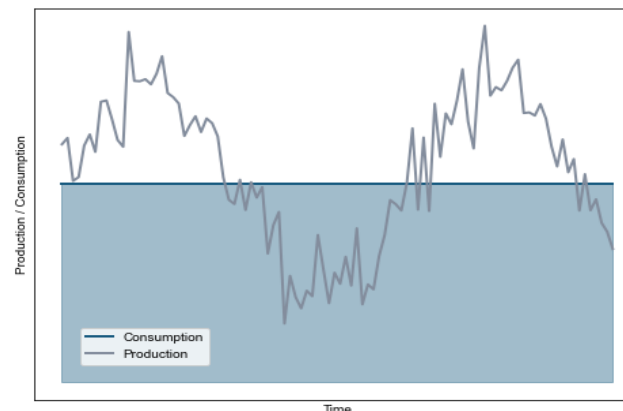
Call to action / Roadmap

Next Steps

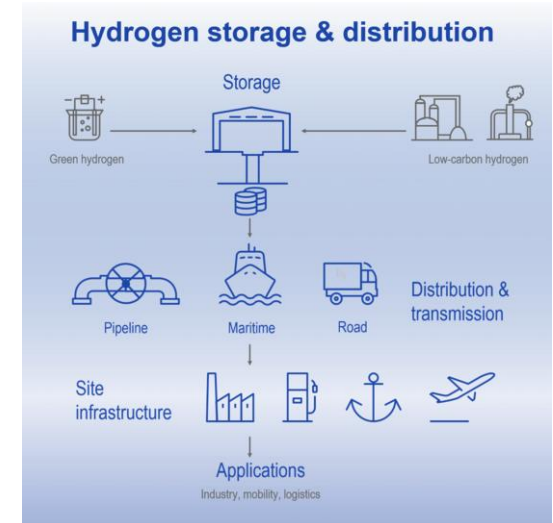
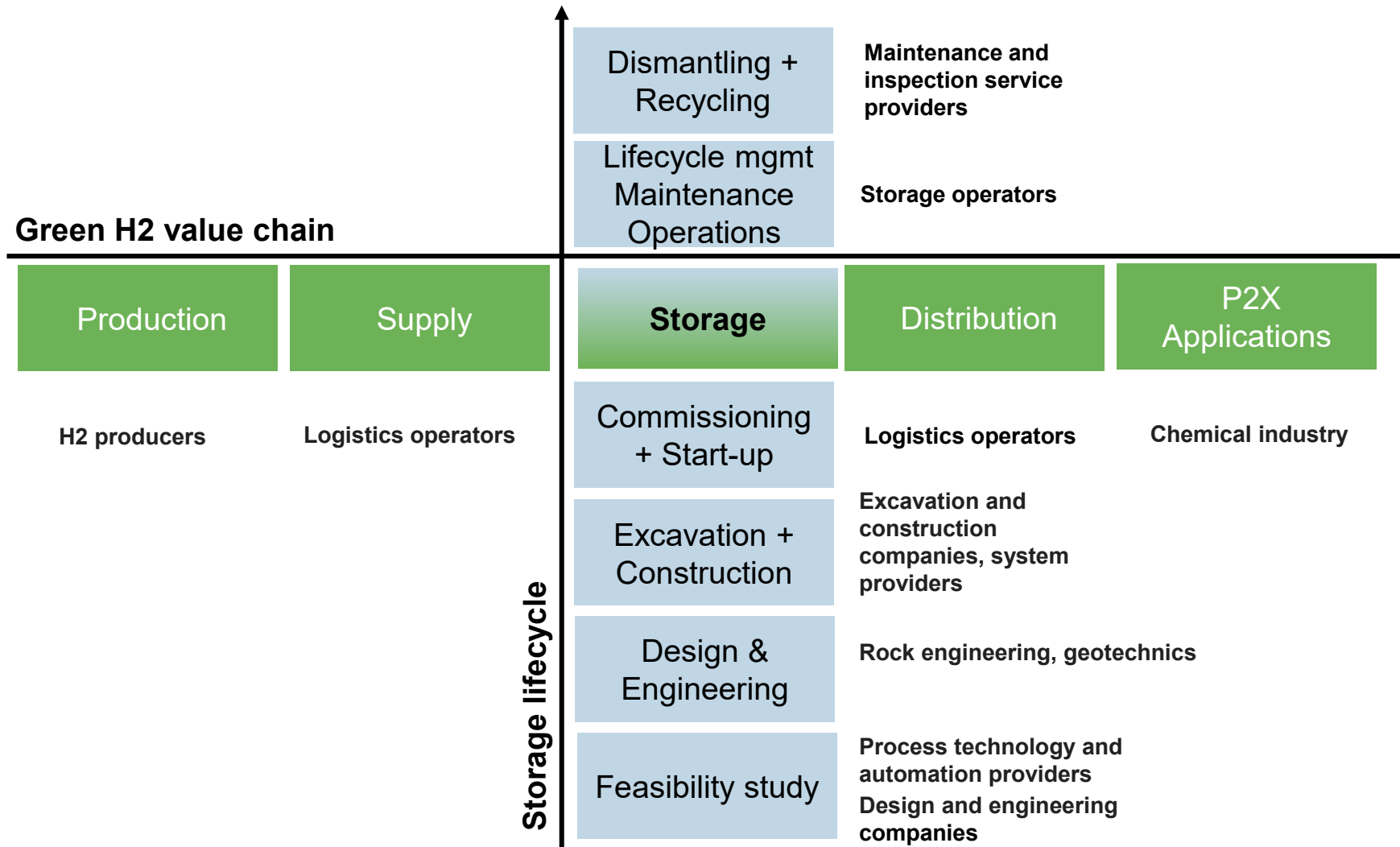
World Café arrangements

HUG – Hydrogen UnderGround

Large scale Hydrogen underground storage is a key enabler of the hydrogen economy - it allows hydrogen production and consumption to be decoupled from each other, and thus stable H₂ distribution to its users.



HUG – relevant for the whole ecosystem



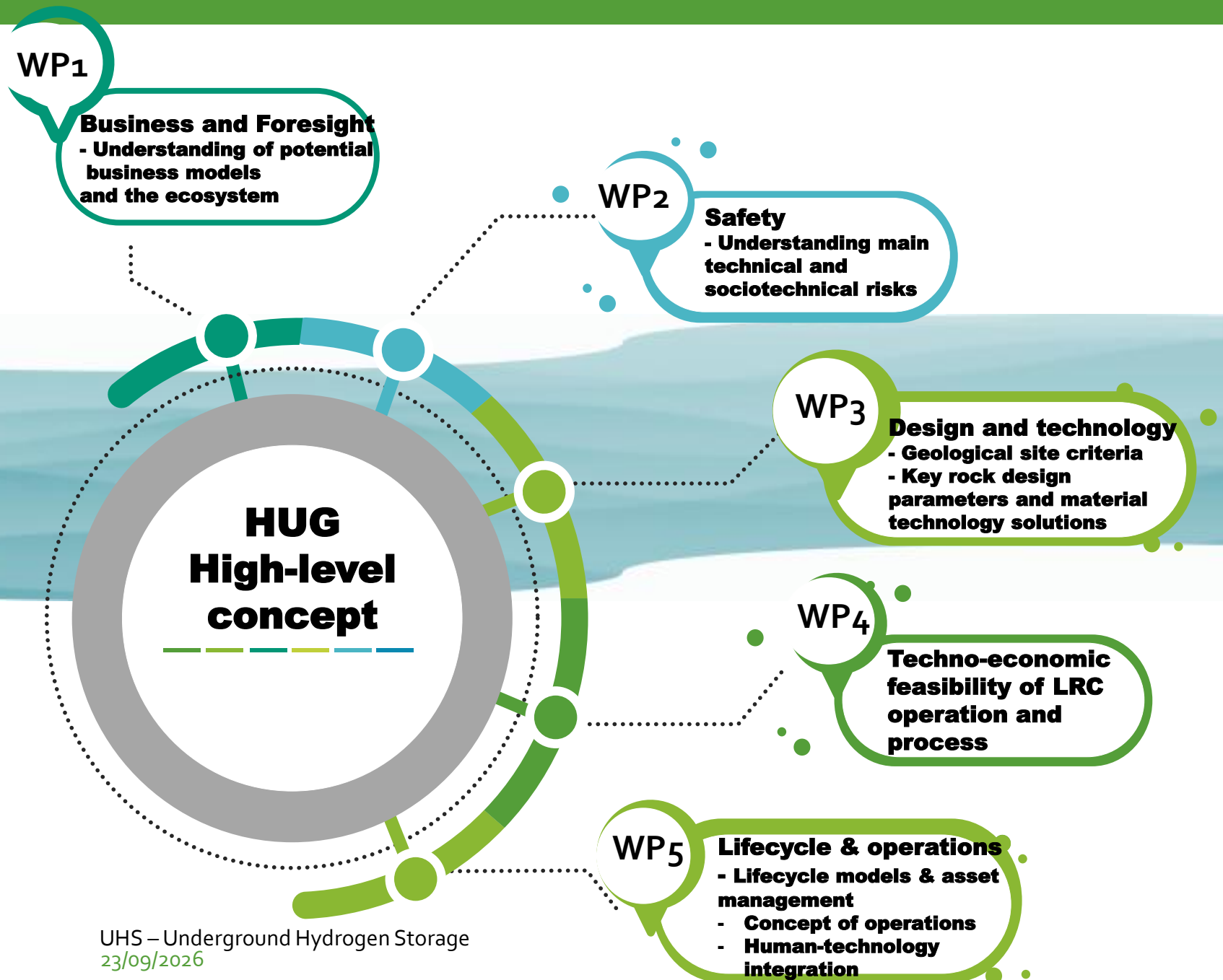
<https://www.tuvsud.com/en-id/themes/hydrogen/explore-the-hydrogen-value-chain/hydrogen-storage-and-distribution>

Regulatory body:

- TUKES

Other relevant external stakeholders:

- Vetyklusteri (audience)
- Huoltovarmuuskus



Target

Create the basis for a large-scale underground hydrogen storage concept in the business and technology ecosystem of the Finnish hydrogen industry

- Building a competitive advantage for international business → technology and services
- Large hydrogen reserves ensure a stable fossil free renewable energy system, supply of H₂ to further refiners and seamless ecosystem operation

23/09/2026

Results

1. To present 2 technical and business case studies for the construction hydrogen storage facilities in Finland
 - Technoeconomic assessment, roles of companies in the value chain and business model for storage and distribution,
 - Development roadmap together with the ecosystem
 - Cookbook for results; main takeaways for identified stakeholders
2. IP landscape and preliminary concept design of a LRC storage
3. Technical and operational safety guidelines for permit procedures for large underground hydrogen storage facilities
4. Policy brief: Strategic Deployment of Underground Hydrogen Storage in Finland

VTT – beyond the obvious

KEY TAKEAWAYS

WP1 ECOSYSTEM & BUSINESS MODELS

Peter Ýlen

Ecosystem & Business models:

Future UHS ecosystem and key bottlenecks

Key takeaways:

- UHS business ecosystem is complex, involving a wide range of stakeholders with different roles, sizes, and interests.
- UHS business ecosystem consists of both public and private sector organizations as well as third and fourth sector actors
- Key bottlenecks in UHS ecosystem development are strongly linked to business and ecosystem dynamics

UHS 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, site selection and permitting, UHS construction, operations and digital monitoring, and post-storage delivery to the customers.

There are strong interdependencies between these actors, and **no single stakeholder can develop viable UHS business models in isolation**. **Ecosystem coordination and alignment of roles** are therefore critical for successful co-evolution.

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**.

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Ecosystem & Business models

Future scenarios and potential business models

Key takeaways:

- Four relevant future scenarios reflecting different ownership and business models, and stages of hydrogen economy development in Finland were identified: 1) Open large-scale LRC in the transmission network, 2) Closed large-scale LRC in the transmission network, 3) Local small-scale LRS in the distribution network and 4) Local medium-scale LRC in the distribution network
- Five different potential business models were identified: 1) Capacity-leasing model, 2) Infrastructure-as-a-service (IaaS) model, 3) Market-driven model, 4) One customer model and 5) public-private partnership model

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 Gasgrid 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. There are unclear regulative issues related to this scenario, and the large-scale 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 well suited for the early scale-up phase and the small-scale LRS could be operational earliest in 2028. 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.

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. 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 business. Private actors design, build, operate and maintain UHS.

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Ecosystem & Business models: System Dynamics Modelling

- Chicken-and-egg dynamics
- Weakest-link dynamics
- Resource-competition dynamics

Key takeaways:

- Both models are “volatile”: In many runs no H market is created, but in some runs a vibrant H₂ market is indeed born, depending on random numbers.
- The significance of early (optimistic) adopters stands out: they encourage others to follow them.
- But with no early adopters, the Hmarket just dies...

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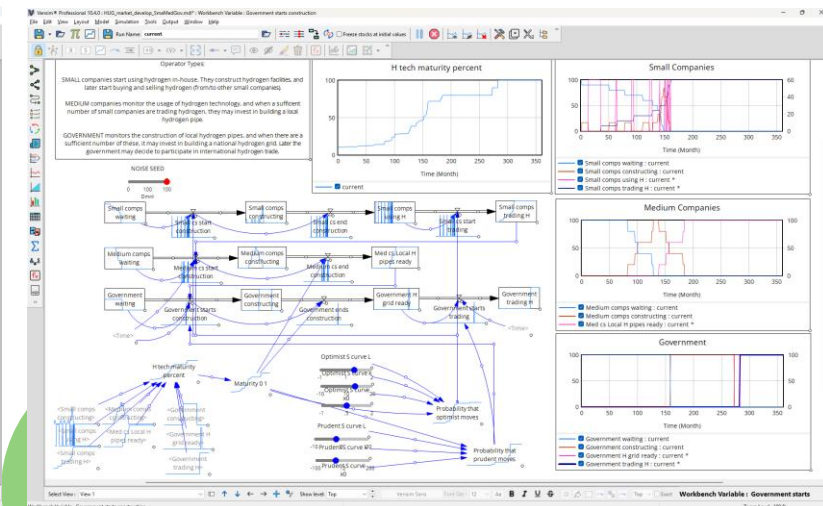
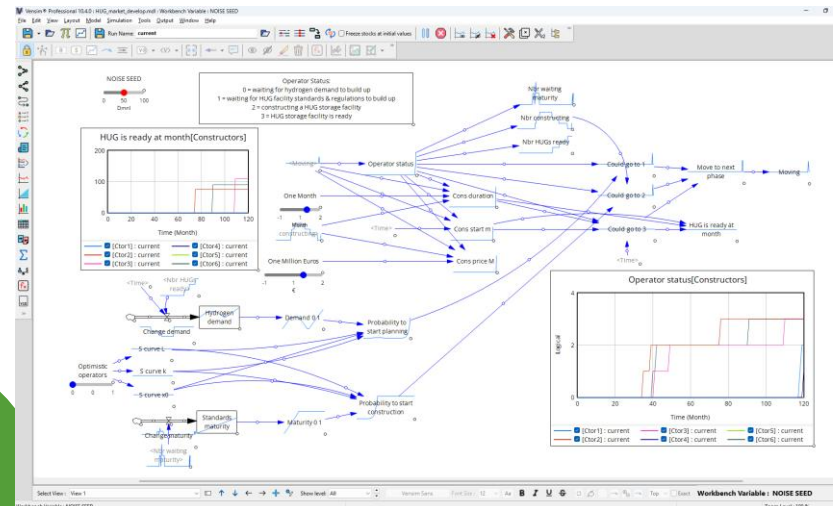
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INTERNAL

Two System Dynamics models were created:

- A number of companies (=potential investors) are waiting for H market to build up. After that they wait for standards and regulations to mature. If they decide to invest (i.e. build), they may have to compete for resources with other H builders.
- Organic, bottom-up H market: First, small companies may decide to invest in H technology in-house. Then they may decide to trade H with each other. After that, medium-sized companies may decide to build local H pipes. Finally, the government may decide to connect these local H pipes into a national H grid, and finally it may decide to start international H trading.



WP2 SAFETY

Nadezhda Gotcheva / Tero Välisalo

Technical safety:

Main hazards

Key takeaways:

- Small leakages are probable but manageable in UHS.
- Massive leakages are possible mainly in pipeline connections or tunnel plugs.
- Contamination of hydrogen with air/oxygen can cause severe hazard.
- The main parameters that affect the size of safety area of massive pipeline leakage are storage pressure, size of the surface connection pipeline and blowout direction.

The main types of hazards that endanger safety of UHS are contamination and leakage. Contamination can either deteriorate H₂ quality and/or create flammable mixture inside the storage. When storage is pressurized, contaminants can be caused by disturbances in the H₂ production. When it is depressurized, contaminants can also enter the storage from atmosphere outside.

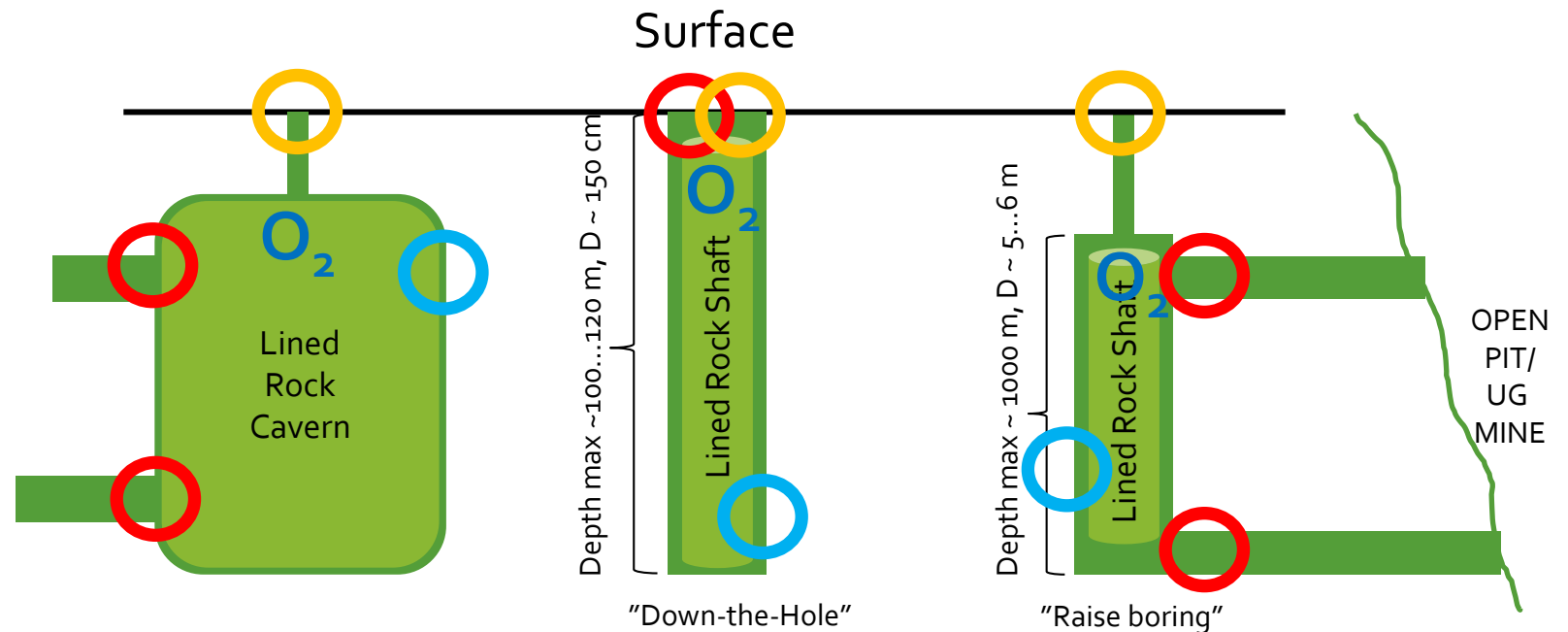
Small leakages are probable in UHS, but they can be detected in early phase if there is a dedicated pathway built in the wall structure. Massive leakages are not probable in the underground structure, but in the surface connection and plug structure this is possible.

For leakage events, there should be free storage capacity available where most of the hydrogen can be transported in case of a leakage. Water must always be available at the site, as complete emptying and filling of completely empty storage safely requires as much water as the storage volume is.

Technical safety: Common risks of different lined rock UHS types

Key common risks

- Plug failure = 
- Liner leakage = 
- Pipeline leakage = 
- Contamination = 



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Sociotechnical safety framework for UHS ecosystem

Key takeaways:

- UHS is a **safety-critical sociotechnical system**, in which **human actors** (designers, operators, managers, contractors), **technical artifacts** (machines, materials, equipment, infrastructure) and **organizational structures and practices**, as well as **external factors** interact to affect overall safety.
- We developed **UHS ecosystem sociotechnical risks framework** that helps stakeholders start thinking early about key questions at the concept stage. It supports building organizational capability to broadening safety thinking and identifying risks proactively.
- The framework integrates **structural, organizational, technological, epistemic, and cultural sources of risk**, as well as **safety culture** and **social license** aspects.
- Unwanted hydrogen event can occur if safety measures are gradually compromised through **interacting technical, organizational, and operational vulnerabilities**.
- Such vulnerabilities can be related to design, inspection and maintenance, operational practices, monitoring, organization and competences, project management and supply chain, or emergency preparedness gaps.

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WP3 GEOLOGICAL CONDITIONS

Teemu Lindqvist, GTK

Geological site selection & characterization

Key three main questions to be answered:

- 1) What are the geological criteria for underground hydrogen storage site selection?
- 2) How to evaluate geological conditions of a site?
- 3) What are the design parameters of the storage and is it technically feasible?

Main answers:

- 1) Site areas should be selected based on a number of geological criteria such as distance to major fault zones and overall homogeneity of the site. The determined criteria were applied to nine preliminary study areas. As a result, three use case sites were selected for a more detailed study. The Porvoo site was selected as best-suited for the field investigations.
- 2) The geological conditions of the selected site can be evaluated by a characterization work consisting of desktop studies, bedrock mapping, geophysical surveys and drilling.
- 3) Lined Rock Caverns (LRC): 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. The most suitable host rock is competent but fractured. 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. Raise boring enables larger dimensions.

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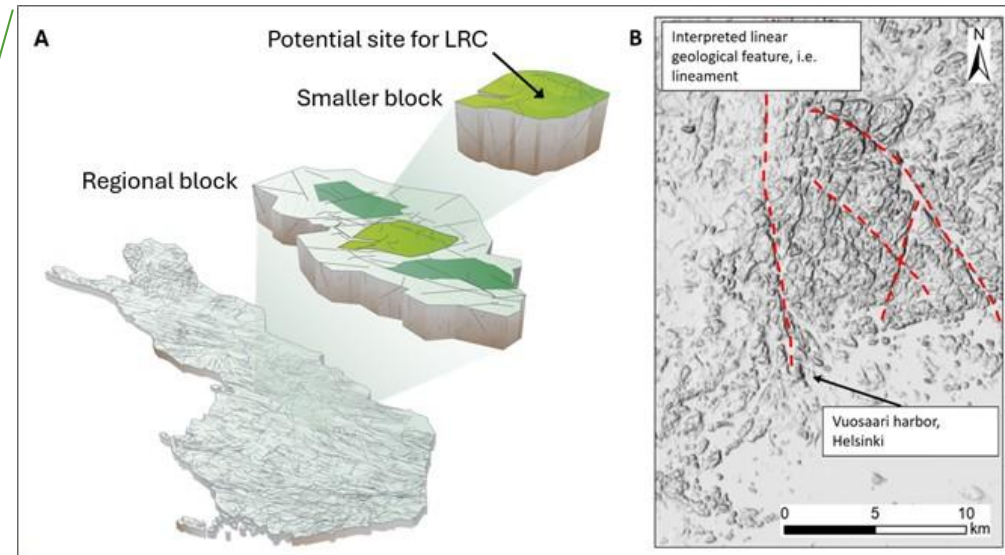
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Favourable geological conditions, vital for a technically feasible design

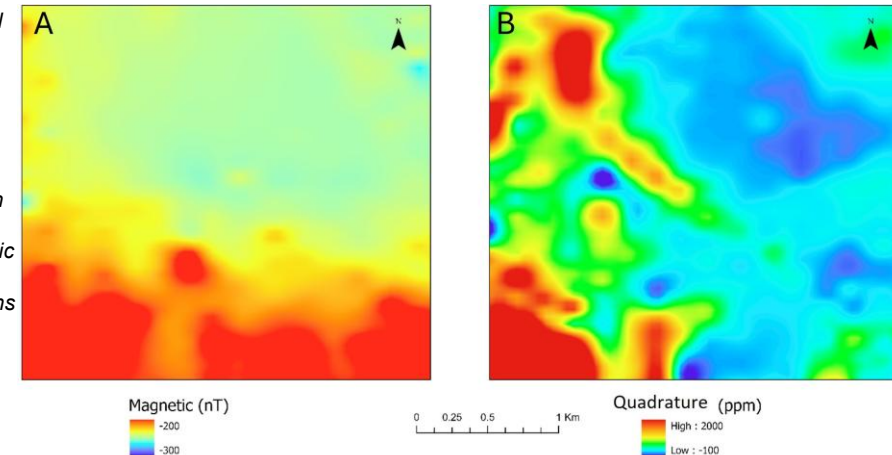
Key takeaways:

- 1) Early-stage characterization of geological conditions through desktop studies is essential for any LRC or LRS hydrogen storage project. An ideal host rock for an underground hydrogen storage facility is homogeneous, isotropic, mechanically strong, and contains a pre-existing fracture network. The site should also be located away from major faults.
- 2) Geological site characterization for LRC/LRS provides valuable information about the geological properties of the site being a framework for the technical design of the storage.
- 3) Both LRC and LRS are technically feasible as hydrogen storage concepts in Finnish crystalline bedrock. While LRC is targeted at larger scale, LRS is suitable for specific purposes that are more limited in volume.



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.

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 homogenous conditions in the northeast and more heterogeneous conditions in the west.



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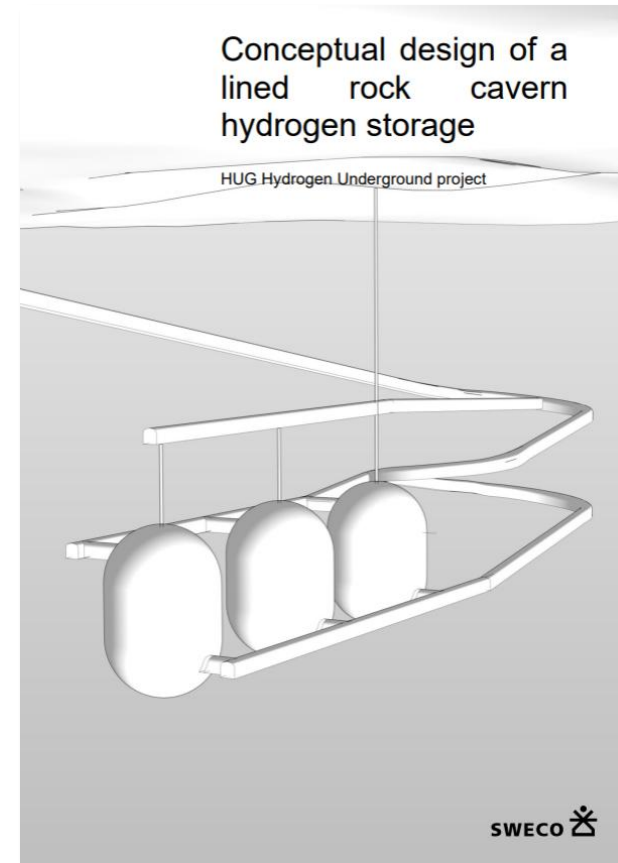
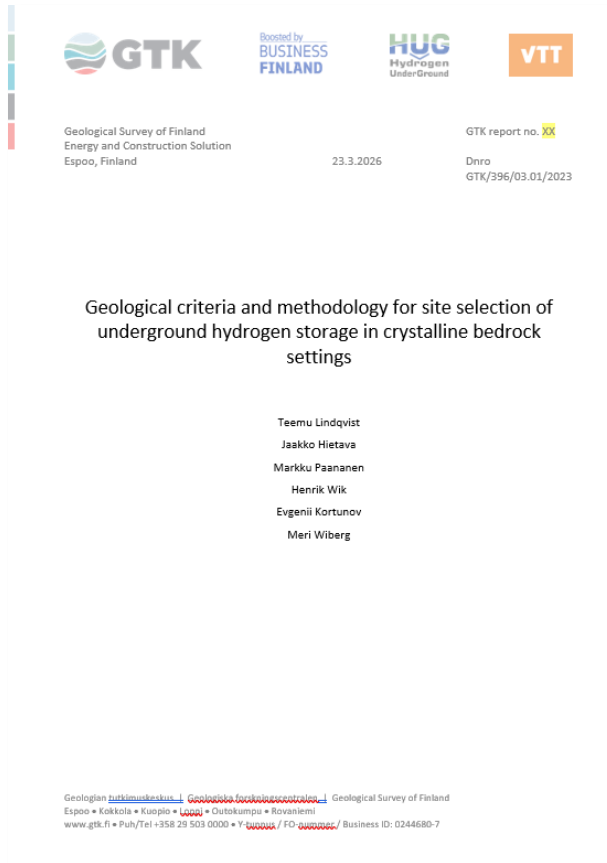
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Related key reports



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WP3 MATERIALS & STRUCTURES

Elina Paukku/Pekka Pohjanne

Design & technology / Materials and Structures

Key three main questions to be answered:

- 1) Steel liner: Map the material options that are suitable for the LRC/LRS inner liner and identify the knowledge gaps.
- 2) Concrete materials: Identification of the exposure environment and defining of accurate research needs for concrete and other cement-based materials for the liner structure.
- 3) Structure: What are the LRC/LRS construction concepts.

Main answers:

- 1) Critical performance aspects and research needs identified
- 2) Needs for testing of 2-3 suitable mix compositions in relation to fresh mix, durability and mechanical properties and selection of the final concrete mix chemical composition on the basis of test results:
 - Raw material characterization, mix design options
 - Fresh mix tests (concrete rheology, workability, pumpability, segregation, bleeding, isothermal and adiabatic calorimetry etc...) and microstructural analysis (SEM, XRD, TS)
 - Freeze-thaw, ASR, DEF and ISR, leaching properties, chloride and sulphate migration, concrete pore structure and permeability properties, hydrogen transport and interaction with moisture in concrete etc., and modelling of these + sudden temperature effects
 - "Normal" compressive strength, triaxial compressive strength, bending strength, splitting tensile strength, e-modulus, creep properties, shrinkage properties (free and restraint), effects of seismic actions etc., and modelling of some combinations in relation to structural integrity and material degradation, modelling of material behavior under static loading
- 3) Preliminary ideas of the size of the storage structure and construction feasibilities of it identified

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The inner steel liner ensure the gas tightness

Key takeaways:

The primary function of the welded steel liner is to provide a gas-tight barrier that prevents hydrogen leakages.

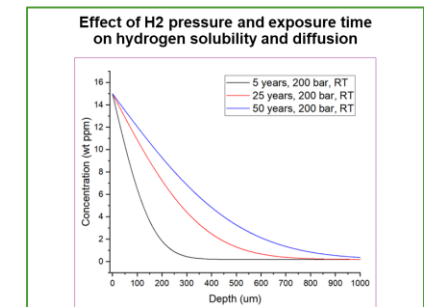
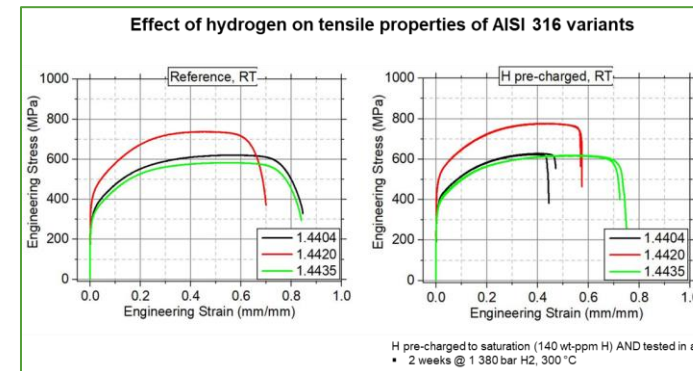
1) The steel liner, typically 8 mm to 15 mm thick, does not carry primary loads but it must withstand the maximum operating gas pressure and resist the deformation due to cyclic pressurization as well as withstand stresses and strains resulting from the cavern wall deformation.

2) The main requirement for the steel liner is hydrogen embrittlement resistance and that it can withstand significant low-cycle fatigue.

3) From outside the steel liner will be in contact to concrete and groundwater thus diverse mitigation and protection measures against external corrosion is required depending on the ground water control measures.

Austenitic stainless steels are the most probable choice for the LRC and LRS inner liner

	EN 1.4404	Carbon Steels
Crystal Structure	Austenitic (FCC)	Ferritic/Martensitic (BCC)
HE Susceptibility	Low	Moderate/high
Hydrogen Diffusion	Slow	Fast
Key Weakness	Expensive	High strength = High HE risk



Knowledge gaps regarding performance in environments and operating conditions unique and relevant to LRC's and LRS

- Hydrogen embrittlement and weld integrity in thick plates
- Long-term high strain low cycle fatigue in high pressure hydrogen and role of hydrogen impurities
- Liner corrosion in ground water and the role of concrete chemistry and sliding layer.

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WP4 TECHNO-ECONOMIC FEASIBILITY

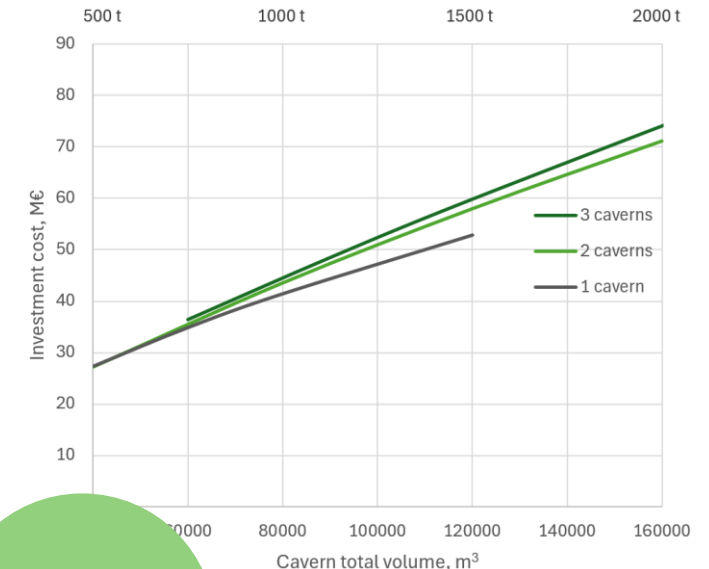
Markus Hurskainen

Techno-economic feasibility

Key takeaways:

- **Lined rock caverns (LRCs) are technically feasible and cost-effective for large-scale hydrogen storage in Finland**
- Hydrogen storage plays a decisive role in optimizing green hydrogen production systems.
- Thermodynamic behaviour is a critical design and operational driver for LRC storage - Dynamic process and CFD models are essential tools for LRC design and operation.
- Multi-stage oil-free reciprocating compressors are the most promising technology for LRC applications.

- 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 exhibits strong economies of scale, with **specific investment costs in the range of ~30–75 €/kg H₂**. These costs are a magnitude lower than those of above ground storage but significantly higher than for salt caverns.
- **Dividing total capacity into multiple caverns incurs only a modest cost penalty** and offers advantages in operational flexibility, resilience, and risk management.



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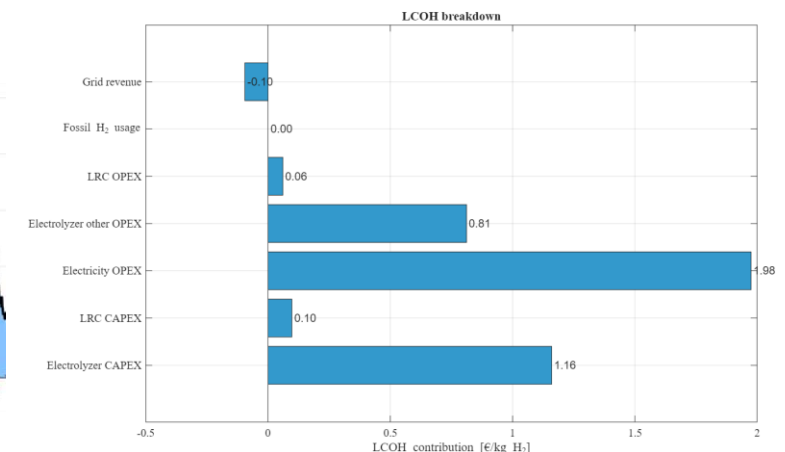
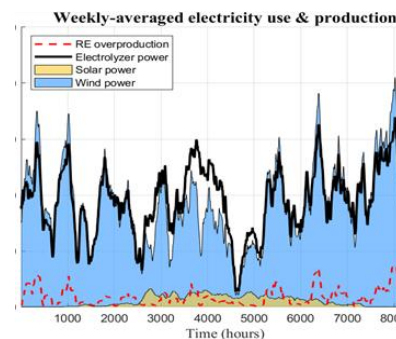
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Techno-economic feasibility

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- Multi-stage oil-free reciprocating compressors are the most promising technology for LRC applications

- Electricity is likely to remain the main cost driver of hydrogen production via electrolysis.
- It is difficult to produce RFNBO compliant hydrogen without a source of flexibility.
- Optimal storage sizes with historical market data were very large (some weeks) but similar LCOH could be achieved with significantly smaller storages by increasing the overcapacity of wind and PV
- Overall, LRC storage constitutes only a minor share of the total green hydrogen supply cost



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Techno-economic feasibility

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- **Thermodynamic behaviour is a critical design and operational driver for LRC storage - Dynamic process and CFD models are essential tools for LRC design and operation.**
- Multi-stage oil-free reciprocating compressors are the most promising technology for LRC applications.

- Dynamic simulations showed pronounced temperature variations and stratification during filling and withdrawal, which can constrain storage operation and can affect liner and rock integrity. Accurate prediction of these effects requires advanced modelling, namely CFD.
- Dynamic 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.

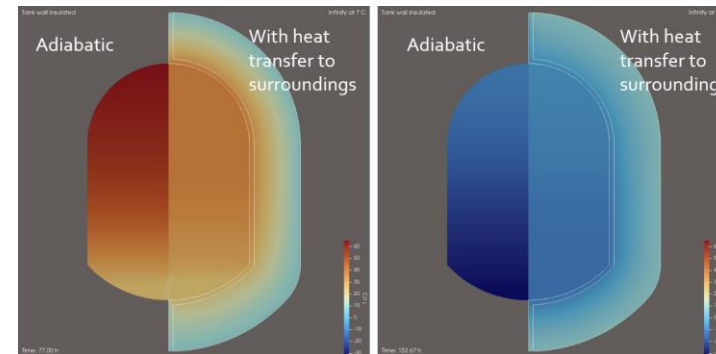


Fig. 1. Temperature stratification after filling and withdrawal

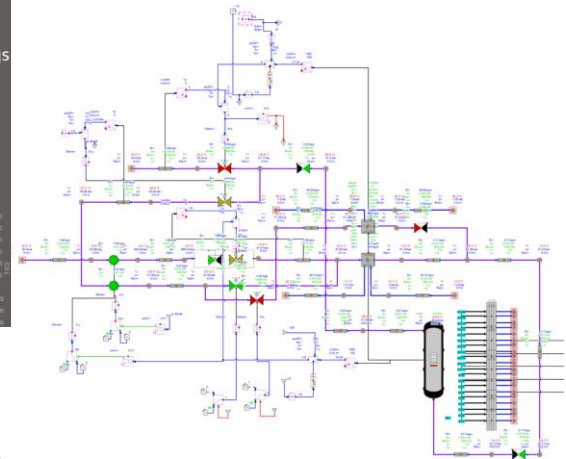


Fig. 2. Dynamic Apros model of LRC with recirculation gas system for temperature management

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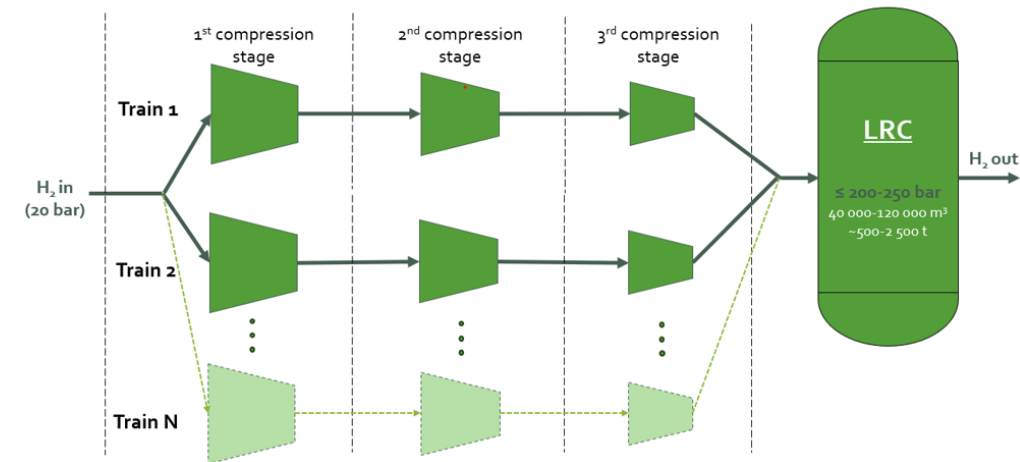
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Techno-economic feasibility

Key takeaways:

- Lined rock caverns (LRCs) are technically feasible and cost-effective for large-scale hydrogen storage in Finland
- Hydrogen storage plays a decisive role in optimizing green hydrogen production systems.
- Thermodynamic behaviour is a critical design and operational driver for LRC storage - Dynamic process and CFD models are essential tools for LRC design and operation.
- **Multi-stage oil-free reciprocating compressors are the most promising 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 upstream buffer storage.



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WP5 LIFE-CYCLES & OPERATIONS

Hanna Koskinen / Bastian Tammentie

Life-cycles & operations

Key takeaways:

- UHS is a first-of-a-kind (FOAK), safety-critical sociotechnical system. Thus, safety depends on technology, people, organizations, and regulation evolving together.
- A substantial knowledge gap in UHS operations and human factors was identified in the literature review and still exist.
- Work Domain Analysis (WDA) of UHS exposed storage system as a complex functional structure with many safety-critical dependencies.
- Human contribution to risk persists despite the advancement of automation. Importance of monitoring concept is highlighted.

UHS is a FOAK, safety-critical sociotechnical system. There is no operational experience in Finnish conditions, UHS-specific incident database, or well-established human factors for UHS.

Substantial knowledge gap on UHS operations and human factors: Literature on UHS focus on technical aspects; operational work, operator roles, and human system interaction are largely unaddressed. Meanwhile accident data from other H₂ applications show human and organizational factors are part of most adverse event sequences – there are no purely technical failures.

Work Domain Analysis (WDA) of UHS helped identify critical system dependencies, operator information needs, and safety-relevant functions. All these aspects need to be addressed as part of the storage design.

It is suggested that higher level of automation shifts the operator role from active control to monitoring, changing rather than reducing cognitive demands and making situation awareness (SA) support critical requirement for UHS monitoring concept.

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Overall objectives of WP5 were:

- Build an integrated understanding of how UHS should be operated safely, responsibly, and efficiently across its lifecycle.
- Enable integration of a human factors engineering (HFE) perspective into UHS design from the outset

Resulting key takeaways:

- A general problem in complex engineering projects is that HFE is integrated too late; as every design decision has operational consequences,
→ late integration risks leaving operator and operational implications insufficiently understood and design decisions incompletely informed.
- While WP5 has produced fundamental analyses of UHS operations (e.g., WDA and UHS monitoring concept), the work remains at an early level;
→ additional analyses are needed to define what tasks UHS operators will perform, under what conditions, and in what roles.
- Focusing on individual technical problems
→ risks overlooking system-level effects and unintentionally creating unfavourable paths that can lead to economic and safety-critical consequences.

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Monitoring concept: 10 key monitoring themes and operator-critical information requirements were identified

- Structured collaborative exercise (Teams whiteboard)
- Focus: UHS monitoring, plus operational risks, system behavior, lifecycle challenges
- Qualitative analysis of themes and information needs

H ₂ quality	Structural integrity	Environmental impact	Injection of H ₂	H ₂ storage inventory
Withdrawal of H ₂	Energy market	UHS Maintenance	Knowledge management & operational experience	Alarm concept and deviation detection

	Injection of H ₂	H ₂ storage inventory	Withdrawal of H ₂
Real-time	Injection /withdrawal rates, pressure, flow, temperature Leak, purity or pressure anomaly indicators	Inventory volume & pressure; Fullness/emptiness alarms Purity levels	Withdrawal rates, pressure, flow, temperature Leak, purity or pressure anomaly indicators Live price and demand signals; real-time grid status
Daily/shift	Shift-based planning and review Pressure, flow, temperature trend	Shift handover data; daily impurity checks; small sample testing Pressure, flow, temperature Daily maintenance planning and work-order follow-up	Shift-based planning and review Pressure, flow, temperature trend
Weekly/monthly	Weekly market planning and demand forecasting	Weekly trend analysis of purity and contaminants, Environmental compliance samples	Weekly market planning and demand forecasting

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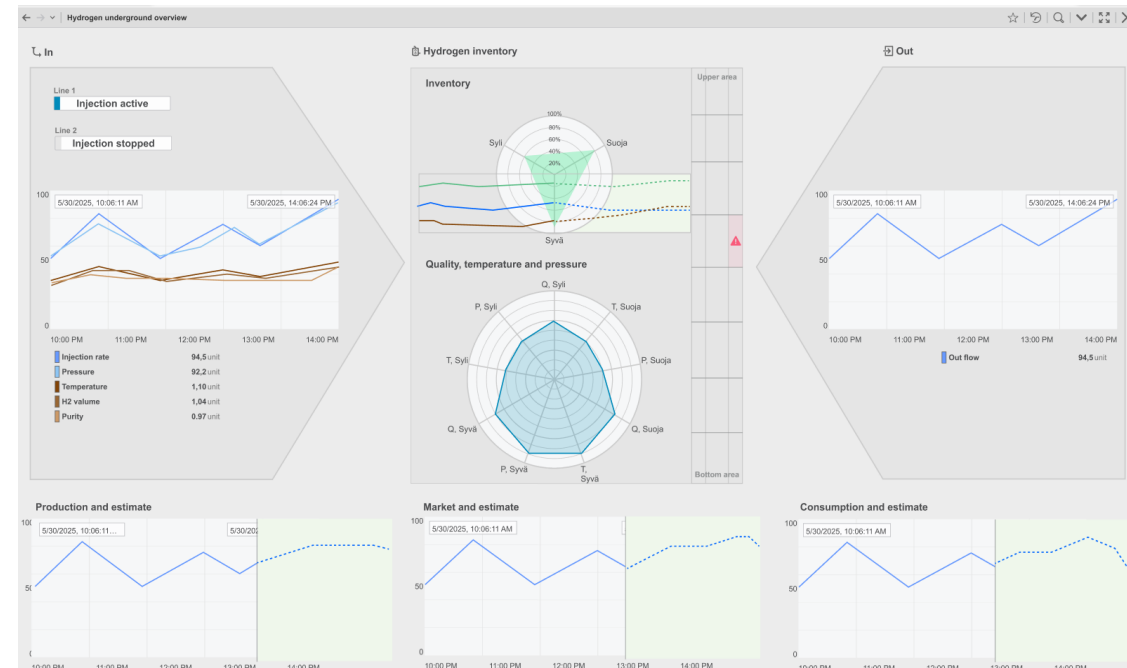
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Mock-ups produced: conceptual displays (overview/monitoring views) were created to illustrate how information could be integrated to support situation awareness (SA) and disturbance management.



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COOKBOOK

WP1

Business and Foresight
- Understanding of potential business models and the ecosystem

- Business models for HUG
- HUG Foresight radar
- HUG ecosystem map

WP2

Safety
- Main sociotechnical risks and mitigation methods

- Main technical risks in H2 storage have been identified
- Consequence analyses for high-pressure hydrogen leakages has been conducted
- H2 storage ecosystem-level sociotechnical risk knowledge

WP3

Design and technology
- Geological site criteria
- Key rock design parameters and material technology solutions

- Detailed research needs for materials and structural requirements are well identified now
- H2 storage geological site criteria has been determined based on literature, conceptual engineering and field studies.
- Conceptual engineering study of lined rock cavern (LRC) H2 storage done. Preliminary technical boundary conditions delineated for lined rock shaft (LRS) H2 storage.

WP4

Techno-economic feasibility of LRC operation and process

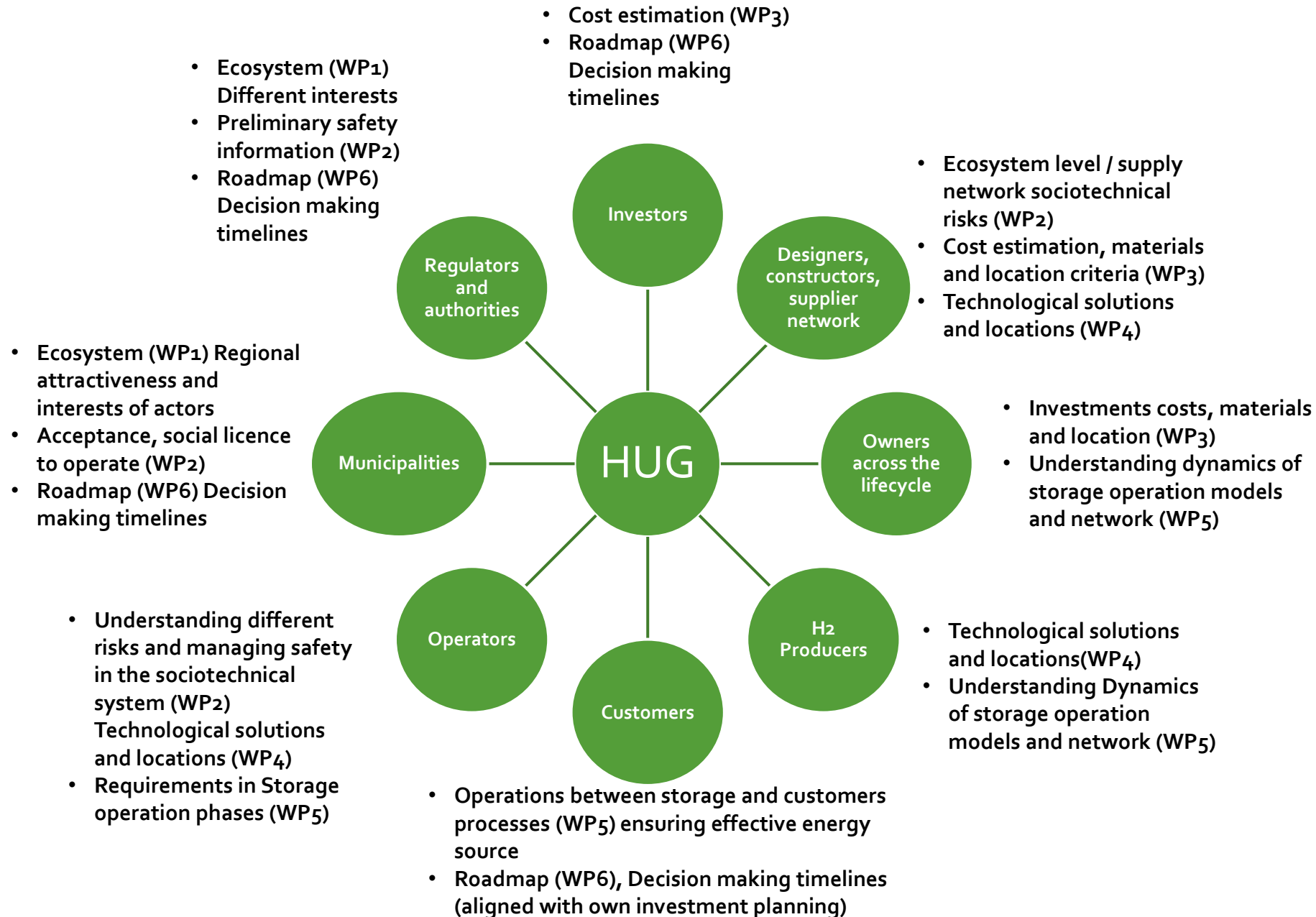
- TEA and business cases on LRC value chain
- Modelling of LRC processes
- High-level process automation aspects and compression solutions

WP5

Lifecycle & operations
- Lifecycle models & asset management
- Concept of operations
- Human-technology integration

- Operational demands and control functions from human perspective
- Monitoring framework has been determined (i.e. key information requirements).
- A plan that integrates RAMS and HFE perspectives into comprehensive guidance for safe and effective operation.

HUG
High-level concept



CALL TO ACTION

Single statement

Jaakko Paasi

Policy brief included to the projects report

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, safe and sustainable use of technologies, and business models for green hydrogen economy, including underground storing of hydrogen.

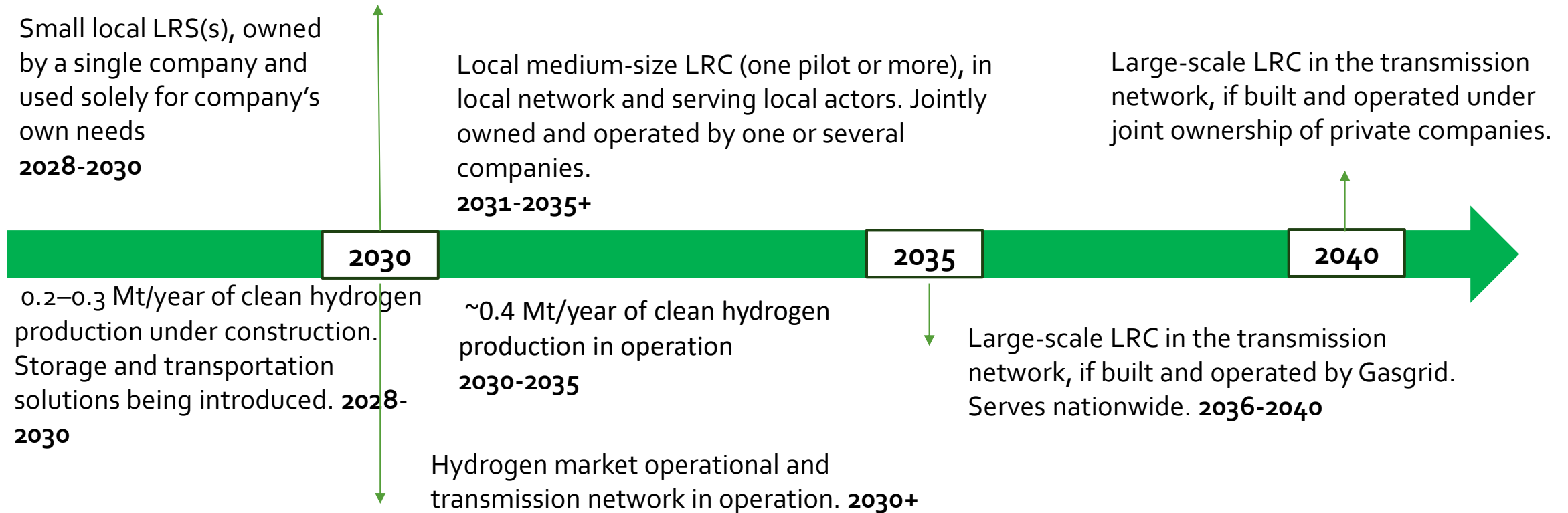
For research funders:

- A dedicated research project focused on material performance and structural design in lined rock caverns for hydrogen storage is needed before initiating a real construction work.

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 balancing resource in the emerging hydrogen system.

HUG Roadmap



NEXT STEPS

HOW TO CONTINUE

HUG2 preparation ongoing

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janne.pakarinen@vtt.fi

HUG2

Design requirements and specifications for the industrial scale H₂ storage

PILOT project
Construction and operation

00

Q1 – Q2 2026

01

Q3 2026 –
Q4 2029

02

2029->

03

2035 ->

HUG2 - Research-based design requirements and specifications

- Technical solutions for structures, materials, and rock engineering, incl. safety aspects
- Operational and lifetime management models
- Geological site characterization and rock engineering design
- Cost engineering
- *Common learning what is required to design and operate storage system*

Design target: one module of LRC, size 40 000 m³

Locations: Kilpilahti and transferability analysis of the design in Raahe/Oulu/Tornio region

Industrial scale underground hydrogen storages

Project duration:
April 2024 –
June 2026